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Building Sustainability into Your Infrastructure Plan

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Abstract: Understanding the financial and environmental sustainability of infrastructure is no longer an option, it is a requirement of any modern business endeavour. There are many technical and organizational challenges in developing and communicating a long-term business strategy and financial plan to deliver a defined level of service based on sustainability and life-cycle management principles. Many municipal organizations have their budget and resource allocation entrenched in historical based budgeting processes that focus on budget inputs rather than service, financial and environmental outputs and outcomes. Sustainability by definition is about understanding the current and future impact of our decisions and requires robust forecasting models. It is the act of acquiring, operating, maintaining, renewing, and enhancing infrastructure that determines both the affordability and the environmental footprint of communities. Building on a sustainability framework developed in Canada, network and project level performance models were developed using Markov chains to forecast service levels, economic and environmental outcomes for different policy options. This cases study provides insights and lessons learned in using this sustainability framework in the development of a 10 year, 200 million dollar integrated capital and operating infrastructure plan for the City of Saskatoon's water distribution system. This work has been recognized in the 2011 edition of the International Infrastructure Management Manual as case study 13.

1 Introduction

The business plans of many organizations express commitment to sustainability. What does this really mean when it comes to making infrastructure decisions and linking those decisions back to community benefits, service levels, cost of service, the technical evaluation of infrastructure performance, risk, and the environmental footprint of the infrastructure? Ultimately, in setting clearly defined goals in the community planning process and the infrastructure asset management plan, we must consider all of these elements, and convert them into specific program and budget actions each year.

One of the well-recognized definitions of sustainability was defined by the Brundtland Commission of the United Nations in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WECD 1987).

There is an increasing awareness that the barrier to delivering better service at lower cost with a reduced environmental footprint is not merely a technical one (Woodhouse 2011) but rather the method for putting the technical elements together. The critical questions is how to analyse, integrate, and present the cornerstones of sustainability to decision-makers and stakeholders, given that truly integrative sustainability assessments have rarely been undertaken (Optimized Decision Making, 2004). The challenge then is to transform the principles of sustainability into practical operations models (Sahley 2005).

A national initiative in Canada proposed a set of objectives and performance indicators within a framework founded on sustainability (Engineers Canada 2009) as shown in Figure 1.

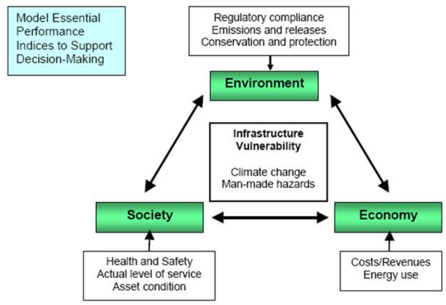

Figure 1 Proposed framework in Canada

Sustainability principles require stewardship and effective management over all resources. Public infrastructure is a unique class of assets in which the asset itself is intended to provide the basic facilities (e.g. buildings, roads, and power supplies) needed for the operation of society. Using this framework the social corner of sustainability is where you can define service to the community by setting level of service standards that support broader community benefits and outcomes (eg. a road provides mobility to support commerce, access to hospitals and other emergency services, general social needs, etc.). This is an important concept wherein the technical evaluation of infrastructure and risk frameworks should incorporate zoning, property use and other outputs defined through the community planning process. The cost of service is evaluated at the economic corner and the environmental impact of service is evaluated at the environmental corner.

Infrastructure management is complex and multi-dimensional, making it easy to stall out before getting to the end, with the end being a measurable business strategy to accomplish the desired community outcomes. Without reaching the end, we cannot assess whether the decision is sensitive to any one specific input. The purpose of this case study is to demonstrate the need to get through all elements typically considered critical in optimizing infrastructure investment while integrating the social, environmental and economic outcomes in the assessment. These critical elements included development of an asset risk framework, an inventory hierarchy and management segmentation topology, condition assessment and characterization for strategic tactical and operational decision making, development of network/portfolio performance models to forecast and evaluate different level of service policy options, life cycle economic analysis, long term financial requirements, development of a methodology to determine carbon emission profiles for each service level policy options and demonstrate the applicability of the sustainable infrastructure decision making framework proposed in Canada in 2009.

2 Saskatoon Case Study

The work presented in this case study was part of a business review by the City of Saskatoon, Canada to systematically manage its water distribution system to a defined level of service at the minimum long-term cost. Specific objectives included:

1. To provide an integrated service level based budget planning and performance reporting framework, with City Council approved service levels that include community input.

2. To define long-term operating and capital programming and funding requirements for various service-level options.

These are objectives that any organization delivering infrastructure-intense services should strive to design their business planning and technical tools around.

3 Defining Inventory Topology and Hierarchy for Management Purposes

The asset inventory structure and hierarchy is a strategic foundation building block to facilitate effective asset management. One of the first steps is defining a management segmentation hierarchy and topology to determine how you will define the beginning and end of a water main to facilitate the following activities: 1) assess and assign asset risk, 2) develop service level performance measures for capacity, condition and water quality and characterize them on a common unit of inventory, 3) track historical trending to develop performance models for life cycle forecasting to schedule interventions, 4) manage across all life cycle activities (create/acquire, operate, maintain, enhance, and dispose), 5) program planning and delivery, 6) management reporting, 7) budget and program rollup through all organization planning levels.

Saskatoon's inventory is contained in a GIS segmented using pipe fittings. As a result the water system consisted of approximately 29000 discrete pipe segments ranging in length from less than 300mm to a couple kilometers. As the management schema is used to establish both operating and capital programming a number of options were considered: 1) isolation segments (valve to valve), 2) block faces using intersections, and 3) a hybrid of the two. Option three was chosen to establish the management segmentation topology with intersections used for distribution mains less than 400 mm and valves used for mains greater than 400mm (feeder, primary and reservoir fill mains). This also reflected long term policy to restrict services from being connected to mains greater than 400mm. This segmentation schema also better reflects the customer's perspective when it comes to service outages where a valve repair also puts the adjacent valve to valve isolation segments out of service.

This resulted in 250 primary main management segments and 4500 distribution management segments. A set of guidelines were developed to define the management schema. The segmentation was completed by an experienced Engineer that had been involved in both the operating and capital programming of water main renewal. The management segmentation was done using a tooled developed by the corporate GIS group to allow the end user to group pipe segments into management segments and also designate the node attributes (i.e. at a T node the main management segment can be continuous or not through the top of the T and can be the terminal end of a management segment from the leg of the T). Additional nodes also had to be identified where there were no nodes and the mains were considered too long. One of the advantages of this schema is that hydrants and valves are contained within a management segment.

4 Incorporating Risk into the Decision Making Process

Water mains and infrastructure in general differ in their needs depending on whom they serve, where they are located, their function within the network, and the impact of service interruption on individual customers and the community as a whole. As part of the business review, a risk-based service classification/hierarchy framework was developed, embedding sustainability into the framework and developing a strong link to community land-use planning. This framework is presented in Table 1.

The service classification categorized each water main management segment into one of three service classes based on whom the main services, adjacent land and property use, right-of-way use above the water main, function in the distribution system, the hydraulic criticality of the main, and the economic, environmental, and operational risk associated with service failure. Service classes provide a structured approach to set different service-level measures, targets, and maintenance triggers, and to define the management approach (proactive versus reactive) to deal with infrastructure service delivery. This type of risk-based classification framework is the starting point for incorporating sustainability principles into the infrastructure decision-making process. The service-class definitions that were developed were also included in a service level study and strongly validated by the community.

Table 1 Risk Based Service Classification Framework

	Risk Based Service Classification Framework		
	Critical	**Run to Failure**	
	Service Class 1	**Service Class 2**	**Service Class 3**
Environmental, Social, and Economic Consequence of Service Loss	Critical mains with very high consequence associated with service loss	Mains with moderate consequence associated with service loss	Mains with a low consequence associated with service loss
Operational Impact of Failure	Failure cannot be handled in an effective manner	Failure can be accommodated but strains operations	Failure can be addressed through normal operations
Probability of Failure	No tolerance for performance uncertainty	Moderate tolerance for performance uncertainty	High tolerance to performance uncertainty
Management Approach	Extensive use of monitoring and assessment to plan and continuous proactive maintenance and rehabilitation to avoid service failure.	Some failure can be tolerated. Increased use of monitoring and assessment to plan.	Run to failure is an acceptable policy.

A vulnerability assessment used a calibrated hydraulic model to systematically take each segment of main out of service to evaluate the impact on the system water supply. Hydraulic vulnerability was not found to be important on the small diameter distribution mains (less than 400 mm) because they are designed with extensive system redundancy. The results of the service classification are summarized in table 2.

Table 2 Water Network Service Classification Results

Network Class	Total	Service Class 1		Service Class 2		Service Class 3	
		Critical		**Run to Failure**			
	Meters	**Meters**	**%**	**Meters**	**%**	**Meters**	**%**
Distribution	891,057	0	0	158,994	17.8	732,064	82.2
Transmission	100,841	22,907	22.7	46,910	46.6	31,024	30.7
Total	991,894						

The principle is that City Council should be managing the trade-offs between service levels and not trade-offs between project priorities that represent different risk profiles (as represented by each service class). Specifically you do not include critical and non-critical infrastructure in a single project prioritization process. This type of risk-based service classification also reinforces who is accountable for setting business goals and who is responsible for delivering innovative service solutions.

The significance of the service level classification results in terms of selecting technical measures to characterize condition and the forecasting approach are summarized as follows:

- All distribution mains which represent approximately 91% of the distribution system can be run to failure. Therefore break frequency, density and duration can form the basis of service level definitions for condition performance. Statistical models using Markov chains can therefore be used as the basis of performance models to do life cycle forecasting and define the probability of failure for the asset risk framework. Also because the only distinction between service class 1 and 2 is the intervention threshold for renewal it was decided that performance data could be pooled to develop a single network level performance model.

- 77.3 percent of the transmission mains can also be run to failure and managed in a similar manner to distribution mains.

- 22,907 meters of transmission mains were identified as critical and require a failure avoidance approach to manage condition. More sophisticated mechanistic models would be a better choice as part of life cycle forecasting and risk management. Following an assessment of each of these critical mains it was concluded that a separate unique intervention plan should be developed for each critical main management segment.

5 Defining Service Levels and Developing Performance Models.

Management literature has long acknowledged that decision making typically occurs at three levels: operational, tactical, and strategic. We must keep this in mind when measuring and communicating infrastructure performance and developing forecasting models, setting the level of service goals, and developing policy, procedures, and standards. It is very important to ensure that all levels of programming and delivery are working to the same goal, and that roles and responsibilities are clearly defined to foster accountability and innovation.

Water mains, like most assets, have multiple condition measures. The condition must be defined for setting the level of service for the customer and determining the most appropriate maintenance and rehabilitation intervention. The management level (strategic, tactical, and operational) determines the detail required to define condition.

Every customer should know the standard of service that will be provided and the current and predicted future performance of the infrastructure serving them. The service outcomes of each section of a water main can be defined around the following three technical performance measures: physical condition (availability), capacity, and quality. To define the level of service, each section of a water main must be evaluated against the community's performance expectations. Each of these service criteria can also have a stated level of reliability, responsiveness to restore service, and willingness to pay.

As the primary issue with the water distribution network was structural condition a proof of concept was developed to incorporate all three key service performance measures and performance models were developed only for structural condition.

There is no one single way to characterize the structural performance of a water main and relate it directly to customer expectations. Depending on the circumstances customers are sensitive to the total number, frequency, density, time of day and duration that service interruption occurs due to water main breaks or valve and appurtenance failures. Performance metrics were generated for each water main management segment. This analysis included spatial assignment of almost 13,000 break records spanning 50 years to the water main management segments, and the development of a spatial history of water main renewal. This allowed the analysis to retroactively test different performance metrics back 15 years for their robustness in defining pipe condition. When you choose to define management segments based on intersection rather than by material, year of construction or isolation segment it impacts how you develop your network performance models for life cycle management and forecasting future condition. As a result water main management segments can have both mixed materials and years of construction. This is an issue that both operations and capital planning must consider when undertaking emergency repairs and developing renewal programs.

In the end a non-conventional approach was taken to defining distribution water main structural condition based on the severity and extent of service outages/water main breaks. Severity was defined based on the break density in 100m of water main (as opposed the typical industry norm of break density per km) binned into three discrete severity levels: slight (S), moderate (M) and extreme (X). The actual break density metric was calculated based on the metallic length within the management segment. Extent was defined based on the percent of metallic main within a management segment and binned into one of three extent levels. Two additional conditions states were added to these definitions to include “excellent” for mains comprised of 100 percent PVC and non PVC mains that have experienced no breaks. We call these resulting eleven unique conditions states tactical condition states and use them to identify priorities for water main maintenance and renewal with both operations staff responsible for fixing water main breaks and capital planning and renewal staff. The tactical condition states are then grouped into strategic condition states for setting customer service levels. The tactical and strategic service levels definitions are shown in Figure 2 where green is excellent and good, yellow is fair andred is poor. This results in the following condition states: Excellent, Good, (Fair: S1, S2, S3, M1, M2, X1) and poor (M3, X2, X3).

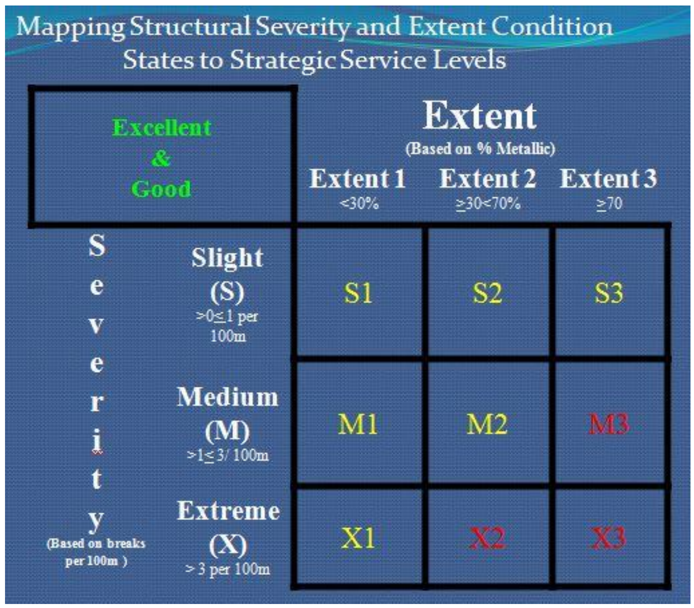

Figure 2 Water Main Service Level Definition

For the purpose of defining customer service levels for strategic decision making, three to five levels are commonly used to define the network condition for City Council, the community, and national report card initiatives. Common strategic-level reporting schemata often include the use of good fair poor; three- to five-star ratings; or the alphabet (A, B, C, D, E/F). Whatever terminology is used to communicate service level and network condition, it must align with the organization’s business processes to develop programs and budgets, and evaluate the cost of service and environmental impacts.

It is very easy to expand the level of detail at the strategic-reporting level without recognizing the consequence of this decision in terms of supporting evidence based decision making. The decision to characterize the performance of the network for three performance measures (structural, capacity, quality) at three or five levels would result in 27 versus 125 unique combinations of condition respectively. This significantly impacts the robustness of the decision support tools.

It has been recognized that to optimize intervention strategies, infrastructure performance should be evaluated in terms of the severity and extent of separate performance indices (Baladi 1994, Chartier 1997). To define strategic service levels around customer service outages, the severity and extent of water main breaks were characterized for each water-main management section. This generated three strategic service levels (excellent+good, fair and poor) and 11 tactical condition states. Markov performance models were developed to forecast different service-level options in terms of condition, operating and capital programming and budget, and environmental carbon emissions.

These strategic service-level definitions were also used to stratify the network sample for a customer service Level Survey.

The existing network condition mapped into the severity and extent matrix is shown in Figure 3

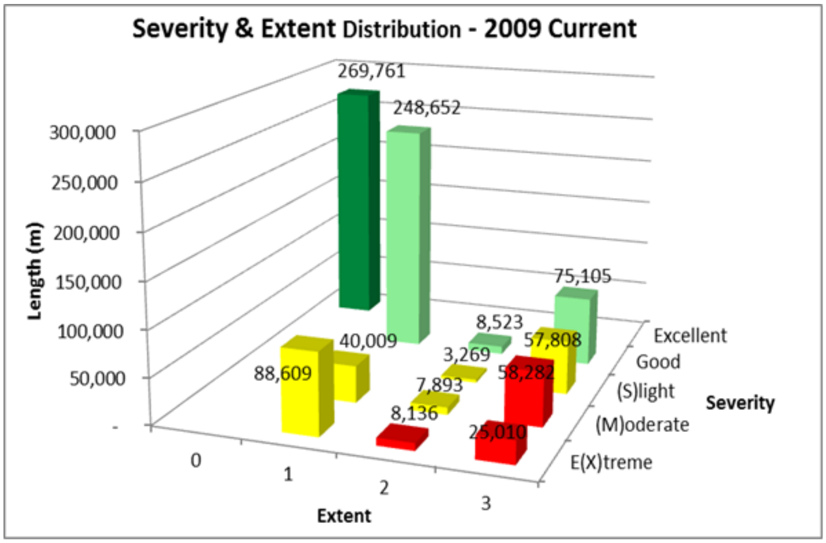

Figure 3 Existing Condition at the End of 2009

6 Economic Sustainability: Cost of Service

Life-cycle economic analyses were undertaken on each of the 13 tactical condition states and the preferred least-cost strategy considering operating and capital investment was identified based on 5, 10, 15, 20, 30, and 50 year analysis periods. The recommended investment strategy required a capital-intense investment of almost $29 million over a 3-year period, which would be returned within 10 years through reduced operating expenditures. Both condition and budget were forecast for the 10-year period from 2010 to 2019.

Cured-in-place lining and hydro excavation technology fundamentally changed the economics of operating the water distribution system. Due to this technology, the city identified a $29 million investment backlog, of which $6 million comprised a service backlog based on historical service-level policy, and $23 million was a financial backlog where it was cheaper to renew the water main than to continue to repair and then renew them at the stated service-level policy.

Stated differently, the cost of doing the status quo would cost the same over 10 years but would deliver significantly poorer service levels.

7 Environmental Sustainability

The acquisition, production, and distribution of water can be evaluated in terms of resource conservation and environmental emissions. Water resource conservation is realized through water efficiency, including demand management and water-loss reduction through active leakage control and pressure management. The environmental impact of service policy options can also be evaluated based on trade-offs between capital and operating activities and their impact on the carbon footprint.

The business review focused on determining the emission reduction associated with the operating and capital impact of the different policy options.

Forecasting the environmental footprint associated with the different options required:

- ✓ Quantifying the trade-off between capital and operating expenses for a given service strategy and the timing of the expenditures based on performance models
- ✓ Forecasting the footprint required identifying the activities that make up the operating and capital components of the service strategies and their unit production of carbon emissions.
- ✓ Work management breakdown of activities (from maintenance management and job-costing systems)
- ✓ Fleet Management fuel consumption records from the fleet management system fed into the work management system

In the long term, work and fleet management systems need to generate standard reports to support the evaluation of environmental impacts related to the operation of its business.

The carbon profile of the different service strategies were forecasted and are shown in Figure 4

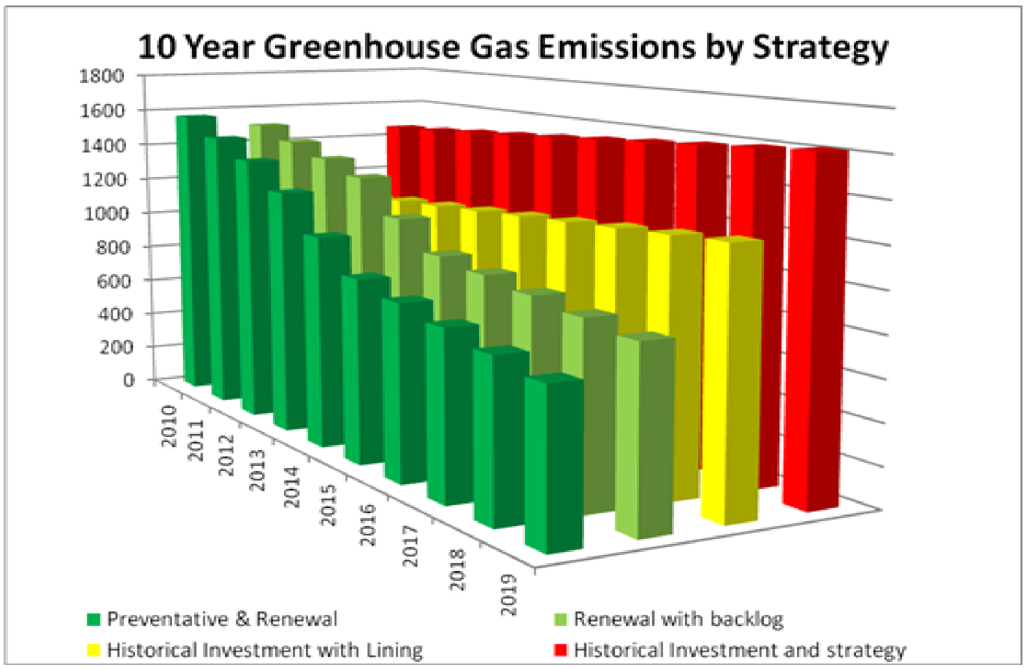

Figure 4 Carbon Equivalents Forecast by Strategy Option

It should be noted that the emissions by strategy does not account for the difference in the network condition at the end of the 10 years for the different service options. In fact, at the end of 10 years, there is still a 35 km deferred backlog for the historical strategy (red—open excavation—and yellow—cured-in-place lining renewal) compared to the optimal strategies (green). The net reduction in greenhouse emissions over the 10-year period when adjusted for this service backlog was estimated to be approximately 5000 tonnes.

The source of the emission reductions are presented in Figure 5. This graph shows that the reduction in emissions is primarily due to avoiding the operational foot print of repairing water main breaks.

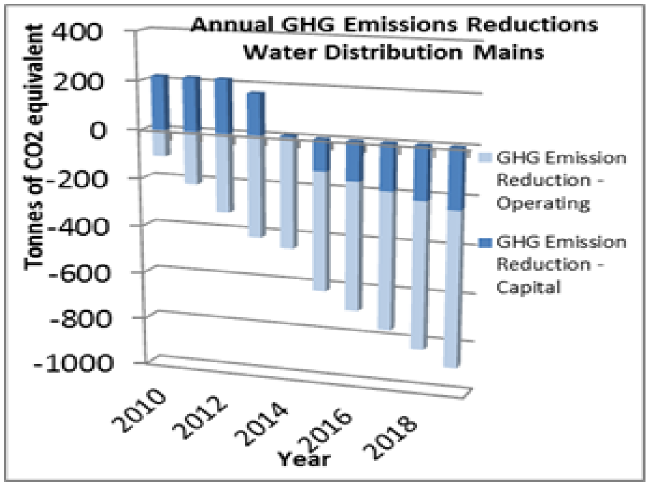

Figure 5 Sources of Emission Reductions

An issue we identified as part of the emissions forecasting was how best to evaluate the equivalency between a unit of carbon emissions today against a unit of carbon emissions in the future. In forecasting models this is typically handled by applying a discount rate to the associated cost. In this case we forecasted both service levels and carbon emissions. One option we considered was to discount the carbon emissions in addition to economic discounting. This issue was also identified by Sydney Water in their development of a tool to evaluate carbon emissions. Within their tool they provided for both options.

8 Conclusion

Sustainability must be founded on a customer-centred asset management business model that links the purpose of infrastructure with clearly stated service levels and standards at the social corner in language that can be understood by the community. The environmental and economic corners are a consequence of the service choices and should be articulated and communicated in terms of those service outcomes and policy options. Only then can the community make informed decision about trade-offs between the level of service, cost of service, and the environmental impact of service. At the environmental corner, emissions and resource conservation are two key performance indicators. Cost of service stated in terms of the cost to the customer must anchor the economic cornerstone.

There is a large environmental footprint associated with the operation, maintenance, and renewal of infrastructure. Significant reduction in greenhouse emissions can be realized by understanding the trade-offs between ongoing operations, and maintenance and renewal.

Sustainability is about understanding the current and future impact of our decisions and requires robust forecasting of level of service, cost of service, and the environmental impact of service.

- For water distribution, the City of Saskatoon was able to calculate the long-term funding needs and infrastructure gap using:

- An objective evaluation of infrastructure service level and condition

- A service-level study to define community service expectations

- An assessment of risk through the establishment of service classes/priorities and performance models

- Life-cycle cost analysis that considered various analysis periods based on the condition of current inventory, actual deterioration rates, and available maintenance, rehabilitation, and replacement options.

In doing so, Saskatoon was able to frame the infrastructure decision in terms of the three cornerstones of sustainability: social, economic, and environmental.

Communities can deliver better service at lower cost with significantly reduced carbon emissions.

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