Overview of Decision Support Tools for Sustainable Infrastructure Management

D.J. Vanier[1], T.M. Froese[1]
[1]Department of Civil Engineering, The University of British Columbia

Abstract: There has been considerable and well-documented concern about the current state of Canada's infrastructure. 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 support and improve this capability, The University of British Columbia is developing a research program to advance the state of decision support tools for sustainable infrastructure management. This paper describes this proposal and summarizes the state of practice in Canada regarding decision making in sustainable infrastructure management. It then outlines a course of action to address the current needs. The proposal addresses three important areas 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.

Keywords: Sustainable Infrastructure Management, Decision Support, Assessment, Interoperability

1   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). The recent report on the state of Canada's municipal infrastructure points at many concerns for both the current situation and the future condition of infrastructure (FCM 2012). The stated challenges in these 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, and
- Demographic and population shifts (baby boomers, retirees, gen-X, economically displaced).
- New requirements and priorities arising from sustainability concerns.

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 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 equalling 10% of the value of infrastructure inventory (Mirza 2007).

The above numbers should only be considered as averages and are not necessarily a "doom and gloom" scenario for Canadians. In fact, some Canadian 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).

The managers of all types of civil infrastructure assets must supervise a large and diverse set of assets ranging from complex underground networks to self-standing structures, from roadway systems to parks, and from transit systems to treatment plants. In addition, the municipalities/utilities/provinces/federal departments of Canada are also responsible for a varied selection of buildings and facilities including social housing, police and fire stations, recreation centres, maintenance depots, parks, training facilities, etc. All these civil infrastructure assets are subject to degradation and deterioration due to aging, geological and environmental conditions, climate change, over usage, and changes in use. Many para-governmental agencies and crown corporations are in similar situations and share similar challenges.

The net effect of these challenges is increasing the pressure on infrastructure managers to make optimum decisions about targeting scarce infrastructure resources, primarily funding. Many Canadian municipalities have made progress in recent years in improving their infrastructure management practices (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 in 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 Canadian 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 outlines previous and ongoing work, as well as proposed research, that seeks ways of answering this question. Given the current situation of this aging and deteriorating infrastructure, inadequate levels of funding, changing population demographics and need for addressing sustainability, the following challenges have been identified in research literature for all types of organizations (Lounis et al. 2010):

• Many governments/utilities do not know the extent and/or value of their infrastructure assets.
• Many are not aware of the amount of their deferred maintenance or renewal requirements.
• There is little knowledge how specific asset classes deteriorate, and how quickly or slowly.
• The technical (i.e. *in situ*) service life of many asset classes is not known, even to experts.
• There are considerable amounts of non-digital data in this community and the current trends indicate that more and more digital data are being collected, and these are accumulated without any consideration to communication and interoperability issues.
• Decision support tools are not available to infrastructure managers and decision makers, or are making very slow inroads into the community.

2   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 making and sustainable infrastructure that is compatible with existing commercial systems, integrates disparate data sources, and provides a platform to analyse and visualize infrastructure management data.

The following sections outline existing frameworks and the state of practice for these three technical domains. The purpose of the following section is to document our findings to date for our own usage and to share this knowledge with other practitioners; it is not intended to be all-inclusive at this time.

3   Existing Frameworks and State of Practice

3.1   Sustainability assessment for infrastructure

This section describes significant sustainability initiatives in Canada related to public infrastructure. They are listed in authors' opinion of their significance and summarized to set the context for the proposal.

National Guide to Sustainable Infrastructure: This is Canada's foray into developing Best Practices for "sustainable infrastructure". Funded by Infrastructure Canada for approximately seven years at a cost of over $ 25 million (including in-kind costs from municipalities), the deliverables includes 55 Best Practices (in both English and French) and a number of case studies and E-Learning tools (InfraGuide 2013). Although the InfraGuide provides detailed solutions to specific problems in the industry, a specific stream of reports (i.e. Decision Making and Investment Planning) are dedicated to general guidance to senior managers and elected officials. These Best Practices were available in printed and electronic format; however, it is increasingly more difficult to locate documents (Infraguide 2013 – this reference identifies an Internet search strategy that can locate electronic copies).

PSAB 3150: The Canadian Institute of Chartered Accountants (CICA) provide Public Sector Accounting Board guidelines for Tangible Capital Assets (PSAB 2007). Although not directly related to sustainable infrastructure, PSAB 3150 provides guidance with respect to the proper stewardship of public infrastructure and mandates that the public sector record the extent of assets, the historical value of assets, and the remaining useful life in their annual financial statement (PSAB 2007). The authors believe that these inventory identification, asset valuation and service life prediction functions are essential elements of sustainable infrastructure management.

Core Public Infrastructure: The National Round Table on Sustainable Infrastructure (NRTSI) and the National Research Council Canada (NRC) partnered in an initiative, funded by Infrastructure Canada, to produce a *Model Framework for Assessment of State, Performance, and Management of Canada's Core Public Infrastructure* (CPI 2013). The framework recognized the need to investigate the well-documented pillars of sustainability and developed concepts to identify performance measures to evaluate the required criteria, objectives, and impacts related to identified performance measures. A framework was developed that was endorsed by many in the community (Engineers Canada 2013). The framework was further supported with detailed research by the National Research Council Canada (Lounis et al. 2010).

The Natural Step (TNS) Framework for Strategic Sustainable Development: TNS is a sustainability framework that has been adopted by a number of Canadian cities including the Resort Municipality of Whistler BC, Halifax Regional Municipality NS, the City of Saskatoon SK, District of North Vancouver BC, Town of Canmore AL, and Town of Olds AL, to name a few (TNS 2013). The TNS framework is broken

into five self-explanatory levels: System, Success, Strategic, Action, and Tools. The main aspect of the Strategic Level is the use of "backcasting": a term used to describe visioning the future community where the four sustainability principles (see below) are not violated and then to develop strategies today (i.e. backcast) that will enable the vision to happen. Their four sustainability principles are oriented toward elimination of: (i) systematic increase of concentrations of substances extracted from the earth's crust; (ii) systematic increase of concentrations of substances produced by society; (iii) systematic physical degradation of nature and natural processes, and (iv) conditions that systematically undermine people's capacity to meet their basic human needs. TNS sees the benefits of the framework as: shared community vision, improved decision-making, employee loyalty and trust, improved stakeholder alignment, cost savings, increased citizen engagement, improved reputation, and more cohesive policy decisions.

Whistler Sustainability Model: Whistler developed its model based on the TNS Framework and consists of *Priorities* established by the community, a number of related *Strategies* and a number of related *Indicators* (Whistler 2013). The Priorities form the centre of Figure 1: Enriching Community Life, Enhancing the Resort Experience, Ensuring Economic Viability, Protecting the Environment, and Partnering for Success. In the framework, no Priority is more important than another. The specific Strategies of the left hand side of Figure 1 that relate the "Protecting the Environment" Priority are: Built Environment, Energy, Material & Solid Waste, Natural Areas, Transportation and Water.
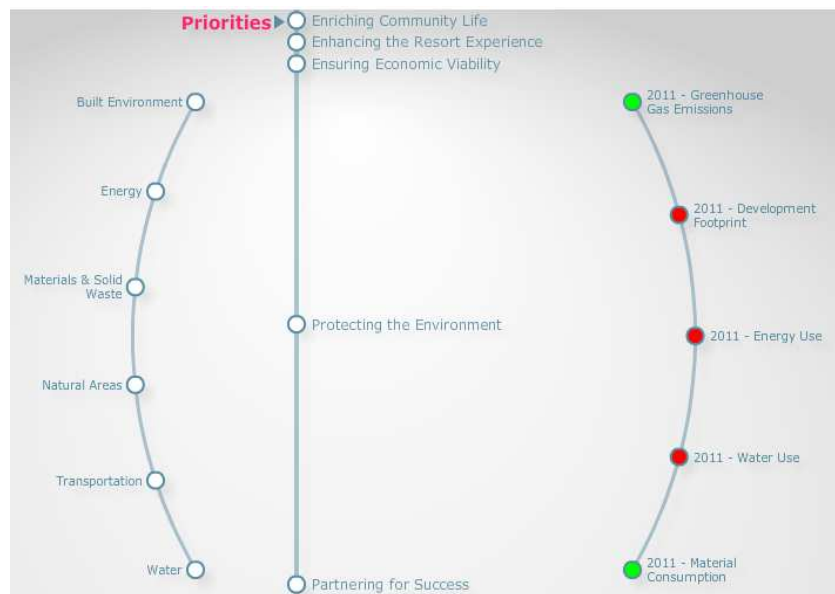

Fig 1: Whistler Sustainability Framework (Whistler 2013)

There are 17 Strategies in total in the Whistler model, but only the six above relate to this specific Priority. The Indicators related to this Priority are shown on the right of Figure 1 and include: Greenhouse Gas Emissions, Development Footprint, Energy Use, Water Use, and Material Consumption. Each of these Indicators is displayed as either red or green points if they are trending negatively or positively, respectively. Whistler does not self-evaluate to assign a specific sustainability index, but displays how it is performing or "trending" in discrete areas over a one-year and a three-year horizon.

Triple bottom line (TBL): "Triple bottom line (TBL) accounting expands the traditional reporting framework to take into account social and environmental performance in addition to financial performance" (Wikipedia 2013). It is being adopted by corporations and communities; for example, a TBL Policy was adopted by the City of Calgary on September 12, 2005.

University of Waterloo Systems Dynamics Model: Waterloo is developing a framework that considers the impact of complex feedback loops that typically are integral to sustainable asset management (Rehan et al. 2011). The research is still in progress and Figure 2 illustrates the representation of the complexity

of such systems and the large number of related feedback loops such as Infrastructure Condition (R1), Capital Expenditures (B3) and Revenues (R2) that continually update information and results.
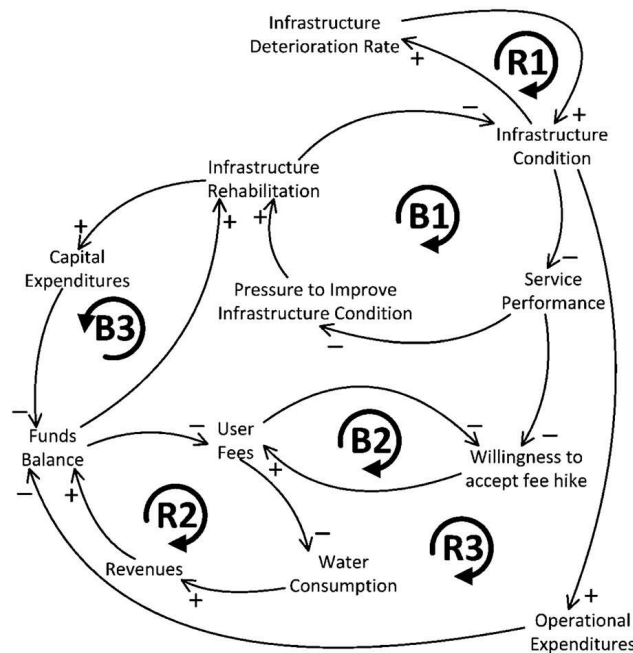

Figure 2: Systems Dynamics Model (Rehan et al. 2011)

Leadership in Energy and Environmental Design (LEED): The U.S. Green Building Council (USGBC 2013) developed LEED as a guide for green and sustainable design. It is a "credit" rating system that evaluates the environmental performance of a building in terms of five main areas: (i) sustainable sites; (ii) water efficiency; (iii) energy and atmosphere; (iv) materials and resources; and (v) indoor environmental quality. Credits are earned when a specific requirement is achieved. LEED-ND (Neighbourhood Development) looks at the environment around "green buildings", and establishes metrics for how a building fits into a neighbourhood according to the following: (1) Smart Location and Linkage, (2) Neighbourhood Pattern and Design, and (3) Green Construction/Infrastructure and Buildings. LEED-ND creates guidelines for designers and decision-makers with respect to the selection of location, design alternatives, and construction materials of new residential, commercial, institutional and mixed use projects, thus addressing contentious issues regarding how green buildings form part of a neighbourhood.

Green Globes: The Green Globes environmental assessment and rating system is based on *Building Research Establishment Environmental Assessment Method* (BREEAM 2013). The Canadian Standards Association published a product entitled *BREEAM-CANADA - An Environmental Performance Assessment for Existing Office Buildings* (CSA BREEAM 1996). The major objectives of this document are to: (i) provide recognition for reduced environmental impact for candidate buildings; (ii) identify best practice for environmental performance assessment, and (iii) raise awareness to the environmental impact of decisions made by the building community in planning, design, maintenance and operations

Envision Sustainability Rating System: Developed at Harvard University as a joint project with the Zofnass Program for Sustainable Infrastructure and the Institute for Sustainable Infrastructure (Zofnass 2013), it applies LEED principles to sustainable infrastructure to: educate citizens and stakeholders, encourage inter-disciplinary discussing, assist the adoption of sustainable design, and provide metrics to grade infrastructure projects. There are 60 credits in their checklist that each fall into the following domains: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk. The user self-evaluates the project's sustainability, answering yes/no to each credit to determine a final score.

Condominium Act: Although unrelated to municipal infrastructure or public infrastructure, legislation for condos in British Columbia, Alberta, and Ontario, to name a few provinces, has mandated that condo councils prepare: a physical inventory of building systems, an estimate of anticipated maintenance, repair and replacement costs over 30 years, and a financial forecast that contains three funding models for contingency reserves (BC 2013). These are similar requirements to PSAB (2013), noted earlier.

3.2   Advanced analysis and decision-support for infrastructure management

The following reviews are presented in alphabetic order and are summaries of information provided on the respective company's website. They do not reflect a deep knowledge or proficient understanding of the software. A limited number of applications were selected based on the usage by Canadian municipalities. Italicized words are official terms used by the respective company.

Envista www.envista.com, Beverly, MA

Envista is an enterprise suite of web-based, map-based solutions to problems within the public right-of-way (ROW). Their *Enterprise Suite* consists of the following modules:

- *Project Coordination* – centralizes all data and displays upcoming paving schedule.
- *Permit Workflow Management* – allows users to apply for permits online and display status of permits.
- *Special Events* – displays all construction and maintenance events and traffic impacts, including road closures, detours, parking restrictions, etc.
- *Street Incidents* – allows users to alert others of unplanned incidents.
- *Attachment Management* – allows users to upload, download, store documents.
- *Citizen's View* – presents public view of controlled information and exports data in map-based format.

Riva Modeling www.rivamodeling.com, Toronto ON

The RIVA software focuses on utilities, public sector, and infrastructure asset management. It is used by a number of Canadian municipalities. It is an operational and strategic tool that addresses the following requirements: *Asset Investment Plan Creation and Development*, *Asset Lifecycle Costs Management*, *Long Range View of Asset Planning*, *Finance*, *Integration*, *View and Presentation*, *Reporting and Dashboard*, and *Mobility*. The software can produce the following types of reports:

- Asset Lifecycle Forecasts – Plan expenditures for up to 100 years.
- Budgets – Budget and identify all costs and funding requirements.
- Key Performance Indicators (KPI) – Identify and monitor KPIs.
- Integrate – Connect to key data sources: geospatial (GIS) and Enterprise Resource Planning (ERP).
- Valuation – Calculate the valuation of all assets.
- Depreciate – Perform depreciation calculations to determine reserve levels.

VEMAX Management www.vemax.com, Saskatoon SK, Sydney Australia

VEMAX has over 14 years experience in Australia and Canada in the domain of infrastructure budgeting, accounting, and management. It consists of a number of self-explanatory modules:

- *Designer* – to identify asset data, and develop the agency database.
- *Visualizer* – to capture and update asset data, and develop the agency database.
- *DataViewer* – to view and analyse asset data.
- *MMS* – to assist staff to plan, organize, schedule, track and review tasks.
- *iBOS* Productivity Suite to enable users to create new databases, entry screens and enter data.
- *PPT Strategic* – to allow users to determine optimal annual maintenance and rehabilitation.
- *PPT Tactical* – to allow users to find optimal project level strategy for a given year.

VFA www.vfa.com, Boston, MA

VFA, formerly known as Vanderweil Facility Advisors, is an international company serving over 600 organizations in the USA, Canada, UK and some 30 other countries. These organizations are using VFA software solutions to manage capital assets. Recently, it announced its purchase of the Altus Capital

Planning Division of the Altus Group (Altus 2012), which had the software rights to Physical Plant Technologies Inc. and Harfan Technologies Inc.

The company has identified the key benefits of it software suite to be: gain insight into facility condition across the portfolio, establish industry standard benchmarks (i.e. defining the Facility Condition Index or FCI), prioritize capital projects for budget allocation, proactively achieve financial objectives, reduce costs, and obtain needed funding. It also includes specialized assessment services in the following domains**:** *Green Building Assessment Services*, *Energy Assessment Services*, and *Seismic Assessment Services*. Key components of its software suite include:

- *VFA.facility*: manages data, estimates life cycle costs, models scenarios and trade-offs, allocates resources and evaluates targets and performance. Facility Condition Index (FCI) and System Condition Index (SCI) calculate asset condition (ratio of outstanding repairs to replacement value).
- *VFA.spendManager*: produces budget to minimize spending, aggregates costs, forecasts cash flows, displays capital expenditures and tracks the status of expenditures and projects.
- *AssetFusion*: integrates data with other computerized maintenance management systems (CMMS).

3.3   Information Interoperability and Integration for Sustainable Infrastructure

From an information technology (IT) perspective, sustainable infrastructure management can be viewed in terms of the *IT tools (software applications)* that support infrastructure management processes, the *information (data sets)* that describe the infrastructure systems, and the *information exchanges or transactions* that take place to move the information between different users, processes, and data sets. In order to carry out the sustainable infrastructure management analysis and processes described in this paper, software tools are required that draw from a very broad spectrum of information about the infrastructure systems. This information is generally available within existing software, but it is distributed across a wide range of applications (e.g. CAD systems, geographic information systems, Enterprise Resource Planning, computerised maintenance management systems, etc.). Municipalities currently employ a broad range of software systems to support their infrastructure management activities (Zeb et al. 2012) – the full life cycle of development, design, construction, and operation of infrastructure projects may involve many tens of distinct software applications. These data are typically not easily accessed from outside of their original software applications.

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 help to improve information interoperability in the infrastructure domain are: data exchange standards and information integration systems.

Data Exchange standards for infrastructure systems: Although there are no widespread data exchange standards that cover the broad range of infrastructure development and management processes, there are existing standards that cover portions of the domain:

- GIS-based standards: Much of the existing infrastructure management software uses GIS-based approaches. GIS-based approaches combine geospatial data (e.g., linear geometries such as the location of a pipeline, areas such as a parcel of land, or terrain models – mostly based on surface geometry), along with infrastructure system topology (e.g., network models of roads, water systems, etc), and system data (e.g., material used for pipe segments, number of traffic accidents at specific locations, etc.). Standards exist for the exchange of GIS-based information, led by the Open Geospatial Consortium (OGC) with the ISO 19100 standards series and CityGML standard.
- Building Information Modeling-based standards: Within the building construction industry, much of the software is based on Building Information Models (BIM): data models of building components along with 3D geometry (e.g., 3D CAD geometry) and related component data (e.g., materials, locations, energy modeling, costs, suppliers, construction schedules, etc.). Open BIM standards are

led by the BuildingSMART organization and their standards ISO 16739, ISO 29481, and ISO 12006-3. Although these standards relate mainly to buildings and not to infrastructure projects, there are currently some areas of overlap, such as bridges, tunnels, and building sites.

- Process Plant standards: Open data exchange standards used in process plant industries, such as off-shore and on-shore oil and gas facilities, along with related domains such as piping and wiring networks are led by the POSC/Caesar organization and are based on the ISO 15926 standard.

Thus, although no data exchange standards currently exist that provide comprehensive coverage of the infrastructure domain, there is a rich history and portfolio of technology in many related areas. A number of leading organizations in these areas are turning their attention to infrastructure and exploring ways to collaboratively extend their respective technologies to provide data exchange standards for infrastructure.

Information Integration Systems: Drawing upon lessons learned from data interoperability in building construction, practical data integration solutions require neither monolithic software applications that include all data and processes within a single integrated tool, nor central models that attempt to share all project data with all users across all software applications. Rather, feasible solutions require that different users work with different software applications for different tasks, and that these software applications have the ability to import and export well-defined data sets (partial models) as required by well-managed data exchange transactions, supported by shared data model server systems (model-servers).

4   Current Activities in Canadian Engineering Departments related to Sustainable Infrastructure

Table 1 provides an outline of engineering courses offered at Canadian Universities in subjects related to sustainable infrastructure management and decision making. It is not intended to be comprehensive as data of the type are dynamic. Table 1 generally illustrates that most courses of this type are offered at the graduate level and are offered at most universities in Canada with a Civil Engineering department.

Table 1: Canadian University Courses related to Infrastructure Management or Decision Making

University	Course	Instructor	Title
Alberta	CivE709	S. Abourizk	Advanced Topics in Construction Engineering
Calgary	ENCI619.10	L. Cowe Falls	Advanced Pavement Design and Management
Carleton	CIVE5404/5809 IPIS5102	L. Newton/ S. Goodman	Introduction to Infrastructure Management
Carleton	IPIS5502	G. Felio	Infrastructure Assets Management
Concordia	INSE-6311	A. Hammad	Sustainable Infrastructure Planning and Management Systems
Concordia	BLDG6931	M. Nokken	Infrastructure Rehabilitation
McGill	CIVE624	S. Mirza	Durability of Structures
Saskatchewan	CE898	G. Sparks	Introduction to Asset Management
Toronto	CIV1252H	H. Schell	Infrastructure Renewal
Toronto	CEM1005H		Integrative Decision-Making
Toronto	CIV1281H	H. Osman	Asset Management
Toronto	CIV577H1	C. Kennedy	Infrastructure for Sustainable Cities
UBC	CIVL598V	D. Vanier	Sustainable Asset Management
UBC	CIVL598R	A. Wood	Management of Civil Infrastructure
UBC-O	ENGR330	S. Tesfamariam	Decision Analysis and Optimization
UBC-O	ENGR431	S. Tesfamariam	Infrastructure Management
UNB	CE5241	T. Hanson	Introduction to Pavement Management Systems
UNB	CE5612	J. Rankin	Construction: Financial and Industry Issues
UNB	CE6206	T. Hanson	Pavement Management Systems
Waterloo	CIVE332	C. Haas	Civil Engineering Systems
Waterloo	CIVE720	S. Tighe	Infrastructure Management
Waterloo	CIVE740	S. Tighe	Topics in Transportation Engineering

A new series of courses is being offered by the University of Waterloo to address the needs for certification in the asset management domain (epCIP 2013). *Asset Management for Buried Infrastructure*

has the following goal: "to enable municipal infrastructure professionals to understand the fundamentals of asset management with particular emphasis on buried utilities (water and wastewater pipelines)."

In addition, the Ontario Good Roads Association is establishing an *Academy for Municipal Asset Management* (OGRA 2013). Its first course will take place in June 2013 entitled *Asset Management for Public Buildings* and it will be followed by *Asset Management for Road Networks* in October 2013. Core courses in the Academy are: *Asset Valuation and Capital Investment Planning, Asset Data Collection and Condition Evaluation, Municipal Asset Management, and Information Systems and Project Management for Municipal Assets.* Many courses will be presented by university faculty identified in Table 1.

5 Proposed D-SIM Research Activities and Key Building Blocks

The proposed D-SIM project will focus on three primary research areas:

1. *Sustainability assessment for infrastructure*: There are increasing pressures from many segments of society for our civic systems to become more socially, economically, and environmentally sustainable. To respond to these priorities, it requires 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. Numerous sustainability assessment systems have been developed for buildings (e.g., LEED, Green Globes), with extensive debate about the advantages and disadvantages of various approaches. Much less work has gone into assessing the sustainability of urban infrastructure systems. D-SIM will evaluate and build upon previous relevant approaches described above to develop practical and meaningful techniques to evaluate the sustainability of infrastructure assets. Notable building blocks for this work include the Infraguide Best Practices, *Model Framework for Assessment of State, Performance, and Management of Canada's Core Public Infrastructure*, Whistler Sustainability Model, and University of Waterloo System Dynamics Model.

2. *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-making 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 Defence (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.

3. *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 domain of infrastructure to support sustainable infrastructure management. This work will involve identifying and modeling work processes that require infrastructure data from multiple sources, articulation of the exact data required, extensions of existing data models to be able to represent the required data, and development of selected import/export capabilities for target software applications.

A portion 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.

References

Altus (2013) Press release, <www.vfa.com/2012/05/vfa-to-acquire-altus-groups-capital-planning-division> (Accessed 16 Feb 2013).

BC (2013) CPI (2013) Depreciation Report Guide, <www.housing.gov.bc.ca/pub/stratapdf/Guide12.pdf> (Accessed 16 Feb 2103).

BREEAM (2013) BREEAM Website, <ww.breeam.org> (Accessed 16 Feb 2013).

CSA BREEAM (1996) BREEAM-CANADA - An Environmental Performance Assessment for Existing Office Buildings, Product "PLUS 1132", Canadian Standards Association, Rexdale, ON.

Engineers Canada (2013) Engineers Canada: *The Profession's Position*, <www.engineerscanada.ca/files/ w_Infrastructure_en_2012.pdf> (Accessed 16 Feb 2013).

FCM/McGill (1996) *Report on the State of Municipal Infrastructure in Canada*, Available from: Federation of Canadian Municipalities and McGill University.

FCM (2012) *Canadian Infrastructure Report Card,* <csce.ca/custom-content/uploads/2012/06/ Infrastructure_Report_Card_ENG_Final1.pdf> (Accessed 16 Feb 2013).

Gallaher, M., et al. (2004) *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry,* National Institute of Standards and Technology, NIST GCR 04-867.

Infraguide (2013) Use an Internet search engine and following text string to find 116 URLs for English and French Best Practices: "site:fcm.ca/Documents/reports/Infraguide", (Accessed 16 Feb, 2013).

Lounis Z., Vanier D.J., Daigle L., Sadiq R., and Almansour H. (2010) *Framework for Assessment of State, Performance and Management of Canada's Core Public Infrastructure*, Client Report B5332.5, National Research Council Canada, Ottawa, 339p.

MIIP (2013) Municipal Infrastructure Investment Planning Project Website, <archive.nrc-cnrc.gc.ca/eng/ projects/irc/municipal-infrastructure.html > (Accessed 16 Feb 2013).

Mirza, S. (2007) *Danger Ahead: The Coming Collapse of Canada's Municipal Infrastructure*, Federation of Canadian Municipalities, Ottawa, Canada.

PSAB (2007) *Guide to Accounting for and Reporting Tangible Capital Assets,* Public Sector Accounting Group, Canadian Institute of Chartered Accountants, Toronto, Canada.

Rehan R., Knight M.A., Haas C.T. and Unger A.J.A. (2011) *Application of system dynamics for developing financially self-sustaining management policies for water and wastewater systems*, Water Research, Volume 45, Issue 16, 15 October 2011, pp. 4737-4750.

TNS (2013) TNS Website, < http://www.naturalstep.org>, (Accessed 16 Feb 2013).

USGBC (2013) US Green Building Council website, <www.usgbc.org> (Accessed 16 Feb 2013)

Vanier D.J., and Rahman S. (2004) *MIIP Report: Survey on Municipal Infrastructure Assets*, NRC-IRC Report B5123.2, Ottawa.

Vanier D.J., Newton L., Rahman S. (2006) *A Framework for municipal infrastructure management for Canadian municipalities*, NRC-IRC Report B5123.7, Ottawa.

Vanier D.J., Newton L., Rahman S. (2009) *Implementation Details to Support a Generalized Framework for Municipal Infrastructure Management*, NRC-IRC Report B5123.14, Ottawa.

Whistler (2013) Whistler Sustainability, <www.whistler2020.ca> (Accessed 16 Feb 2013).

Wikipedia (2013) Definition, <en.wikipedia.org/wiki/Triple_bottom_line> (Accessed 16 Feb 2013).

Zeb J., Froese T., and Vanier D. (2012) *Survey of information technology use for municipal infrastructure management*, ITcon Journal, pg. 179-193, www.itcon.org/2012/11 (Accessed 16 Feb 2013).

Zofnass (2013) Website <www.sustainableinfrastructure.org> (Accessed 16 Feb 2013).