Issues in Decision Support Tools for Sustainable Infrastructure Management

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ABSTRACT

There has been considerable and well-documented concern about the current state of public infrastructure—roads, bridges, water and waste systems, etc. The causes of these challenges are common to many government and utility owners: aging and deteriorating infrastructure; inadequate funding; competing organizational objectives; questionable maintenance, repair, rehabilitation and replacement practices in the past; demographic and population shifts, and new understandings about sustainability objectives. These challenges necessitate that the infrastructure industry excel at developing and managing their infrastructure systems to their maximum potential. To meet these needs, the infrastructure domain requires improvements to the decision support tools that currently exist for sustainable infrastructure management. This paper reviews this problem with a particular focus on the Canadian context, and outlines a course of action to address the current needs. The proposal addresses three domains in the field of sustainable infrastructure management. First, it builds on work to develop comprehensive techniques to assess the sustainability of infrastructure systems. Second, it attempts to advance multi-objective optimization techniques and tools for predicting the long-term performance of infrastructure systems and optimal strategies under a variety of maintenance regime alternatives. Third, it develops data interoperability solutions to create an infrastructure data integrator as a computing platform for this work.

DEFINING THE PROBLEM

There has been considerable and well-documented concern about the current state of Canada's infrastructure (FCM 1996, Vanier et al. 2006, Mirza 2007, Rehan et al. 2011, CPI 2013); and this warning applies to many of the developed countries of the world. A recent report on the state of Canada's municipal infrastructure points at many concerns for both the current situation and the future condition of this country's infrastructure (FCM 2012).

The stated challenges in these Canadian reports from researchers and national organizations generally relate to causes or symptoms that are endemic to infrastructure management in large utilities or at government offices at local, provincial, national and international levels, and that are echoed by owners of properties with vast and diverse holdings: Aging and deteriorating infrastructure; Inadequate funding; Competing organizational objectives; Questionable maintenance, repair, rehabilitation and replacement practices in the past; Demographic and population shifts (baby boomers, retirees, gen-X, economically displaced); New requirements and priorities arising from sustainability concerns.

The challenges in developing countries are similar, but exacerbated by the rapid move of their citizens to urban centres and the extrapolated challenges of double digit annual growth. It has been estimated that the total value of civil infrastructure systems in Canada is over $ 5.5 trillion (Vanier and Rahman 2004); this is a vast amount of civil infrastructure to replace in the near term as a considerable portion has reached the end of its service life (FCM 2012). The ratio of built assets per capita can be assumed to be similar in other developed countries. The Federation of Canadian Municipalities has tagged the current amount of unfunded deferred maintenance at $125 billion (FCM 1996), but independent studies indicate that many large governmental and para-governmental organizations (municipalities, utilities, provincial-territorial/federal government agencies, etc.) have levels of unfunded deferred maintenance equaling 10% of the value of infrastructure inventory (Mirza 2007). In fact, the engineering field has not provided proper or consistent definitions of terms such as deferred maintenance, infrastructure gap, maintenance debt/deficit, so it is impossible to calculate what is what.

The above numbers should only be considered as averages (broad brush strokes) and are not necessarily a “doom and gloom” scenario for Canadians, or by extrapolation, citizens of the world. In fact, many organizations are managing their assets efficiently and comfortably; however, many others are struggling to meet basic health and safety requirements, to maintain basic functionality, to preserve acceptable levels of service, and to sustain their infrastructure economically (Mirza 2007, Lounis et al. 2010, FCM 2012).

There is increasing pressure on infrastructure managers to make optimum decisions about targeting scarce infrastructure resources, primarily funding. Many municipalities have made progress in recent years in improving their infrastructure management practices (GASB 2001, PSAB 2007), particularly in specific asset management functions (e.g., asset inventory systems and asset valuation practices), but a need remains for more advanced techniques; more specifically, this requires improved ability in all of the five basic asset management functions (Lounis et al. 2010):

1. Identifying and tracking existing inventory assets.
2. Assessing the current asset condition and performance and level of service.
3. Predicting asset life-cycle performance and future service demands.
4. Selecting optimal repair / replacement while balancing technical, economic and social objectives.
5. Carrying out operations, maintenance and rehab efficiently, cost-effectively and sustainably.

In addition, an extremely big question is now looming in front of owners of assets: “Is our organization sustainable?” This question is not directly related to a current trend towards “green” infrastructure, but to a much larger, and important, view of sustainability: Are public sector organizations able to sustain their infrastructure given the projected revenue base? And this question naturally implies: Are their infrastructure assets technically, economically, socially and environmentally sustainable?

This paper references previous investigative work in the field (Vanier and Froese 2013), identifies key initiatives in the field, as well as proposing research that addresses these challenges.

PROPOSED SOLUTION

The authors believe that the solution to the aforementioned challenges lies in the investigation of the three following technical domains:

- *Sustainability assessment for infrastructure*: To build upon emerging frameworks to develop practical and meaningful techniques for evaluating the sustainability of infrastructure assets.
- *Advanced analysis and decision-support for infrastructure management:* To provide analysis and decision support that is compatible with—but extends beyond the capability of current software. The focus includes performance prediction, multi-objective optimization, and data visualization.
- *Integrator platform:* To develop, test and validate a software system related to decision support and sustainable infrastructure that is compatible with existing commercial systems, integrates disparate data sources, and provides a platform to analyze and visualize infrastructure management data.

The first domain would provide essential research required in the near term by municipalities and owners of similar infrastructure assets. The second domain would greatly assist elected officials and senior managers to make logical, objective, and rational decisions about infrastructure maintenance, repair, rehabilitation and replacement. The third domain would establish standards for data interoperability that will be essential to infrastructure management in the upcoming decades.

The following section overviews the state of practice for these three technical domains (See Vanier and Froese 2013 for complete descriptions of the related initiatives, including outlines of educational courses currently available in Canada related to infrastructure management).

EXISTING FRAMEWORKS AND STATE OF PRACTICE

Sustainability assessment for infrastructure: There have been a number of significant sustainability initiatives in Canada related to the management of public infrastructure. These include the National Guide to Sustainable Infrastructure (InfraGuide 2013); PSAB 3150 (PSAB 2007), which provides guidance with respect to the proper stewardship of public infrastructure and mandates the public sector to record the extent, historical cost, and remaining useful life of assets in their annual financial statement; MIIP, the Municipal Infrastructure Investment Planning project (MIIP 2013); the Model Framework for Assessment of State, Performance, and Management of Canada's Core Public Infrastructure (CPI 2013). The details of these and several other initiatives are highly relevant to this research, but are beyond the scope of this paper.

Advanced analysis and decision-support for infrastructure management: A number of software systems exist that provide decision support for infrastructure management, though there is significant opportunities to further advance the analytical capabilities. A limited number of applications selected based on the usage by Canadian municipalities include: Envista www.envista.com (Beverly, MA); Riva Modeling www.rivamodeling.com (Toronto ON); Solutions Modex www.solutionsmodex.com (Montreal QC); VEMAX Management www.vemax.com (Saskatoon SK, Sydney Australia); and VFA www.vfa.com (Boston, MA).

Information Interoperability and Integration for Sustainable Infrastructure: Data exchange within the infrastructure domain is highly inefficient due to the lack of data standards for exchange of information across the spectrum of software tools. The National Institute of Standards and Technology (NIST) estimated that inadequate interoperability within the property, construction, and facilities management causes a financial loss of 1-2% of the industry's cross-market value, amounting to $15.8 billion per year in the USA (Gallaher et al. 2004). The infrastructure industry is further behind general construction in terms of data interoperability standards, and larger in terms of public spending. Two components that can improve information interoperability for infrastructure are: data exchange standards (including both Geographic Information System (GIS)-based and Building Information Modelling (BIM)-based standards) and information integration systems.

PROPOSED D-SIM RESEARCH ACTIVITIES

Sustainability assessment for infrastructure: Increasing pressures from many segments of society are demanding asset managers to become more socially, economically, and environmentally sustainable. To respond to these challenges, a careful definition of sustainable development goals, identification of suitable indicators for these goals, practical data sources, and appropriate evaluation techniques for both the current state of existing infrastructure systems and the predicted future state of proposed systems are required. Numerous sustainability assessment systems have been developed for buildings (e.g., LEED, Green Globes). Much less work has gone into assessing the sustainability of urban infrastructure systems. D-SIM will evaluate and build upon relevant approaches mentioned above to develop practical and meaningful techniques to evaluate the sustainability of infrastructure assets.

The research in this first domain will concentrate on the infrastructure classes identified in the Core Public Infrastructure project (Lounis et al. 2009), namely: roads, bridges, water, wastewater and transit. The first set of key tasks relates to "developing the engineering" behind PSAB (2013). The knowledge acquisition will follow a standard investigative format: review results of Canadian Infrastructure Card (Report Card 2013), analyse current PSAB reporting for participating municipalities, survey participating municipalities, identify best practices and standard practices, interview municipal staff on best practices, identify existing and potential key performance indicators (KPI) for sustainability and report on best practices KPIs.

The Engineering behind PSAB 3150: The recently-introduced PSAB guidelines for municipal reporting of infrastructure assets has proven to be a significant driver for pushing municipalities to review and update their infrastructure tracking and management practices, but while PSAB requires this reporting to be done, it provides little details as to techniques and practices. The technical foundations for the PSAB requirements are needed to support and guide the municipalities' corresponding infrastructure management practices. The research will create meta-data required to support Tangible Capital Asset inventory, valuation and useful life determination (PSAB 2013): identify representative nomenclature such as: deferred maintenance, infrastructure gap, maintenance backlog, functionally obsolete, functionally deficient, asset classes, hierarchy structures, performance, condition, useful life, service life, level of service, risk analysis, life cycle costing and decision support.

PSAB +: Work is also required to create the meta-data required to support the existing Statement of Recommended Practices (SORP) of PSAB 3150. This involves identifying and reporting on the representative nomenclature used in practice such as: level of service, life cycle costs, discount rate, depreciation, deterioration, risk analysis, consequence and probability of failure, criticality, decision support, and decision rating, ranking and prioritization.

Advanced analysis and decision-support for infrastructure management: Perhaps the central challenge in sustainable infrastructure management for most practitioners is to identify the "best" course of action (i.e. optimal, most cost-effective, most sustainable) from a wide range of possible infrastructure development, operations, and maintenance actions, given the constraints of limited resources. The difficultly arises from assessing the relative benefits and costs of alternatives across a wide range of criteria, predicting these relative values over long life spans, and aggregating, prioritizing, comparing, and ranking the (often conflicting) priorities to select preferred solutions in the face of multiple stakeholders' differing values (e.g. decision makers, city councils, citizens, technical staff). The D-SIM project will extend existing techniques in future performance prediction, simulation, and multi-objective/multi-stakeholder decision support to develop tools and technique for optimizing sustainable infrastructure management decisions.

The Municipal Infrastructure Investment Planning (MIIP) project was a four-year collaborative project between the Institute for Research in Construction, five large Canadian cities, one medium-sized Canadian city, three major regional municipalities, and the Department of National Defense (MIIP 2013). The MIIP project laid groundwork that will be used for this proposal. Two significant deliverables of the project were primers on infrastructure management (Vanier et al 2006 2009), and they provide a foundation for research and development work in the future. Analysis of existing frameworks (PROs and CONs) Analyze frameworks applicable to municipalities and report on the pros and cons as they apply to participating D-SIM industry partners. Focus on the CPI, Envision Infraguide, MIIP, Waterloo and Whistler frameworks described earlier. Recommend most suitable selection of frameworks for participating municipalities.

SSAM-I: A deliverable of the MIIP (2013) project was the Sustainable and Strategic Asset Management – Integrator (SSAM-I 2007), which models multi-year maintenance, repair, rehabilitation and replacement alternatives given a constrained budget and projected deterioration of a static number of assets and asset classes in a portfolio. It uses techniques such as multi-criteria decision making (MCDM) to prioritize between asset engineering objectives such as asset condition, LCC and risk; Analytical Hierarchy Process (AHP) to determine weights for MCDM, and benefit-modification factors and benefit cost analysis to prioritize projects using a constrained annual budget. The research will extend SSAM-I V0.9 to incorporate: unlimited functional objectives, unlimited intervention methods, unlimited number of assets, unlimited deterioration models (beyond linear and geometric), inherited hierarchical asset class attributes, automated infrastructure asset generation (to create a portfolio, or portions thereof, when data are missing), alternative condition rating schemes, multi-year optimizations (as opposed to single year), faster calculation speed, dynamic growth or reduction of assets in a portfolio, simulation of failure of assets (risk of failure analysis), multiple prioritization methods (e.g. genetic algorithms, multi-objective optimization, compromise programming, etc.), right-of-way (ROW) comparisons (where individual assets and their combinations of ROW assets are prioritized), and integration of SSAM-I with asset management software providers The SSAM-I data structures created will be populated with asset, class, valuation, deterioration, service life, life cycle cost and risk data obtained from the participating D-SIM industry partners.

AHP: Analytic hierarchy process (AHP) will be investigated to supplement the model developed in the MIIP (2013) project, as shown in Figure 1. This will include investigation of methods to solicit and validate knowledge and information from senior technical staff (Steps b and c); to canvas staff to develop weights for municipal priorities (Step d); and to interview senior municipal managers and elected officials to select suitable project candidates (Step e). Step a will be discussed in the following section.

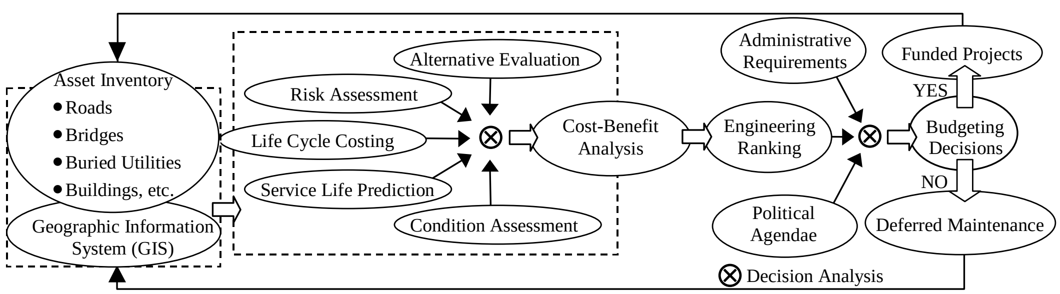

Figure 1. Decision model for Municipal Infrastructure Mgt. (Vanier et al. 2009).

Integrator platform: Recent studies have shown that municipalities currently employ a broad range of software systems to support infrastructure management activities, but that none of these systems is regularly used for the full spectrum of these activities (Zeb et al 2012). In the building sector, Building Information Modeling (BIM) is becoming a transformational technology to unify teams around computer-based models of building projects. A new focus on "horizontal-BIM" is extending this technology to infrastructure. The D-SIM project will develop an integrator platform that uses interoperability techniques to combine data from disparate existing software systems and provides a toolset for the assessment and analysis techniques described above. A key component of this work will be to collaborate with the Institute for BIM in Canada on international standards for Infrastructure Interoperability. Part of the development work proposed here towards sustainable infrastructure management practices will include participation in international efforts to extend existing data exchange standards into the infrastructure domain to support infrastructure management.

This work will involve three major components: 1) *As-is analysis* will develop case studies, use cases, ontologies, and process/information flow models to thoroughly map the existing information exchange landscape and articulate the exact data required; 2) *Interoperability technologies* will work to identify and extend the appropriate GIS and BIM-based data standards, explore level-of-detail complexities, and develop appropriate data exchange frameworks; 3) *Integrator platform development* will design, produce, and test a platform that can accumulate infrastructure data from a wide variety of sources, creating the necessary import and export capabilities for target software applications, explore system architectures, data modeling, and user interface issues, and make this information available for the decision-support described above.

Part of the research in this program will develop an infrastructure information integrator platform that will not replace existing software used by municipalities, but will be able to collect data from a broad range of infrastructure-related software, combine it into an integrated data set, and use combined data to implement the infrastructure management analysis and processes described in this paper.

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