A Comparison Between Optimization and Prioritization Solutions for Municipal Fund Allocation

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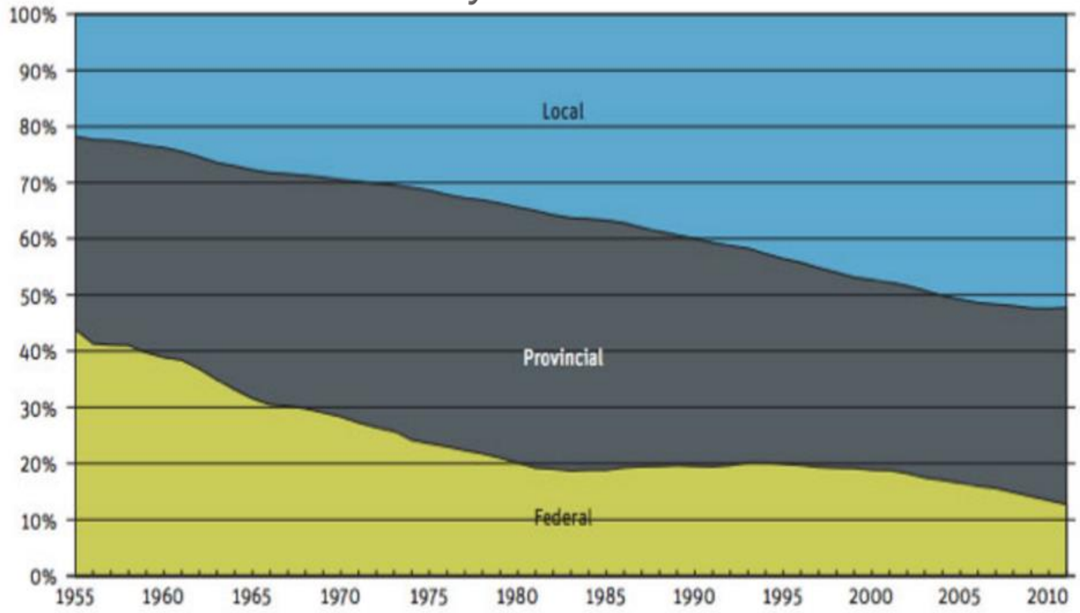
The Challenge

Municipal governments, especially smaller and medium size communities, are struggling with aging infrastructure and rising infrastructure deficits. There is a constant need to **DO MORE WITH LESS**!

Asset Shares by Order of Government



Source: Canadian Center for Policy Alternatives, 2013

Almost 60% of Canada's core public infrastructure is owned and maintained by municipal governments.

The Fund Allocation Problem

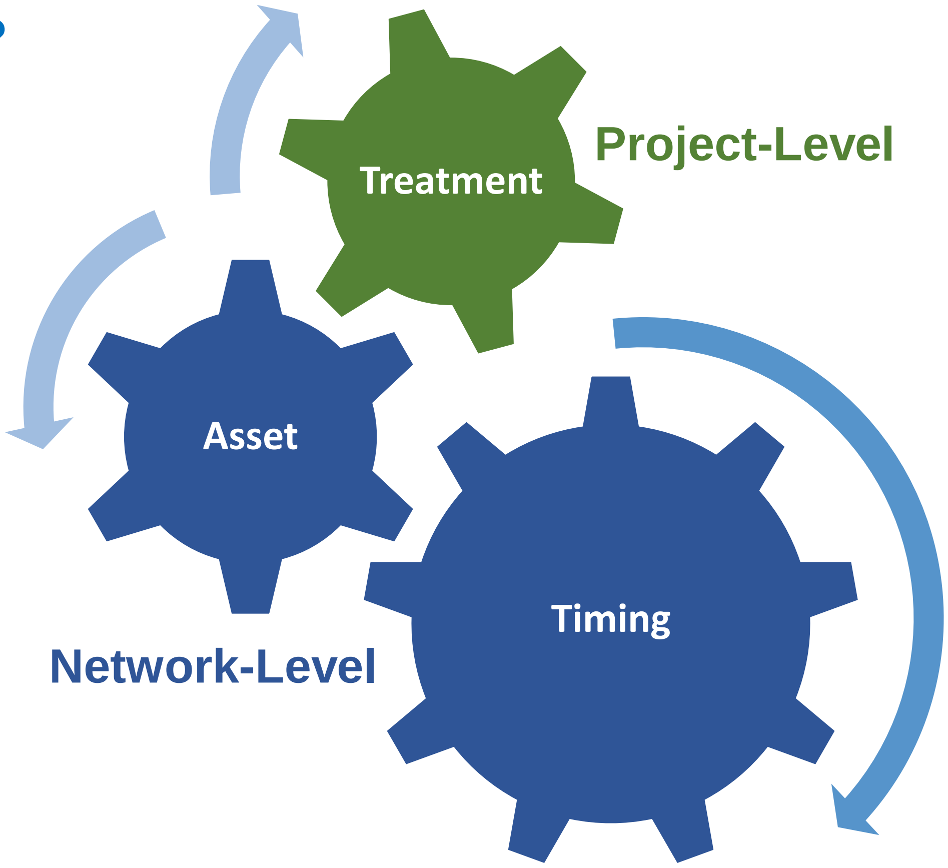
which municipal assets to fix?
with what treatment?
at what time?

to

Maximize Performance
Minimize Cost

while satisfying

Budgetary limits
Serviceability objective
Socio-economic considerations
Operational requirements
and etc.



Decision-Making Methods

- Priority Ranking
- Multi-Criteria Analysis (MCA)
- Cost-Benefit Analysis (CBA)
- Optimization

Considering the levels of investments in asset preservation projects, **even small improvements** in the quality of the solution can be translated into **millions of dollars in cost savings**.

Sample Road Network Data

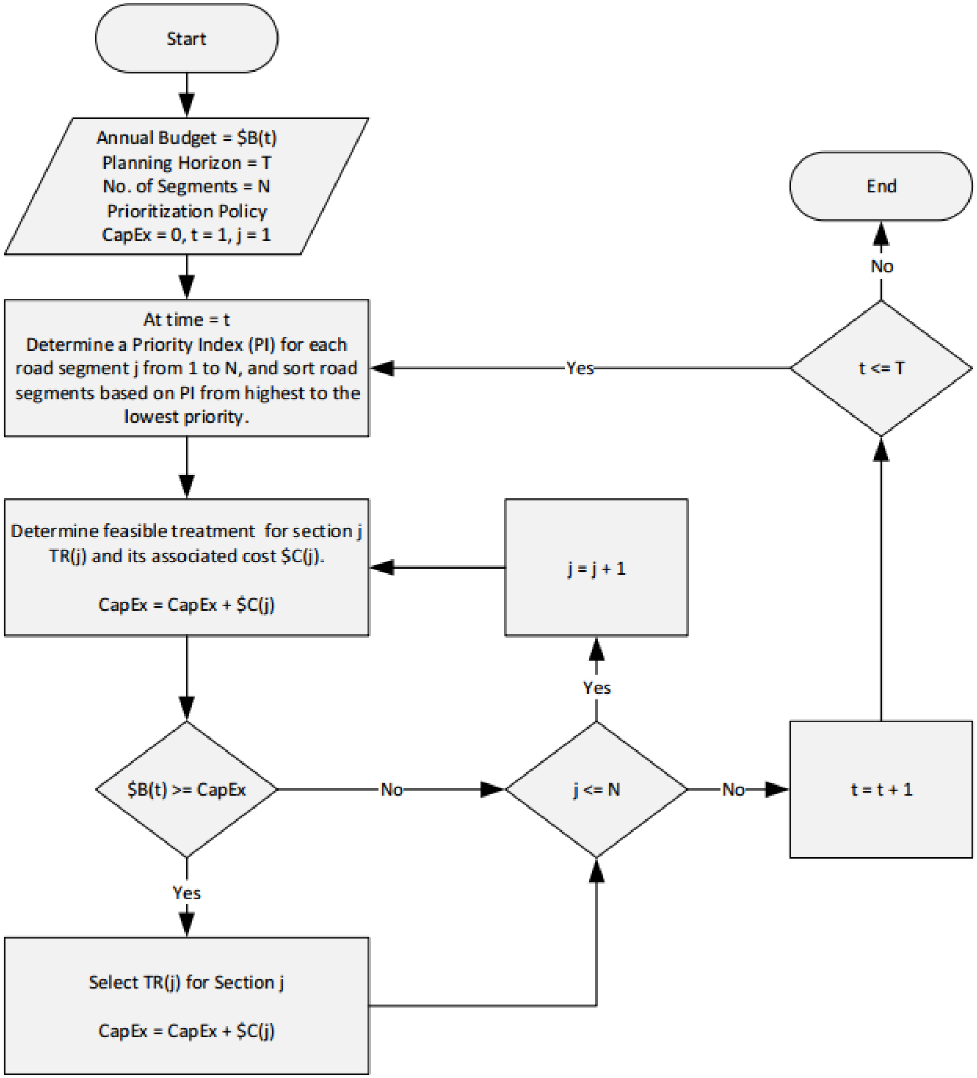
3-Year Planning Horizon

$50,000 Annual Budget

Section ID	Functional Class	MMS	AADT	Service Type	Surface Type	PCI
1	Local	5	50	RES	HMA	72
2	Local	5	160	RES	HMA	65
3	Local	5	215	RES	HMA	90
4	Local	4	85	RES	ST	80
5	Collector	3	590	RES	HMA	68
6	Collector	3	1100	RES	HMA	54
7	Collector	3	1000	RES	HMA	68
8	Minor Arterial	2	4850	COM	HMA	73
9	Collector	3	2100	RES	HMA	49
10	Local	5	210	RES	HMA	12.5

Priority Ranking

Priority ranking has been suggested and used in many pavement management applications (Zimmerman et al. 2011; Wolters et al. 2011);



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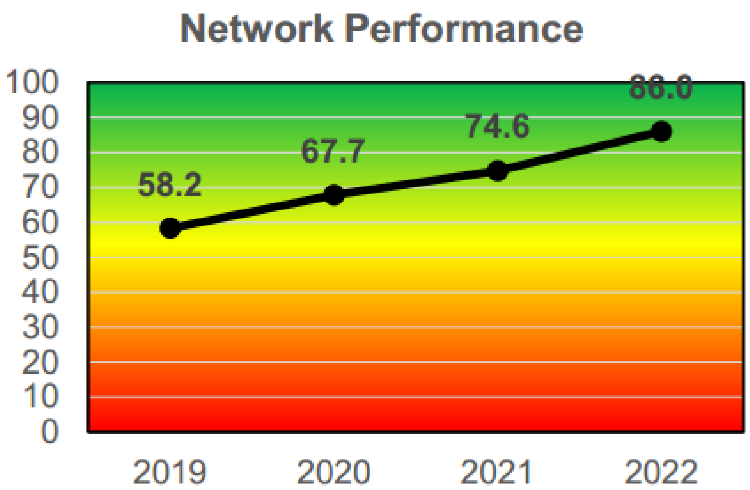
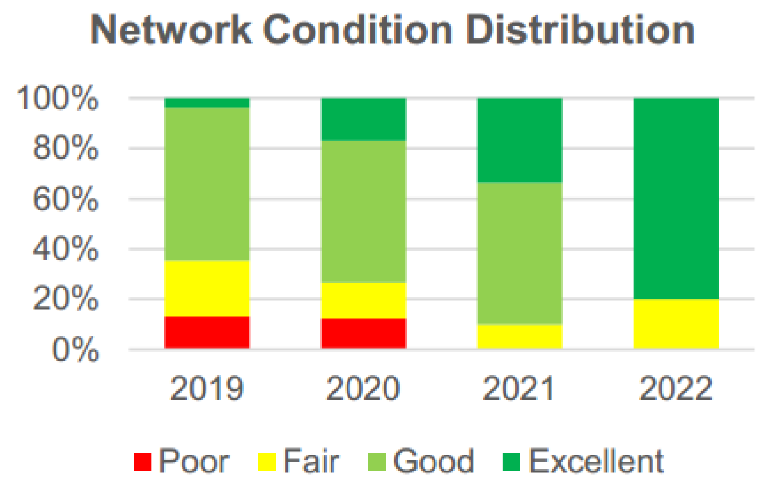
Results using Priority Ranking

Table 2: Fund allocation plan using Priority Ranking

Intervention Time	Section ID	Treatment	Budgeted Cost
2019	3	HMA-Crack Seal	$164
2019	10	HMA-FDR & EAS & Ovly	$48,198
2020	2	HMA-Ovly	$7,456
2020	9	HMA-FDR & 2Ovly	$39,200
2021	1	HMA-ST	$3,570
2021	4	ST-SST	$4,505
2021	6	HMA-FDR & 2Ovly	$29,120
2021	7	HMA-Enh2Surf	$10,080





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Pros and Cons: Priority Ranking

- **Simple** and easy to understand
- The resulting “**worst roads first**” approach. Under this strategy, the most deteriorated roads, which require major rehabilitation treatments, are a huge sink into which the largest proportion of municipal road budgets is poured.
- The **large percentage of roads in fair condition** by the end of the plan is an indication of this phenomenon. These sections will deteriorate further into poor condition at a higher rate (assuming that deterioration rates increase as condition decays) and will become future backlog.
- Omits the **time dimension of the analysis** and does not have the capability to analyze the impact of time delays on the overall allocation of budget and network performance. Road network models need to be dynamic with the status being upgraded continually as maintenance work is performed.
- Another key limitation of priority ranking is its inability to **incorporate multiple constraints** into the analysis, when in reality agencies have to deal with a multitude of constraints.

MULTI-CRITERIA ANALYSIS (MCA)

A wide range of MCA methods were developed in 80s and 90s and since 2000 have become more widely considered in various domains. MCA techniques are diverse in both the kinds of problem they address and in the techniques they employ.

Examples of some of the more widely used MCA methods include:

- **Analytical Hierarchy Process (AHP)** (Saaty 1990; Saaty 2008),
- Fuzzy AHP (van Laarhoven and Pedrycz 1983),
- Multi-Attribute Utility Theory (Keeney and Raiffa 1993),
- Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) (Lai et al. 1994).

MCA methods can be used to complement monetary evaluation methods such as cost-benefit analysis.

Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process (AHP) is perhaps one of the most widely used MCA techniques for **converting subjective assessments** of the relative importance of a set of criteria into a set **of numeric weights**, by focusing decision maker attention on developing a formal structure to the decision-making problem.

AHP is easy to implement and requires answers to a series of simple questions regarding the importance of various criteria relative to each other.

Table 3: Pairwise comparison preference weighting

How important is criterion A as compared to B?	Preference Index
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values	2, 4, 6, and 8

AHP Structure

A hierarchical structure is developed to capture key criteria and their hierarchical relations to arrive at the desired outcome.

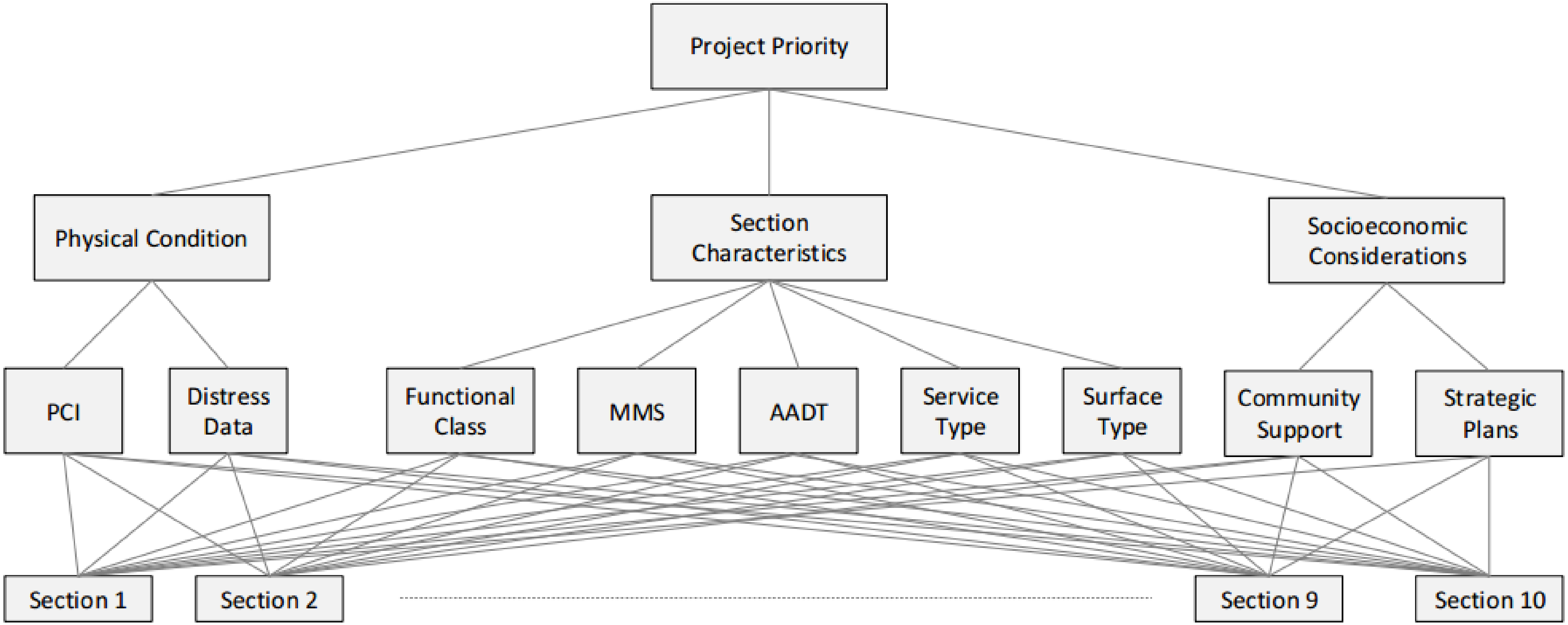

Figure 3: AHP structure for pavement preservation project prioritization

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AHP Calculations

$$Aw = \lambda_{max} w \qquad (1)$$

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}$$

Pairwise Comparison Matrix

Relative Importance of different criteria

	a1	a2	a3	a4	a5	GM	w
a1	1	0.33	1	5	7	1.6345	0.222
a2	3	1	3	5	9	3.3227	0.450
a3	1	0.33	1	5	9	1.7188	0.233
a4	0.2	0.2	0.2	1	3	0.4743	0.064
a5	0.14	0.11	0.11	0.33	1	0.2259	0.031

n = 5

RI = 1.12

λ_{max} **5.22**

CI 0.06

CR 0.05

Consistency Ratio:
A **10%** tolerance is used for human judgment errors

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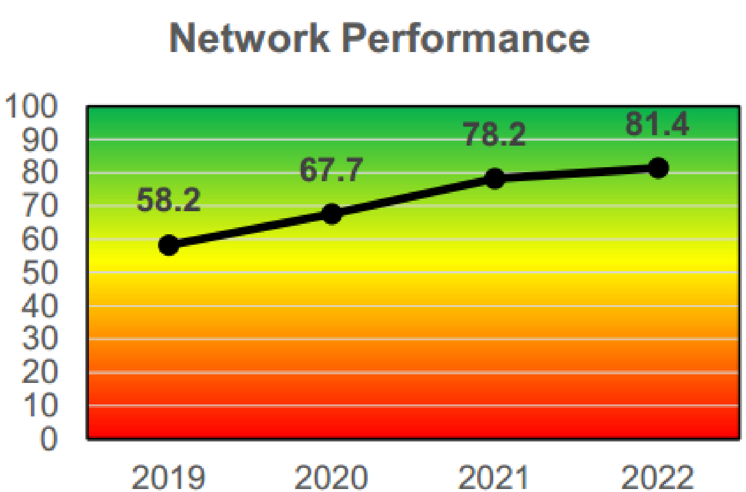
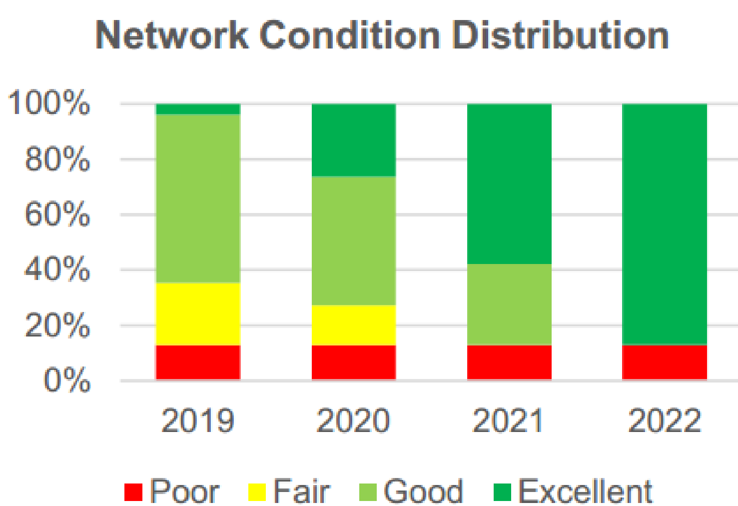
Results using AHP

Table 4: Fund allocation plan using MCA

Intervention Time	Section ID	PI (MCA)	Treatment	Budgeted Cost
2019	3	29.07	HMA-Crack Seal	$164
2019	8	65.20	HMA-EnhSurf	$7,560
2019	9	65.17	HMA-FDR & 2Ovly	$39,200
2020	2	36.57	HMA-Ovly	$7,456
2020	6	62.03	HMA-FDR & 2Ovly	$29,120
2020	7	57.83	HMA-Enh2Surf	$10,080
2021	1	31.21	HMA-ST	$3,570
2021	4	36.54	ST-SST	$4,505
2021	5	56.20	HMA-Enh2Surf	$13,311
Not selected	10	52.32	-	-





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Pros and Cons: Multi-Criteria Analysis

- MCA can help to better capture the variations in priority programing and results in more application of cost-effective preventive maintenance strategies.
- The 1-9 scale has the potential to be internally inconsistent. As an example, if the section A preference index as compared to section B is 2, and B as compared to C is 5, then to be numerically consistent, section A must have a preference index of 10 over C, which is not possible using the 1-9 scale of AHP.
- Lack of a measurement scale for criteria can also contribute to vagueness when performing cross comparisons.
- Although MCA is a better approach as compared to priority ranking and is a beneficial method in terms of focusing decision maker attention on developing a formal structure to the decision-making problem, it **cannot guarantee that the best possible solutions are achieved**.

Cost-Benefit Analysis (CBA)

- CBA is a methodology to explicitly determine benefits and costs associated with a project in money terms (Thoft-Christensen 2012; Fraser and Jewkes 2013).
- An agency can prioritize projects based on the **cost-effectiveness** or the ratio of benefit over cost (**B/C ratio**) of a project.
- In general, an investment alternative is considered desirable when resulting benefit over **cost ratio is greater than one**, or in other words, the expected benefits exceed the expected costs.
- When a set of mutually exclusive alternatives exists, they can be raked based on their B/C ratio and a similar process to priority ranking can be employed to arrive at the final solution.

CBA for Pavement Preservation Programing

Cost

$$TPWC_{jt}^{RN} = pwf_{iN} \times RC_{j}^{RN} + \sum_{k=1}^{t} pwf_{ik} \times VOC_{jk} \qquad (6)$$

Benefit

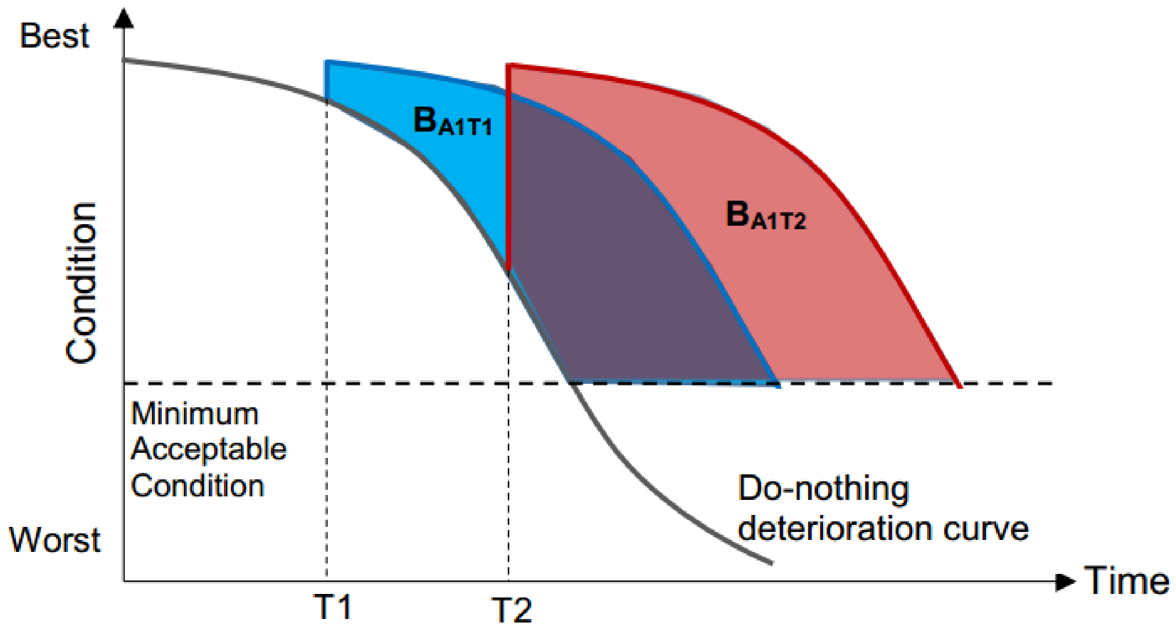

Figure 6: Performance benefit improvements of preservation alternatives

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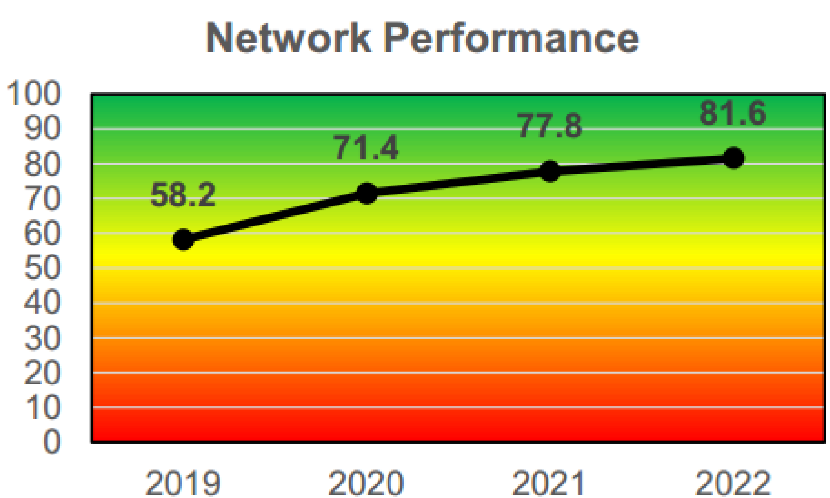
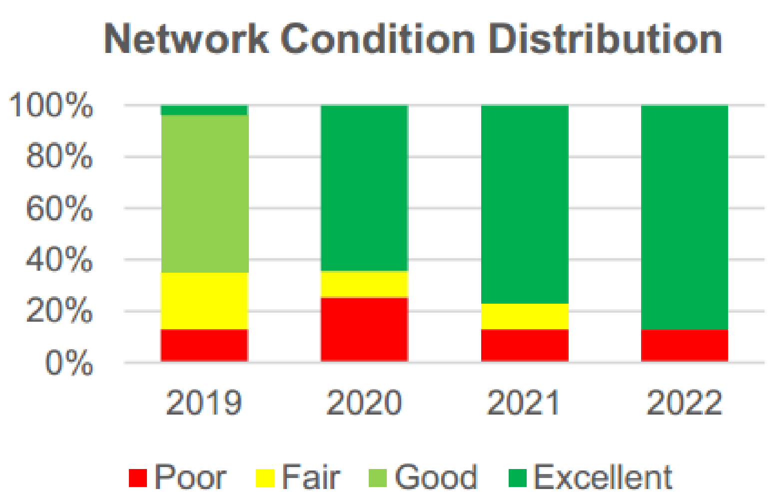
Results using CBA

Table 5: Fund allocation plan using CBA

Intervention Time	Section ID	Treatment	Budgeted Cost
2019	1	HMA-EnhSurf	$3,856
2019	2	HMA-Ovly	$7,456
2019	3	HMA-Crack Seal	$164
2019	4	ST-SST	$4,505
2019	5	HMA-EnhSurf	$7,987
2019	7	HMA-EnhSurf	$6,048
2019	8	HMA-EnhSurf	$7,560
2020	9	HMA-FDR & 2Ovly	$39,200
2021	6	HMA-FDR & 2Ovly	$29,120





Pros and Cons: Cost-Benefit Analysis

- CBA is an effective method to determine monetary implications of project alternatives in terms of costs and benefits.
- Lacks the capability to analyze the impact of time delays or accelerations
- Inability to incorporate multiple constraints into the analysis:
  - fluctuating annual budgets
  - Shifting strategic objectives
  - minimum levels of service objectives
  - safety considerations
  - input from the public
  - requirements for alignment with other projects
  - and many other practical and operational constraints.
- Financial return on investment is only one component of the analytical process.
- Although CBA methods can get the decision-makers closer to a better solution, they cannot guarantee that the ideal or best possible solutions in achieved.

Optimization

- Optimization is branch of science in Operations Research (OR). “Optimization provides **a scientific approach to decision making** that seeks to optimize the **performance of a system**, usually under conditions requiring the **allocation of scarce resources**.”

- Originated during World War II when the British government recruited scientists from different disciplines to solve the operational problems of the war.

- The focus of optimization is, therefore, **to understand the complex operations of any system** so as to predict its behavior over time and <u>**to identify the best course of action**</u> that leads to an <u>**ideal level of performance**</u>, or in other words, an ‘**optimal’ solution**.

Challenges with Performing True Optimization

- Pavement preservation programs represent a complex problem

- Complexity and processing time grows exponentially as the size of the problem increases

- Practical applications require advanced and powerful optimization technologies

- The inherent complexity of formulating and developing mathematical optimization models makes it somewhat unfamiliar and complicated for most mainstream applications in the municipal domain

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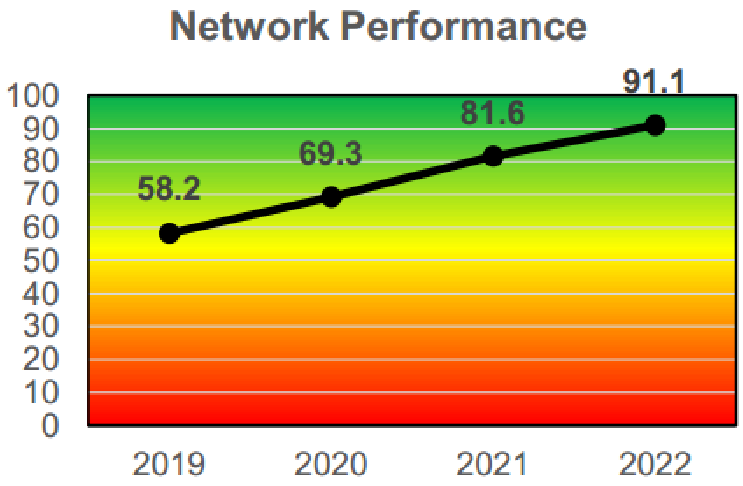
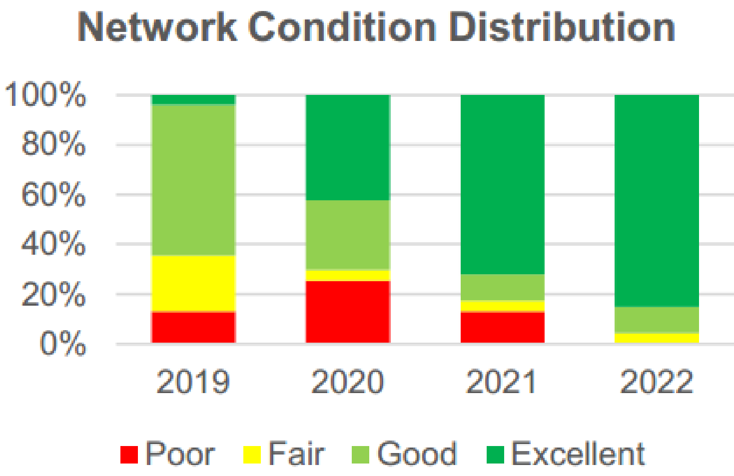
Canadian Experience and Support 50 Canadian Municipalities Participated in the development Process

Results using Optimization

Table 6: Fund allocation plan using optimization

Intervention Time	Section ID	Treatment	Budgeted Cost
2019	1	HMA-EnhSurf	$3,856
2019	5	HMA-EnhSurf	$7,987
2019	6	HMA-FDR & 2Ovly	$29,120
2019	8	HMA-EnhSurf	$7,560
2020	7	HMA-Enh2Surf	$10,080
2020	9	HMA-FDR & 2Ovly	$39,200
2021	3	HMA-EnhSurf	$1,767
2021	10	HMA-FDR & EAS & Ovly	$48,198





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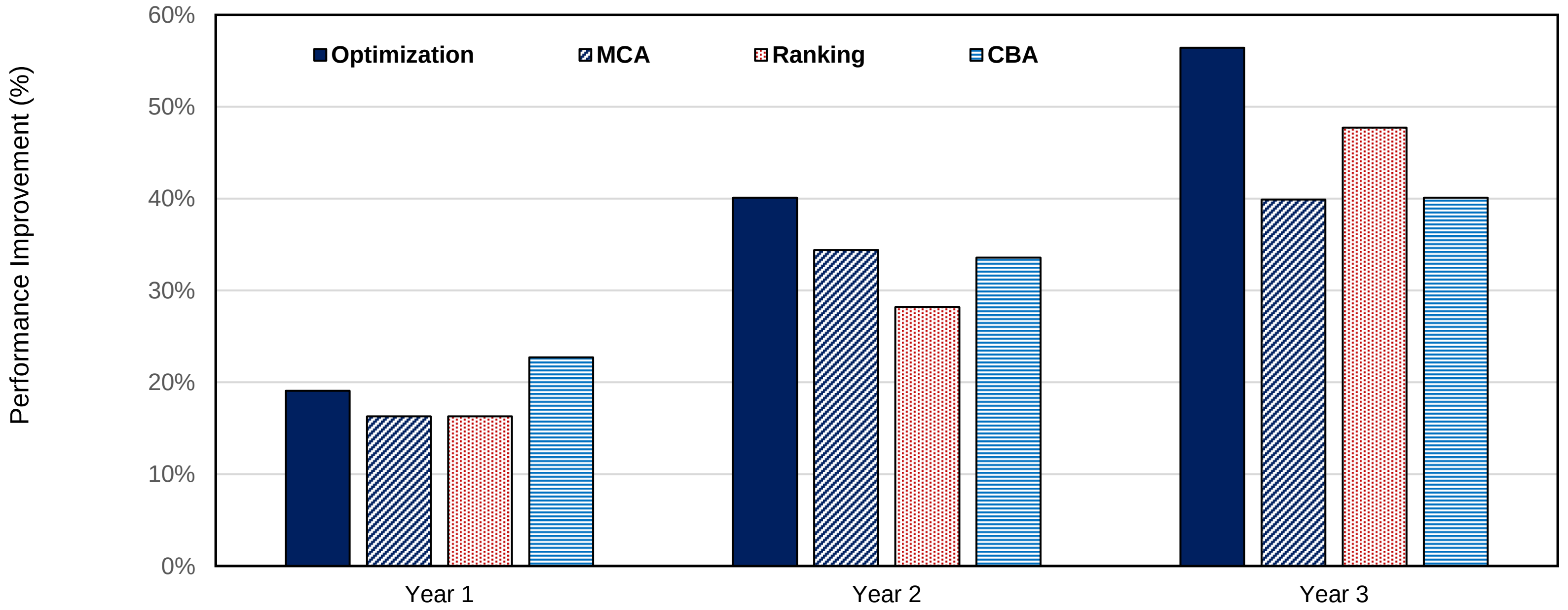
Optimization vs. Other Methods

- ❑ Optimization results in the highest performance at the lowest cost.
- ❑ Our tests confirm a **7 to 17% added performance and cost savings**.

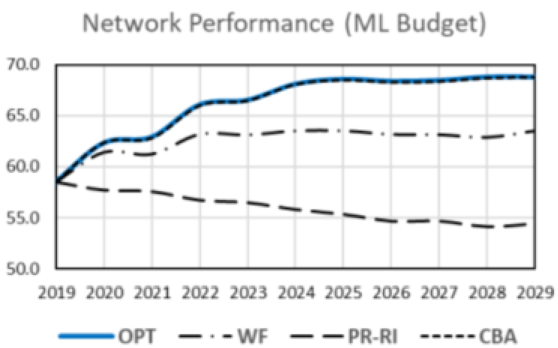


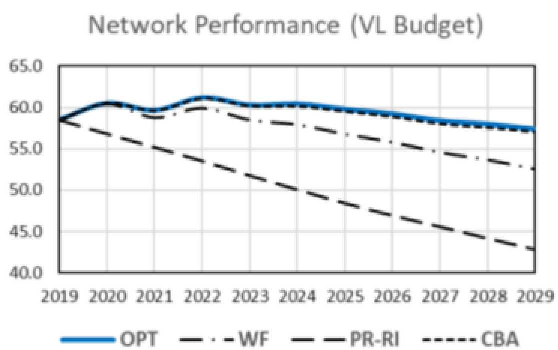
Optimization results in **27.6%, 25.3%, and 19.9% higher performance** gains as compared to MCA, ranking, and CBA, respectively.

Real-Life Examples and Case Studies

Municipal Case Study No. 1

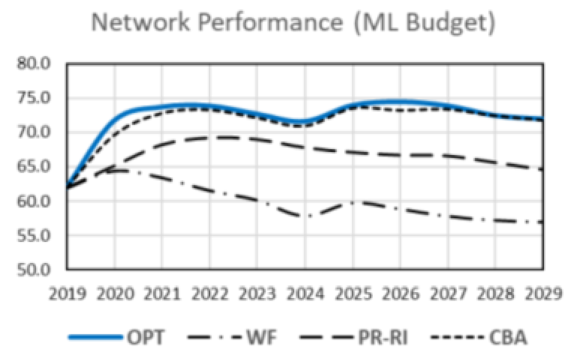
Network Size: 320 Centerline Miles (515 Km)
No. of Road Segments: 3,629
Population: 78,000

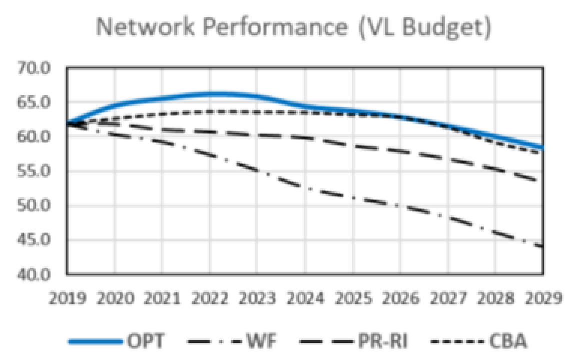




Municipal Case Study No. 2

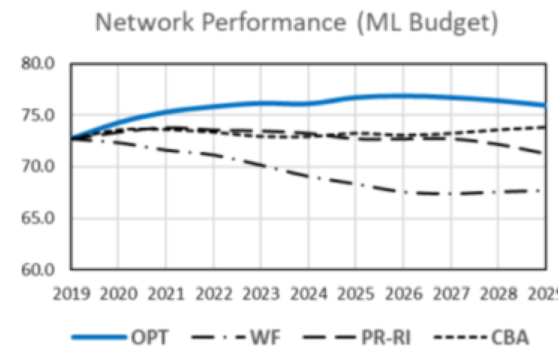
Network Size: 280 Centerline Miles (450 Km)
No. of Road Segments: 2,434
Population: 72,000

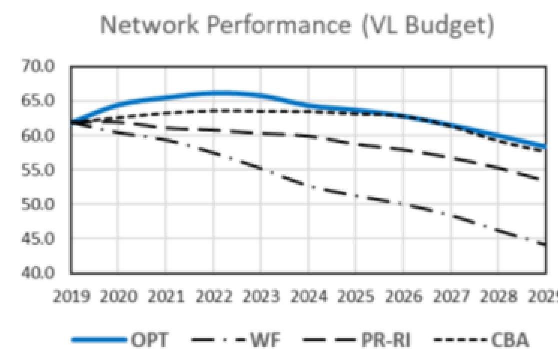




Municipal Case Study No. 3

Network Size: 260 Centerline Miles (420 Km)
No. of Road Segments: 1,845
Population: 30,000

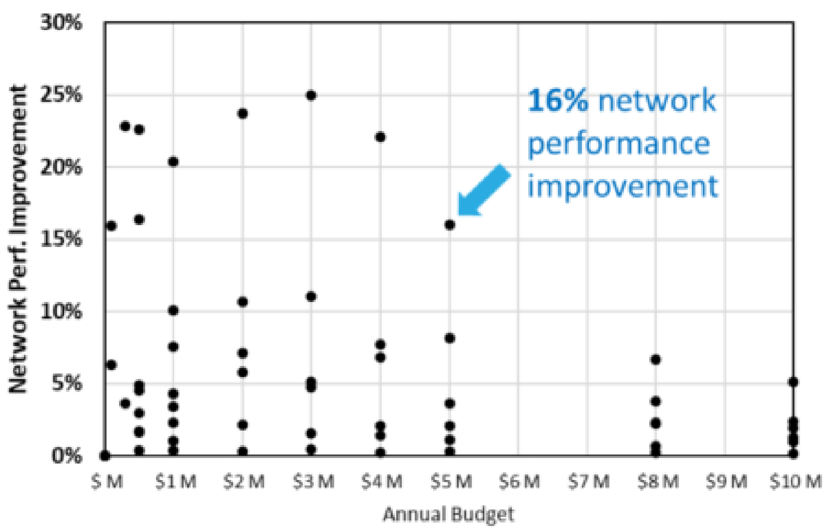




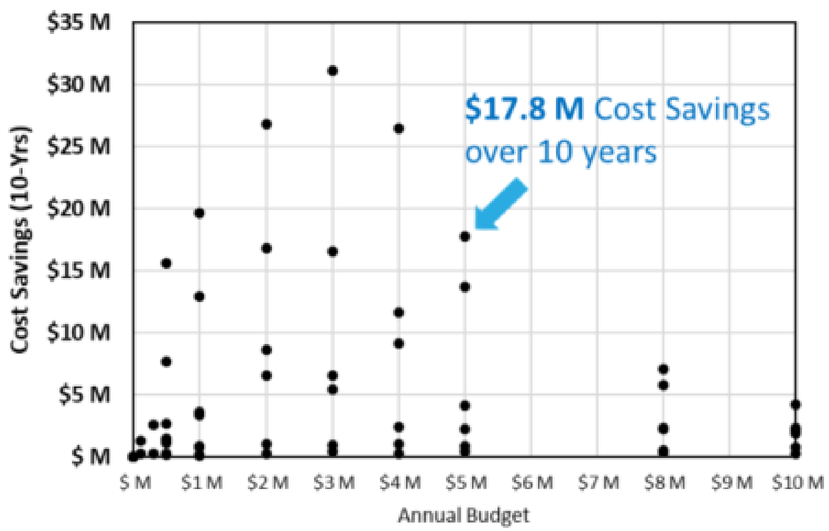
Real-Life Examples and Case Studies

A summary of 56 optimization comparison tests for various real-life municipal cases with different network sizes, populations, and a wide range of annual budget levels.

a) Network Performance Improvement



b) Estimated Cost Savings



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Questions?

Join our upcoming webinars

You are invited to join our upcoming webinar to see these theories in practice as we outline how municipalities across Canada are using industry leading technology to apply these concepts in their approach to planning for sustainable service delivery.

To inquire and register please contact

Dallas Watson at dallas@infrasol.ca or **587-832-5992**

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