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Integration of Municipal Infrastructure Asset Management Processes: Challenges and Solutions

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Abstract: Municipal infrastructure management decision-making is inherently an integrated process that requires the assimilation of a multitude of data, processes, and software systems. Current work practices have resulted in significant process and data fragmentation, which have subsequently created much inefficiency that impede the implementation of effective management strategies. There is a broad consensus in the industry that adopting integrated multi-disciplinary approaches is a key requirement for implementing efficient, sustainable, and proactive asset management programs. This paper discusses the main challenges for implementing integrated municipal infrastructure management environments (MIMEs), and proposes specific solutions to address these challenges. The proposed solutions address the systematization and coordination of work processes, the development of centralized shared data repositories based on non-proprietary integrated data models, and the organization and integration of distributed software tools into a modular and extensible enterprise-wide software environment. The implementation of a prototype sewer management environment based on the proposed solutions is also presented.

INTRODUCTION

Municipalities are facing increasing challenges due to the ageing and deterioration of infrastructure assets, inadequate renewal budgets, climbing renewal deficits, increasing demand levels, and new requirements to comply with stricter environmental and accounting regulations (Danylo and Lemer 1998; Grigg 1999; Halfawy 2004). These challenges have placed significant pressures on municipalities to improve the effectiveness of managing their infrastructure inventory through adopting more efficient, sustainable, and proactive asset management strategies.

The increasing complexity and sophistication of infrastructure management processes resulted in creating diverse areas of knowledge, expertise, and responsibilities within and across municipal departments (e.g. water, sewer, and road management). As a result, a state of process fragmentation was created, and much inefficiency has subsequently arisen primarily due to the enormous volume of complex information that needs to be generated and exchanged, and the difficulty to streamline and coordinate these inter-dependent processes.

Throughout the last two decades, municipalities have made significant investments in implementing software tools to address the increasing complexity of the infrastructure management processes (Vanier 2001; Halfawy et al 2006a). Although the use of these tools has, undoubtedly, improved the efficiency of managing infrastructure assets, ironically it exacerbated the negative impact of process fragmentation by creating information gaps between these processes. The majority of the software tools were developed to function as stand-alone systems, and many have limited or no capability for sharing or exchanging information with other tools. Each tool typically implements a proprietary data model, and stores and exchanges data in a proprietary file format. Oftentimes, data are re-interpreted, transformed and re-entered into different software tools several times. This process is known to be inefficient, time-

consuming, and prone to errors. Subsequently, isolated “silos” of information and a state of data fragmentation are created within and across municipal departments. This fragmentation has negatively affected data consistency, integrity, accuracy, and accessibility.

The desire to implement efficient and optimized infrastructure management strategies has created a strong demand for “bridging the gaps” through adopting integrated approaches. An integrated approach to infrastructure management can potentially eliminate many of the fragmentation inefficiencies by enabling the integration of data and software resources, coordination of decision-making processes, and the efficient sharing and management of asset lifecycle data. The need to adopt an integrated approach to infrastructure management is widely recognized in industry and academia (Lemer 1998; Grigg 1999; Halfawy et al., 2002; InfraGuide 2007a). Danylo and Lemer (1998) described the main role of an infrastructure asset management system as “an *integrator*, a system that can interact with and interpret the output coming from many dissimilar systems.” Shen and Spainhour (2001) emphasized that “the tools and methodologies for infrastructure lifecycle management should integrate environmental, economic, and technical issues into a *total solution*.”

Although significant research efforts have focused on developing techniques and models to support individual infrastructure management processes, the development of integrated models has received little attention in the literature. Ganeshan et al (2001) developed a collaborative and integrated environment (CITYWORK) to support maintenance management of civil infrastructure systems. That study emphasized the need for integrated infrastructure management systems, however, it pointed out that “it will require significant investments in time, effort, and resources to get these environments created and customized.” More recently, Pradhan et al (2007) proposed a three-tiered architecture that separates the functionality

between data, business logic, and applications tiers, to support the development of integrated infrastructure data repositories and decision support systems for disaster management.

This paper proposes solutions that could potentially facilitate the development of integrated municipal infrastructure management environments (MIMEs). The integration problem is tackled by first adopting an organizational approach to coordinate and streamline the infrastructure management processes, and second, by defining a scheme for data integration and management, as well as an open and extensible software architecture for integrating the distributed information and software resources. An integrated process model that systemizes the structure, organization, and information flow among processes is described. The development of integrated data models and shared repositories to assist in assimilating and managing asset data, and facilitating data sharing and exchange is also discussed. A multi-tier modular software architecture that organizes and integrates software tools into an open, coherent, and interoperable environment is presented. Finally, a software prototype that demonstrates the implementation and feasibility of the proposed solutions is discussed.

DEPARTMENTAL AND MULTIDISCIPLINARY PROCESS INTEGRATION IN MUNICIPAL INFRASTRUCTURE MANAGEMENT

An ideal integrated approach should integrate municipal processes across two axes: departmental and multidisciplinary (Figure 1). The departmental, or vertical, integration axis is concerned with the integration of data, processes, and software tools within the same municipal discipline (e.g. sewer management). The processes within any municipal department should address asset life-cycle aspects across the sustainability “tripod,” which includes the economic, social, and environmental aspects. Moreover, the approach should integrate processes across different levels of management: operational, tactical, and strategic, to improve the efficiency

and cost-effectiveness of short-term and long-term plans. Recently, several efforts have addressed the departmental integration of infrastructure management processes. Examples of these efforts include the computer-aided rehabilitation of water networks project (CARE-W 2007), the computer-aided rehabilitation of sewer networks project (CARE-S 2007), and the Federal Highway Administration (FHWA) effort for integrating transportation infrastructure management processes (FHWA 2001).

{Figure 1: Departmental and multidisciplinary integration of municipal infrastructure management processes}

Municipal infrastructure assets are typically managed with little or no consideration to their inter-dependencies. This lack of integration has created significant inefficiencies in maintenance coordination and renewal planning. Optimally, renewal plans for assets at a particular area should be coordinated to span multiple co-located infrastructure assets as much as possible, thus reducing or eliminating unnecessary rework, and minimizing the disruption, costs, and risks associated with maintenance operations. The multidisciplinary, or horizontal, integration axis involves bridging multiple municipal departments to develop holistic, coordinated, and optimized plans for the management and renewal of spatially co-located infrastructure assets (e.g. water mains, sewer, and road assets within a right of way). The multidisciplinary integration dimension has been rarely discussed in the literature, and a systematic method that addresses this issue has yet to be developed. However, a number of practical guidelines have been proposed. For example, an InfraGuide Best Practice (InfraGuide 2005a) outlined some considerations for optimizing the renewal planning of co-located water mains, sewers, and road assets.

The multidisciplinary integration dimension may be extended to include other non-municipal inter-dependent infrastructure systems (e.g. transportation, power) to facilitate regional

infrastructure integration. This level of integration would require sharing data and explicit modeling of infrastructure interdependencies across organizations (municipalities, utilities, etc.). This region-level integration would be critical for supporting and coordinating emergency response and disaster management processes across various organizations (Pradhan et al 2007).

CHALLENGES AND CHARACTERISTICS OF NEEDED SOLUTIONS

Integrated MIMEs must support three main requirements: (i) efficient coordination and information flow between inter-dependent processes; (ii) efficient integration and management of infrastructure lifecycle data, within and across municipal departments, in a unified and interoperable environment that maximizes the reuse and sharing of data; and (iii) integration of various software applications through the use of an open and modular software architecture. Satisfying these requirements would require addressing three main challenges: (i) the process systematization and coordination challenge, (ii) the data integration challenge, and (iii) the software integration challenge. Solutions to these challenges should be based on proper understanding of the organizational and operational aspects of municipal infrastructure management, as well as on an accurate characterization of the methods and technologies currently used to support various processes. This section briefly discusses each of these challenges and the main characteristics and roles of the proposed solutions. Then, the following three sections present specific proposals to implement these solutions.

Explicit Models for Systematization and Integration of Infrastructure Management Processes

Management of municipal infrastructure assets involves many complex, inter-dependent, and data-intensive processes (e.g., condition assessment, renewal planning, etc.). These processes typically involve the generation and manipulation of large data sets with complex

interrelationships. Most of the processes still remain largely heuristic and subjective in nature, documented mainly in the form of guidelines or manuals of “best practices.” Subsequently, many processes are still performed in an unstructured inconsistent manner, which impedes efficient coordination and data flow. The systematization and structuring of these processes should be the first step in developing an integrated infrastructure management approach. Formalization of an explicit process model that defines the structure, organization, and interdependencies of the main processes, and their data flow requirements can provide a critical tool to harmonize and integrate the data and software tools associated with these processes.

Due to their inherent heuristic and subjective nature, specific methods and practices in implementing infrastructure management processes may vary between municipalities. However, these processes still share similar structure and information requirements across municipalities, regardless of the size or characteristics of the infrastructure systems. Also, the increasing complexity and inter-dependencies of these processes created a strong need to systematize the existing practices, and to reduce the subjectivity of the decision-making processes. Therefore, the formalization of a generalized process model seems to be desirable and necessary. Specifically, defining and adopting an explicit process model can serve the following functions:

1. Serve as a tool for documenting the structure and organization of key processes and information flow, which would aid in systematizing the existing practices and reducing the subjectivity of the decision-making processes.
2. Enable municipalities to promote consistent vision and work practices among various departments, which would aid in process planning and coordination.
3. Enable better management of process inter-dependencies within or across municipal departments, and with external stakeholders and organizations.

4. Support process evaluation and continuous improvement to tackle communication and coordination problems, eliminate inefficiencies associated with data flows, and enhance the overall process efficiency.
5. Serve as a framework to classify and organize the vast body of domain knowledge, decision models, and technologies associated with these processes.
6. Assist in eliciting, documenting, and retaining in-house “expert” knowledge.
7. Guide the design, implementation, and deployment of software systems by identifying the required or missing functionality and interfaces, and directing the efforts on developing needed methods and technologies.

Shared Data Repositories and Data Modeling Standards for Asset Data Integration

Data integration is defined as “the process of combining or linking two or more data sets from different sources to facilitate data sharing, promote effective data gathering and analysis, and support overall information management activities in an organization” (FHWA 2001). The main benefits of data integration and sharing include data availability/accessibility; timeliness; accuracy, correctness, and integrity; consistency and clarity; completeness; reduced duplication; faster processing and turnaround time; lower data acquisition and storage cost; informed and defensible decisions; and integrated decision-making (FHWA 2001).

Currently, municipal infrastructure data are mostly shared and exchanged between software tools through file exchange, using neutral or proprietary formats. Some applications provide programming interfaces (API), where sets of function libraries can be used to access the application’s internal, typically proprietary, data model, and to input or extract data, into or from the software. Although some of the vendor’s data models, file formats, or API appear to be de-facto industry standard, the majority of these interfaces remains proprietary and tool-

specific. The use of these data exchange methods imposes unnecessary constraints by requiring the use of proprietary data models and software applications. Moreover, file-based data exchange is extremely limited in supporting the implementation of efficient data management functions needed for data sharing, maintenance, and integration. The sheer size and interdependencies of the data, inconsistencies in data models and formats, and the extensive data flow requirements, make the use of these methods inefficient and impractical.

Municipal infrastructure decision-making requires access to a multitude of data about infrastructure inventory, condition, risk levels, performance metrics, renewal options, etc. Efficient representation, integration, management, and sharing of these data sets can only be practically achieved through the use of comprehensive and integrated databases. Data management services such as multi-user data access and editing, concurrency control, version management, data security and authentication, and other services critical for ensuring data integrity and consistency can only be realized using an integrated database.

An integrated database can generally be implemented using a centralized or distributed architecture. A centralized database stores and manages the data in a single repository, while a distributed database stores the data at multiple, homogeneous or heterogeneous, repositories (Elmasri and Navathe 1999). A main advantage of the distributed architecture is that the database structure can be adapted to the municipal organizational structure by implementing a repository for each department (e.g., water and road departments will have two separate local repositories). Local repositories could be maintained by their respective departments, while being transparently accessed by other departments. Modularity and increased reliability are key advantages of the distributed architecture (Ozsu and Valduriez 1999).

However, distributed databases are traditionally more complex and expensive to build and maintain compared to centralized databases. Data query performance can be significantly

degraded when accessing data across multiple repositories (e.g., a join or update that involves tables in different repositories). Also, ensuring data integrity across multiple repositories may require significant network traffic. Moreover, commercial offerings of distributed databases are still very limited and fairly unfamiliar in the construction and public works industry.

Amor and Faraj (2001) raised some issues against the adoption of centralized databases in the architecture/engineering/construction (AEC) industry. Key among those issues is data ownership and control. Given the nature and organizational structure of AEC projects, where several independent organizations come to share project-specific data during the project duration, using a distributed database architecture may represent a more practical data sharing solution. More recent work to develop “model servers” (SABLE 2007) addressed this issue by enabling partial access and exchange of integrated project data by multi-disciplinary independent project teams.

However, the issue of data ownership and control may not be as significant in the context of municipal infrastructure management. The well-established organizational structure of municipal departments, the long-term business relationships, even with external partners (e.g., consultants and contractors), and the inherent desire and motivation to share data and coordinate decisions, make the use of a centralized repository architecture a more feasible and practical option for MIMEs. Moreover, the increasing trend of deploying centralized enterprise-wide geographic information systems (GIS) repositories in municipalities and utility organizations (GITA 2005; IDC 2005) provides a clear evidence of the practicality and wide acceptance of centralized database architecture in the industry.

A centralized repository provides a single point of accessing and maintaining infrastructure data, which would support software interoperability and improve data flow. The features of today’s commercial database management systems, the experience accumulated in

using and deploying these systems, and the availability of trained personnel makes the adoption of a centralized repository even more attractive.

Open and Modular Software Architectures for Integrating Data, Processes, and Disparate Software Tools

Developing an integrated MIME as one single system is both infeasible and impractical. The enormous scope and complexity of various processes, the substantial investments already made in implementing specialized software tools, and the significant cost and time needed to build a monolithic system, make the development of such a system highly unlikely. An integrated MIME is ideally developed by integrating a set of loosely-coupled, independent, and interoperable software components, organized and integrated to support the infrastructure management processes in a holistic, coordinated, and systematic manner. These environments should also enable the reuse of already existing software tools by supporting open, non-proprietary, and vendor-neutral data models and software interfaces.

Defining a generic “reference architecture” for MIMEs can undoubtedly facilitate their implementation, and improve the consistency, interoperability, and reusability of software tools across municipalities. The notion of “reference architecture” is based on the observation that software systems in a specific domain typically share common characteristics and requirements, and therefore can share a common architecture (Tracz 1994). Tracz (1994) defined the concept of domain-specific software architecture (DSSA) as “a process and infrastructure that support the development of a domain model, reference requirements, and a reference architecture for a family of applications within a particular problem domain.” MIMEs reference architecture would represent an abstraction of a typical environment, primarily describing the organization and overall functionality of the major software components and interfaces for integrating data,

processes, and software tools. Among the many qualities typically desired for software architectures (Chastek and Ferguson 2006), the two most important qualities of MIMEs architectures are: openness and modularity.

First, to maintain the flexibility and extensibility of MIMEs, the reference architecture should be based on open and vendor-neutral protocols (e.g. data models, formats, APIs). An open architecture should enable the integration, reuse, and interoperability of independent software tools. Also, given the availability of many software tools and the rapid technology improvements in these tools, an open architecture should also enable replacing a tool with another or adding new tools without impacting other components. Second, a modular architecture would help separate the responsibilities between various software components according to their role, e.g. user interface, generic services, data repository, or task-specific functionality. A modular architecture would also help to accommodate future modifications and extensions of the environment, and allow for incremental implementation and deployment.

INTEGRATED SYSTEMS IN AEC AND MUNICIPAL INFRASTRUCTURE DOMAINS

After almost two decades of research and development efforts, the construction industry quest to develop integrated systems has yet to adequately address the municipal infrastructure domain. With the recent driving forces to adopt more coordinated and efficient approaches in managing municipal infrastructure systems, the development of integrated MIMEs is currently attracting the attention of many professionals and researchers. Clearly, the development of MIMEs would benefit from and build upon many of the previously developed concepts to realize integrated systems in other domains. Integrated systems in the AEC domain, in particular, seem to exhibit many of the characteristics and requirements of MIMEs.

It may be argued that the goals of data and process integration in the AEC domain, in spite of the significant efforts and investments made, have been only partially realized, and therefore achieving these goals in the municipal infrastructure domain would require similar levels of effort, investment, and time. However, it may also be argued that achieving this integration in the municipal infrastructure domain would be more feasible and attainable for at least two reasons. First, the experience gained and lessons learned during the development and evolution of AEC data models and integration techniques, as well as the recent advances in data management and software development technologies will undoubtedly help expedite the development in the municipal infrastructure domain. Many of these techniques and technologies may only need to be “adapted” to the specific characteristics of the municipal infrastructure data and processes. Second, while researchers frequently identified the lack of “big players” and small size of organizations, and the temporary project-specific business relationships as the main obstacles toward realizing integrated solutions in the AEC domain, these obstacles are not the same in the municipal infrastructure domain. The organizational structure and business relationships in utilities and municipalities are quite conducive to the implementation of integrated solutions. Also, as owners and operators of public infrastructure assets, municipalities can strongly influence industry practices and dictate certain approaches (e.g., data standards, technologies). More importantly, consensus on practice and technology issues (e.g., through best practice manuals) among municipal practitioners can be formulated and adopted more quickly and easily.

AN INTEGRATED PROCESS MODEL FOR MUNICIPAL INFRASTRUCTURE MANAGEMENT

Several process models were defined in other domains such as building construction (Turk et al 1998; Karhu et al 1997) and building maintenance management (Hassanain et al 2003). However, explicit process models are not as common in the municipal infrastructure management domain. Several researchers have described the processes needed to implement municipal infrastructure management programs. Lemer (1998) described these processes as being comprised of two main sets of issues: (i) asset identification, appraisal, and valuation; and (ii) asset deployment, utilization, exchange, and reinvestment. Vanier (2001) identified six main areas of infrastructure asset management that were referred to as the “six whats?.” These areas included: asset identification, valuation, maintenance backlog, condition, remaining service life, and maintenance prioritization. Although these high-level definitions provided insight into the main processes, they did not provide sufficient details about their organization, inter-relationships, and information requirements. Therefore, formalizing a more detailed process model is needed.

Figure 2 provides a schematic of a proposed process model. Based on an analysis and characterization of the processes as they are performed in actual practices, the process model explicitly defines the organization, inter-relationships, and information requirements of a set of nineteen high-level processes that are typically undertaken within municipal departments, albeit with different degrees of sophistication. These processes span the entire spectrum of infrastructure management levels, ranging from operational, to tactical and strategic levels. The model emphasizes the organization and relationship of the processes, rather than the details of individual processes. The relationships between different processes are defined according to their information dependencies, which would imply the order in which these processes are

typically performed. The model is expressed using the standard IDEF0 notation (IDEF 2007). Due to space limitations and the need to describe the entire model, two main deviations from the standard notation were made. First, all the context and non-context diagrams were combined into one diagram. However, this diagram can be easily broken down into its constituent diagrams using the hierarchical feature of IDEF0. Second, the process controls and mechanisms elements were omitted to simplify the model, and only the input and output elements were shown.

{Figure 2. Structure and information flow of a generalized municipal infrastructure management process model}

The apparent complexity of the model reflects the complexity of the processes and interrelationships it represents. Some specific observations about the processes and their interrelationships as depicted in Figure 2 are highlighted below.

- Preparation of the asset inventory databases (P1) is the most basic process that almost all other processes are dependent upon. This process typically requires entering, validating, and reconciling data from different sources (e.g. CAD drawings, maps, databases) and conducting field surveys to collect or verify asset data.
- Work Management (P18) typically includes day-to-day activities such as the logging of performance problems or service requests, issuing and tracking work orders, and scheduling routine maintenance. Most of today's commercial asset management software are mostly work management systems (Halfawy et al 2006a).
- Asset Valuation (P5) establishes replacement costs based on current condition and life-cycle considerations. Recently, this process has been widely introduced by the new accounting

and reporting regulations such as the Government Accounting Standards Board (GASB) Statement 34 in the U.S. or Bill 175 in Ontario, Canada.

- Determining current and future asset condition (P2 and P7) is critical for assessing remaining service life and risk of failure (P9), guiding decisions on inspection and non-destructive testing (P3), selecting appropriate renewal options (P11), and assessing the asset performance to satisfy required levels of service (P12).
- Deterioration modeling (P7) defines deterministic or probabilistic methods to predict the asset deterioration rate and mechanisms, and to determine asset condition at any stage of its lifecycle. Deterioration model are used to support lifecycle cost analysis (P8), asset valuation (P5), prioritization (P14), and renewal planning (P15) processes.
- Performance Evaluation (P4) is often considered as an integral part of the condition assessment process (P2). The definitions of condition and performance measures are often overlapping, and may be used interchangeably (Grigg 2006). In the proposed model, condition indicators (P2) are used to reflect the state of the asset structure, while performance measures (P4) are used to reflect the asset capacity, in its current or projected condition state.
- Performance Monitoring (P6), typically used for critical assets, is important for establishing and validating accurate figures for asset condition state (P2), and for calibrating performance evaluation models (P4).
- The Demand Assessment and Forecast (P16) identifies the current and future levels of demand, which can be used to set policies regarding service levels (P12) and performance requirements. This analysis can guide decisions to prioritize renewal options to efficiently satisfy both current and future demand levels.

- Quantifying the risk of asset failure (P9) is used for supporting asset prioritization (P14), planning of inspection and non-destructive evaluation (NDE) (P3), and determining the need for performance monitoring (P6). The risk of failure is typically measured as the cost consequences of failure multiplied by the probability of failure.
- Selection of appropriate renewal technologies (P11) requires accurate assessment of the applicability of different technologies, expected condition (P2) and performance (P4) improvements, as well as the life-cycle costs (P8) of various options.
- Asset prioritization (P14) uses information about asset condition (P2), risk levels (P9), and the gap between asset performance and required levels of service (P12), to rank the assets according to the urgency of renewal. While there is no agreed upon method for asset prioritization, some guidelines or best practices were defined (e.g., InfraGuide 2005b).
- The renewal planning process (P15) defines short- and long-term plans for asset rehabilitation and replacement. Renewal plans identify the assets to be rehabilitated or replaced and the technologies to be used in a way that optimizes the allocation of budget, maximizes assets performance, minimizes risk of failure, and minimizes life-cycle costs. Plans should coordinate actions across co-located assets, which would require multi-disciplinary integration across different municipal departments.
- Construction Projects (P17) may be initiated by: (i) work orders resulting from service requests, scheduled routine maintenance, or emergencies; or (ii) projects resulting from renewal plans. Data produced from construction projects can be used to update the as-built records and inventory database, and other datasets needed for planning future projects (e.g. costs).

A process depicted in the model does not necessarily indicate a single work task, but rather it may involve a number of other lower-level sub-tasks. The level of granularity of each process

would mainly depend on the sophistication and maturity of the methods and tools employed in a particular municipality. A process, for example, may be executed by one or more persons, supported by one or more software tools, or performed in a manual fashion. Moreover, specific implementations of the proposed model may modify it by decomposing these basic processes into smaller tasks to match the actual processes in a particular municipality. Due to its generic nature, the process model does not describe specific methods to perform these processes. Therefore, application of the process model to specific municipal departments (e.g. sewer management) would require defining asset-specific models and techniques to support each of these processes. For example, a municipality may adopt one of the many available protocols to rate the condition of sewers or use a specific condition rating software.

INTEGRATED DATA MODELS FOR DEVELOPING SHARED INFRASTRUCTURE DATA REPOSITORIES

Building infrastructure data repositories requires the development of an integrated data model, and a corresponding database schema, that represents various life-cycle aspects of the infrastructure assets. During the last two decades, significant efforts addressed the development and standardization of integrated data models in the AEC industry (e.g., Bjork 1994; Teicholz and Fischer 1994; Froese 1996; Brown et al 1996; Eastman 1999; Halfawy and Froese 2005). Recently, some of these models have reached a high level of maturity that offered the industry an unprecedented ability to represent, integrate, and share data. Prominent among these models are the Industry Foundation Classes (IFC) (IAI 2007) and CIMSteel CIS/2 (CIS/2 2007). The success and wide adoption of these models is a strong evidence of the need for and feasibility of developing comprehensive data standards in the construction industry.

Successful infrastructure data models should satisfy the information requirements of each process, and define common semantics to ensure data integrity and consistency across various processes. These data models should be open and based on vendor- and technology-neutral data encoding and exchange formats. The data models should also embody both spatial and non-spatial data. The ability to link and reference various forms of life-cycle data based on the asset spatial attributes significantly enhances the efficiency of data access, management, query, and analysis (Halfawy 2004). The lack of standard data models in the municipal infrastructure domain has impeded the realization of data integration and software interoperability, and hence the development of integrated MIMEs.

During the past decade, some efforts to define data modeling and exchange standards for municipal infrastructure systems were underway. Most notable are the Federal Geographic Data Committee, FGDC standards (FGDC 2007), and the CADD/GIS Technology Center standards (CADD/GIS 2007). Also, significant efforts to define spatial data models have produced widely accepted standards. Most prominent are the standards developed by the OpenGeoSpatial Consortium (OGC 2007) and the ISO/TC 211 (ISO/TC211 2007). These standards can be used to facilitate and expedite the development of municipal infrastructure data models. A review of several spatial and infrastructure data standards can be found in (Halfawy 2004; Halfawy et al 2006b).

The FGDC has defined nineteen data standards to enable the interoperability between municipal geographic information systems (GIS). The FGDC standards are grouped into three sets: the spatial data content standards, the spatial data transfer standards (SDTS), and the metadata standards. Described using the Unified Modeling Language (UML), the data content models represent the semantics of a set of domain objects, their attributes, and inter-relationships, and a set of constraints to ensure data integrity and consistency. The SDTS

defines methods and format for data representation and exchange (SDTS 2007). The metadata standard has recently been harmonized with the ISO 19115 standard.

Two main sets of municipal data standards have been under development since 1992 at the CADD/GIS Technology Center: the "tri-service spatial data standards" (TSSDS) and the "tri-service facility management standards" (TSFMS). Recently, the FGDC's Facilities Working Group (FWG) and the CADD/GIS Technology Center were merged, and many of these data models have been harmonized into a more comprehensive standard known as the spatial data standard for facilities, infrastructure, and environmental applications (SDSFIE). The SDSFIE standards provide a data model that defines asset spatial features, and describes a relational database schema for storing the attribute data associated with these features. The SDSFIE standard have been widely adopted and supported by many commercial GIS software, and was recently approved as a national standard by the U.S. national committee for information technology standards (NCITS), and became known as NCITS 353.

Many industry-led data standardization efforts have also been underway. Prominent among these efforts are the Environmental Systems Research Institute (ESRI) and the Municipal Infrastructure Data Standard (MIDS) data modeling initiatives. ESRI has defined application-specific data models in twenty-four domains (e.g., water utilities, transportation networks) (ESRI 2007). MIDS was developed by the Ontario Tri-Committee on the Utilization of Information Technology in Public Works, which includes the Ontario Good Roads Authority (OGRA), the Municipal Engineers of Ontario (MEO), and the American Public Works Association (APWA) Ontario Chapter (MIDS 2007). MIDS integrates and extends a number of previously defined data models in the Province of Ontario, and defines "business rules" to specify the workflow processes required to maintain data consistency and integrity.

Many of these data models have been used in practice, albeit to a limited extent. However, most of these models have primarily addressed the spatial and physical aspects of the infrastructure assets, and lacked the representation of other lifecycle aspects such as condition, performance, risk assessment, deterioration patterns, maintenance and rehabilitation, etc. Moreover, some data models have not defined data format standards for data exchange, and therefore software vendors have defined their own data exchange formats. The development and standardization of integrated data models is one of the main challenges that the industry at large needs to address. Infrastructure data standardization groups and organizations will need to work closely to develop more comprehensive and harmonized standards that can be widely accepted and supported by the industry.

A MULTI-TIER INTEROPERABLE ARCHITECTURE FOR INTEGRATED INFRASTRUCTURE MANAGEMENT ENVIRONMENTS

To satisfy the openness and modularity requirements of integrated MIMEs, a multi-tier architecture (Halfawy et al 2002, Pradhan et al 2007, Halfawy and Froese 2007) seems particularly suitable. A multi-tier architecture helps separate the responsibilities, and subsequently the implementation and maintenance effort, between the applications, generic services components, and the data repository. Figure 3 shows the proposed four-tier architecture, which includes: the applications tier, the adapters tier, the common services tier, and the infrastructure data tier. The software applications, distributed across various municipal departments, provide the functionality needed to support specific processes. Adapters provide the interface between the applications and the generic services packages. The common services packages implement a set of domain-specific data and workflow management components that interface with the integrated data repository. Using the UML notation, a package is composed

of a set of independent, self-contained, reusable, and binary interoperable components (Szyperski 1998). A component's functionality can be accessed through a set of published interfaces. Components can be implemented using a number of available technologies (e.g., CORBA, COM).

{Figure 3. Multi-tier software architecture for enterprise-wide integrated municipal
infrastructure management environments}

Infrastructure Data Tier

The infrastructure data tier is implemented using a centralized relational Database Management System (DBMS) after mapping the integrated data model onto a relational schema. To integrate spatial and non-spatial data, the DBMS should provide special functionality to support the representation, storage, and management of spatial data. Two recent standards can be used to map spatial data to relational schema: ISO 19107 “spatial schema” standard and ISO 19125 “simple feature access” standard. Originally defined by the OpenGeoSpatial Consortium, ISO 19107 defines the relational representation of spatial data, while ISO 19125 defines structured query language (SQL) data types and functions for exchanging and managing spatial data in relational databases.

Common Services Tier: Data Management Package

The data management package is typically implemented on top of the services provided by the underlying DBMS. This package supports functions to populate, access, query, and manage the repository to maintain data consistency and integrity. More advanced data management services, such as concurrency control, version management, security and authorization, web access, and meta-data services, can also be implemented.

Serving as the interface between process-specific software applications and the shared data repository, the data management package needs to support a consistent, open, and DBMS-independent interface language or API. Any application can access and manage the data repository using this interface language. Relational data access and management are typically performed using SQL queries or stored procedures (Elmasri and Navathe 1999). Most relational DBMS provide language bindings (e.g., C or Java) to construct and execute SQL queries. Recently, several DBMS supported an extended markup language (XML)-based version of SQL to support web-based data access and management. As part of this research, an effort to define an XML-based data access language to support interoperability with relational municipal infrastructure data repositories is underway. A similar effort in the AEC domain is also underway to support access to relational project data repositories (or model servers) supporting the industry foundation classes (IFC) standard schema (SABLE 2007).

Common Services Tier: Workflow Management Package

Efficient coordination of municipal infrastructure management processes requires defining workflow models (WfMc 2007) to systematize the sequencing, business logic, and data exchange rules. A substantial body of knowledge concerning the analysis and implementation of workflow models is currently available. The proposed process model can serve as a framework for defining municipal workflow models. Such models can be used to automate the data routing between different processes, and hence facilitate their tracking and control. For example, a logged service request or customer complaint can automatically generate a “Work Order,” or the data generated from “Inspection” or “Construction Operations” can automatically be validated and integrated to the inventory or condition data in the repository to reflect up-to-date status of the assets. Workflow components may also help to automatically

assign, track, and control work orders, as well as schedule periodic inspections and preventative maintenance activities.

Applications and Adapters Tiers

The software applications tier integrates a set of distributed function-specific applications to support the execution of different processes. An integrated MIME would enable the interoperation of these applications by supporting sharing the asset data in the centralized repository. A recent survey of commercial municipal asset management systems found that the majority of today's applications adopt proprietary data models (Halfawy et al 2006a). Therefore, software translators, or adapters, will be needed to map the data between the adopted integrated data model and the application-specific data models.

Adapters can be implemented in several ways, depending on their underlying application characteristics. The software environment should impose no restrictions on these implementation details (e.g. programming language). An adapter can be implemented as a standalone software tool that interacts with the host application via file exchange, or as an add-on to the host application that accesses the application's object model to use and manipulate its internal data and operations.

Recently, applications are becoming more open through providing access to their internal data models via an API, which facilitates the development of the adapters. For applications that do not provide an API, adapters will be implemented to translate input and output files between different formats. As data standards become more available and directly supported by software applications, the need to develop these adapters will be gradually reduced.

EXAMPLE IMPLEMENTATION: A GIS-BASED INTEGRATED SEWER MANAGEMENT ENVIRONMENT

A prototype MIME based on the proposed software architecture, and data and process models was developed. This prototype aimed to integrate work processes typically conducted by different functional groups within a sewer management department. During the past two years, this prototype has been under development and continuous evaluation in collaboration with the City of Regina, Saskatchewan, Canada. The principal role of the prototype was to demonstrate and validate the feasibility and effectiveness of developing integrated MIMEs based on the proposed integration techniques, and to provide guidance for further development and improvement of these techniques.

Developing an Integrated Data Model for Sewer Networks

An object-oriented data model that integrates spatial and non-spatial data for sanitary and storm sewers was developed. The model represented a comprehensive view of the sewer asset data including structural, condition, performance, and risk characteristics. Based on the ESRI water utilities spatial data models (ESRI 2007), the sewer network data model was defined using UML, and is an extension of an earlier model described in (Weston et al 2001). The data model defined six main classes to describe a sewer network: pipe, manhole, fitting, lift station, pump station, and structure. Each of these classes was further divided into sub-classes to form a class hierarchy.

The ESRI data model was used as a starting point to build the integrated data model for the following reasons: (i) The ESRI spatial data model was found to be more comprehensive than other models in terms of the number of defined objects, attributes, and relationships; (ii) the ArcGIS software, commonly used in municipalities and used in the prototype, natively

supports the implementation of the model; and (iii) compared to other spatial data models, the ESRI model was more specific to municipal infrastructure applications.

Augmenting the ESRI spatial data model with non-spatial data such as those defined in infrastructure data models (e.g. SDSFIE, MIDS) was found to be a practical and cost-effective approach that exploits and builds upon previously defined and validated data models. The ESRI model was expressed using UML notation, which facilitated the augmentation and customization of these models. Figure 4 shows part of the UML class diagram of the sewer network data model. That part shows six classes that define the main attributes for CCTV inspection, condition assessment, risk assessment, and hydraulic modeling. The inspection and condition attributes were primarily based on the Water Research Centre standard (WRC 2001). The extended data model also defined attributes to represent the proximity and inter-dependencies with other co-located assets (e.g., the StreetKeyNumber attribute which defines the sewer's road segment).

{Figure 4: Part of the UML class diagram for the integrated sewer network data model}

Data Repository Schema Generation

The UML data model was input into the ArcCatalog's Schema Wizard, which generated the database tables, fields, and data types based on the ESRI geodatabase object-relational schema (Halfawy and Figueroa 2006). Mapping the data between the relational representation and the geodatabase object-based data model is automatically performed by the ArcSDE software using its Geographic Server (gsrvr) and Geographic Input/Output Manager (giomgr) (ESRI 2004). ArcSDE defines SQL data types and functions, and creates and manages a set of tables (or data dictionary) to store metadata such as spatial references, feature classes, and spatial indexing.

Implementing the repository and the data management package

The centralized data repository was implemented using Oracle relational DBMS, while the data management package was implemented using the ArcSDE software (ESRI 2004). The ArcSDE software supports a number of commercial relational DBMS, and adopts spatial data standards, primarily the ISO 19107 “spatial schema standard,” and the ISO 19125 “simple feature access” standard (ESRI 2004). Conformance with spatial data standards and the ability to interface with several commercial DBMS made ArcSDE an ideal platform for implementing the data management services.

Distributed software applications and adapters can concurrently connect to the data management components by passing SQL statements to query and edit asset data in the repository. The repository supports maintaining multiple versions of the database, which enables keeping track of data update history, and rolling back changes if the need arises. To increase the efficiency of data retrieval, spatial or attribute filters are used to reduce the number of retrieved records. Attribute filters are defined in the form of WHERE clauses of the SQL statements. The WHERE clause can join the ArcSDE business (or non-spatial) table with other related tables to retrieve features (or assets) based on conditions defined in these joined tables. Spatial filters are used to retrieve data based on spatial condition (i.e. location). ArcSDE or the DBMS constructs and applies the spatial filter to reduce the number of retrieved features. The DBMS uses spatial indexing to reduce the search and retrieval time of spatial data. More detail about the implementation of the repository and data management components is described in (Halfawy and Figueroa 2006).

Integrating Applications and Adapters

The sewer management environment integrated a number of applications to support various sewer management processes. To demonstrate the open and tool-independence characteristic of the environment, three of these applications will be discussed. These applications are the inventory data analysis and query, the inspection and condition assessment, and the hydraulic modeling applications.

The inventory data analysis and query application was implemented as an add-on to the ArcGIS software using the ESRI ArcObjects class library (ESRI 2005). The application accesses the data management services to enable users to query the sewer network based on the sewer material, diameter, age, condition state, or location. Summary charts for the entire network showing the total length or number of sewers within various categories can also be displayed. For a particular sewer, detailed inventory data as well as a list of other related or co-located assets could be retrieved from the repository. Figure 5 shows a screenshot of the inventory data analysis and query application.

{Figure 5: Inventory data analysis and query application}

The condition assessment and hydraulic modeling processes were supported using two legacy applications that have been integrated into the environment. Since these applications did not support the adopted data model, adapters were developed to map the repository data model to and from their internal data models. Also, to leverage the role of spatial data in these applications, these adapters were implemented as add-ons to the ArcGIS software using the ESRI ArcObjects library.

The CCTV inspection and condition assessment software, flexidata (Pipelogix 2007), was used for recording inspection data, defect scoring, and calculation of the WRC sewer condition rating. The CCTV data are exported in two formatted text files: one file describes the

details of each inspection including the defects and their scoring across the sewer centerline, and the second file describes the inspection attributes (e.g. date, tape number, start/finish manholes, direction, sewer attributes, etc.). The adapter was implemented to parse these two files and populate related records in the data repository. The adapter accesses the data management components to retrieve the latest and historical CCTV inspection data and condition ratings. Figure 6 shows a typical screenshot of the inspection and condition assessment adapter.

{Figure 6: CCTV inspection and condition assessment adapter}

Support for the hydraulic modeling and analysis process was implemented by integrating the Storm Water Management Model (SWMM) software (EPA 2007). The SWMM adapter is an extension of an older version described in Halfawy et al (2000). This adapter supported two main functions: (i) partial automation of constructing SWMM models by extracting the sewer network data from the repository and generating related sections of the SWMM input file; and (ii) retrieving simulation results from the output files, using the SWMM interface library, to extract information about maximum flow levels, hydraulic grade line, etc., and use this information to populate relevant records in the data repository. Figure 7 shows a screenshot of part of the City of Regina's sewer network hydraulic model.

{Figure 7: SWMM interface and adapter for hydraulic modeling of the sewer network}

Prototype Evaluation

The prototype represented a partial implementation of the proposed integration techniques in the area of sewer management. Several key components of the prototype have already been deployed (Halfawy and Figueroa 2006). The prototype implemented an integrated data model, a

centralized data repository, and data management components, as well as integrated and reused a set of legacy software tools that shared data through the centralized repository.

Unlike conventional software systems, MIMEs cannot be generally evaluated in terms of objective criteria (e.g., correctness, accuracy, speed). Serving primarily as containers of software components, MIMEs functional and non-functional qualities are the cumulative result of the qualities of their constituent components. Perhaps the most important evaluation criteria for the prototype, and MIMEs in general, would be the quality of its integration techniques (e.g., the consistency of these techniques with the current industry practices, and the extent to which they take into account the specific characteristics and requirements of the municipal infrastructure management domain). Lack of objective or standard measures of these criteria makes the evaluation of this prototype a difficult task.

The prototype design and implementation have been evaluated based on feedback and critique from domain experts and potential users, primarily the City of Regina engineers and asset managers. This evaluation has been conducted throughout the development process during a series of workshops. At this development stage, the evaluation primarily emphasized the appropriateness, scalability, and feasibility of the proposed integration techniques and their conformance and consistency with the current practices and requirements of the industry, rather than the “comprehensiveness” of the prototype. As the prototype implementation evolves, more aspects can be evaluated including its efficiency of operation, usability, and cost-effectiveness.

The feedback received from practitioners provided a valuable assessment of the validity, and technical feasibility of the prototype and its integration techniques. In particular, the use of open data models, an explicit process model, modular architecture, and the reuse of existing legacy applications (often emphasized as critical requirements for any practical MIME) were found to be adequately addressed and supported by the prototype.

Several measures and techniques to evaluate the qualities of software architectures have been proposed (e.g., Clements et al 2002). Key among these measures is the modifiability, maintainability, and implementability of the software (Chastek and Ferguson 2006). The prototype's multi-tier component-based architecture provided the modularity and flexibility needed to enable future refinement and improvement, support incremental implementation and deployment, and facilitate its maintenance and extension. Also, the prototype's architecture did not impose any restrictions on the implementation details (e.g., technologies, vendors) of the repository, common services packages, or software tools, which makes this architecture technology- and vendor-neutral.

The process model represented the key work processes and their inter-relationships. This model has been verified, and was found to be consistent with municipal practices. Also, adopting an open data model enabled the prototype to become tool-independent, and facilitated the integration and reuse of legacy software tools. Software tools can be replaced, added, or removed with limited or no impact on other prototype components. The data model classes, attributes, and relationships satisfied the data requirements of the supported processes, and enabled the integration of spatial and non-spatial attributes. The data model also provided cross-referencing between related or co-located assets (e.g., sewers and roads). Moreover, the use of a centralized relational repository enabled the implementation of efficient data access and management functions.

CONCLUSIONS AND FUTURE DIRECTIONS

Municipalities are under increasing pressure to achieve closer integration and coordination of infrastructure management processes to optimize the operational and renewal decisions within and across municipal departments. Municipal infrastructure asset management decision-making

is inherently an integrated process that requires the assimilation of a multitude of data, processes, and software systems. However, fragmentation of work processes and asset data, a typical characteristic of today's practices, is a major obstacle toward adopting more efficient, integrated, and proactive management strategies.

Although there is a broad consensus in the industry on the need to adopt integrated approaches, and on the general integration objectives (e.g., data and process integration, interoperability), there is almost no agreement on the methods and tools needed to realize these objectives. This paper provided some specific proposals to realize the implementation of integrated MIMEs that can potentially provide practitioners with the tools needed to coordinate and streamline the infrastructure management processes. The proposed solutions addressed a number of issues, including: asset lifecycle data modeling, sharing, and management, systematization of municipal processes, and integration of disparate software tools in a flexible and modular architecture. The prototype demonstrated the utility and feasibility of the proposed integration techniques, and provided an insight into the characteristics and key requirements to develop integrated MIMEs, and the appropriate techniques and technologies to satisfy these requirements in practical implementations.

In light of this research, some directions for future work can be proposed. Of particular interest is the development of industry-wide data integration and software interoperability standards in the municipal infrastructure domain. Successful development in other domains (e.g., AEC) should be a catalyst for the development of such standards. The standards should be based on industry-wide consensus, and be defined through consortia of infrastructure managers, public works professionals, software developers, and other stakeholders. A first step should consider the harmonization, refinement, and integration of existing data standards. Municipalities should also take an active role in the development of these standards to ensure

that their requirements are addressed, and to encourage software vendors to support these standards. Other research activities may also contribute to further the application of MIMEs in the industry. One such activity is to assess the organizational impact, costs, and benefits of MIMEs.

Due to the comprehensive nature of the proposed solutions, substantial work still needs to be done to extend the prototype across both vertical and horizontal integration axes. Along the vertical axis, the prototype needs to be extended to support other sewer management processes (e.g., risk assessment, renewal planning). Along the horizontal axis, the prototype needs to be extended to integrate and coordinate with processes across other municipal departments (e.g., water and road departments). Integration with other business processes (e.g., accounting, procurement) or across the organizational boundaries (e.g., with other utilities) can also be pursued. As the prototype implementation evolves, more software tools will be added, and the data model will be further extended and revised. Eventually, a comprehensive and fully operational MIME based on the proposed integration techniques can be realized.

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