Developing and Operationalizing Integrated Cross-Asset Investment Planning for Public Infrastructure

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Paper prepared for presentation

at the CROSS ASSET ANALYSIS AND OPTIMIZATION –

SOLUTIONS FOR INFORMED DECISION MAKING Session

of the 2016 Conference of the

Transportation Association of Canada

Toronto, ON

1. Background

Faced with a record quantity of built infrastructure to manage, agencies are under growing pressure to implement processes that will allow them to do so in an increasingly efficient and effective manner. For the purposes of this paper, the infrastructure asset management field is assumed to be the primary force driving the development and implementation of such processes. It should be noted that the asset management field itself is in its infancy stage, when compared to over a century of modern infrastructure construction. None the less, since its formal conception in the 1990s, there has been ample time for its concepts such as “the right treatment at the right time” to be accepted in managing agencies across the developed world.

Two decades forward, the majority of the concentration appears to have moved from “why” to “how” to fully develop and implement asset management processes. To those that are following the matter closely, it should come as no surprise that the “how” is a substantial task of significant complexity and difficulty, requiring corresponding time and resources. Also, there has yet to appear a unified approach to the matter at a strategic, tactical, and operational level that can relatively easily be applied across the spectrum of managing agencies. The significance of the challenge is reflected in a 2015 study by the University of Toronto, which through a scan of the Ontario municipalities’ asset management plans formulated the key issues as: inadequate human resources, lack of a common asset management model, and inadequate use of technology [1].

Amongst other factors, the variety of asset classes an agency is tasked with managing is a key challenge. This can range from the transportation network to information technology assets. This variety is further amplified in the performance measures, treatment triggers, and life cycle management options which need to be considered. The explicit heterogeneity requires different educational and professional backgrounds to work closely in order to yield maximized value to the public from the infrastructure as one whole, singular societal asset. While professional judgment is likely sufficient for justification of in-year decision making on competing priorities across asset classes, it is difficult to rely on it for future projections of asset performance and needs.

More precisely, it is not likely that professional judgment is deficient, rather, there appears to be a lack of unified means (processes) of “capturing” and effectively communicating it across organizational sections. As a result, it is difficult to develop investment planning processes which are viewed as repeatable and evidence based by different positions / professions across the organization or industry.

This paper proposes a perspective aimed at successful development and communication of cross-asset trade off analysis for bridges, pavements, sanitary, storm, and water distribution networks. A previously developed method for bridges and pavements is recapped in this paper, while the majority of the analysis focuses on the trade-off analysis between pavements and the underground infrastructure. One reason for taking this approach was to maximize the range of asset variety addressed within the prescribed constraints of the paper. The other, closely related, is to approach the challenge of advancing asset management from a multi-asset class perspective, as one agency is typically tasked with managing more than one infrastructure asset.

Engineering risk analysis typically used for failure of component is coupled with organizational theory to develop an active asset management risk framework to catalyze operationalization of asset management plans and processes, including the analysis within this paper, which is assumed to be industry ready.

The audience is assumed to be familiar with the background and importance of asset management principles, hence, in depth literature reviews and discussion on the importance of the topic is not included.

1.2 Purpose

To demonstrate integrated cross-asset investment planning methods between:

- bridges and pavements;
- pavements and sanitary, storm, water networks.

Introduce the concept of active asset management risk.

1.3 Scope

The paper is focused on the development and organizational implementation of asset management processes, including:

- an elaboration on a previously developed method of trading-off pavements and bridges
- development of a method for trading-off pavements and underground pipe network infrastructure
- introduction of a risk framework focused on organizational processes, named Active Asset Management Risk

The overarching scope assumption is that there is not necessarily a lack of professional knowledge, judgment and skill for complete operationalization of asset management plans and processes; but that there is a lack of means of effectively communicating that knowledge across organizational sections when it comes to infrastructure investment planning. Also, the lacking extent does not necessarily mean that organizations are incapable of investment planning, but rather that the industry as a whole has yet yield a common asset management model which can effectively and in a timely manner be implemented within an organization.

Subsequently, the scope is focused on demonstrating how an organization can use its existing information, derived from existing professional knowledge, to perform cross-asset trade-off analysis, which is assumed to be the epicenter of advanced asset management planning. A previously developed method is further elaborated on, mainly to ensure that the scope captures a maximized asset portfolio, but also to discuss its industry readiness.

A trade-off analysis between pavements and underground infrastructure is developed using a model pavement section with an assumed service / utility pipe (e.g. sanitary or sewer or water) below its surface, needing replacement.

Engineering risk, organizational theory, and operational analysis are used to introduce the framework of Active Asset Management Risk, aimed at quantifying risk of failure of asset management processes.

2. Development: Integrated Cross-Asset Investment Planning

Decades of construction, rehabilitation, and maintenance of roadways and pipe networks has yielded generally asset-centric industry expertise. The expertise divide can also be observed in higher education programs. Within an organizational setting, a managing agency, depending on the size of the respective asset class networks, will likely have this asset-centric divide extending from the needs assessment area (e.g. subject matter expert) to the respective budgeting area (e.g. finance / accounting). As record quantities of infrastructure built post WWII mature, stressed under increasing urbanization of populations, it is highly unlikely that managing agencies will not register fiscal and / or user fee pressures in order to sustain a reasonable level of service for the public. It is under these conditions that competition for funding starts to cross the traditional asset-centric lines.

If a 25 year planning horizon is considered, on the higher extreme of the range, the challenge is likely in maximizing accuracy of network deterioration and projecting bulk needs.   On the lower extreme, amongst other, a key challenge is prioritizing projects or treatments which are deemed as being critical irrelevant of their asset class. Limited annual funds are an inherit condition for analyzing corresponding 25 year asset performance.

The following sections examine potential means of cross-asset trade-off analysis, between bridges, pavements, and underground pipe infrastructure networks.

2.1 Bridges and Pavements

The purpose of this section is not to develop a cross-asset trade-off analysis between pavements and bridges, but rather to point to a previously developed method, and thereby maximize the number of infrastructure assets this paper can be a source for.

Development and application of a Structural Integration Factor was introduced in the paper titled Integrated Roadway Asset Management [2]. It is the ratio of average bridge treatment costs to average pavement treatment costs. The Factor is used to transform bridges into equivalent pavement sections. This allows for optimization of one network with one unified performance measure, thereby implicitly trading-off bridges and pavements.

The next section aims to develop a cross-asset trade-off analysis method for pavements and underground infrastructure.

2.2 Pavements and Underground Infrastructure

This section's goal is to develop a method for analyzing the investment trade-offs between pavements and underground infrastructure. More specifically, to provide treatment decision support for varying pavement section conditions which are exposed to pipe failure, requiring excavation and replacement.

A fictitious model pavement section is used as the foundation of the analysis. The following are the assumptions for the section:

- 9,349 m^2 area
- 0.294 portion of section area affected by pipe deficiency requiring excavation
- $ 192,150 cost to replace pipe and restore pavement above
- $ 523,544 cost to rehabilitate entire pavement section at a later date (no excavation)
- $ 1,082,096 cost to reconstruct entire section at time of affected pipe replacement

It is assumed that the investment planner is faced with three options at any point in time over the 25 year planning horizon:

- replace pipe and restore only the portion of the pavement section above the length of pipe replacement
- replace pipe, restore only the portion of the pavement section above the length of pipe replacement, rehabilitate entire pavement section in future years without any underground work
- replace pipe and reconstruct entire pavement section

It is important to note that the decision between the options is assumed to occur in the outer years, even though the 25 year plan is being developed in year zero (0). The following tables contain the development of a performance measure used for decision support.

Table 1 contains a scenario where a pavement section with a Riding Comfort Index (RCI) value of 8.607 is being partially rehabilitated due to necessary underground pipe replacement, requiring excavation.

The deterioration rate is developed by first calculating the number of years between the scheduled rehabilitation and this unplanned intervention. The difference is divided by a value of 25 (planning horizon), this percentage is assumed to be the amplifying factor of increased deterioration of the entire section, not just the part which was excavated. The deterioration rate is a weighted average according to the area affected, where the undisturbed pavement is assumed to continue deteriorating at 0.123 RCI / year. The next row contains the top value of the deterioration curve, which is used to calculate the value of the deterioration curve above the good threshold in the next row. Subsequently, area of good RCI is determined for each year, yielding a unit of "good RCI * year". This unit is used as a pivot for cross-asset trade-off analysis. The cumulative positive (good RCI) and negative (below good RCI) areas are then calculated for the entire 25 year span. Values below the good threshold are treated as negatives and are highlighted for visual contrasting of trends.

The "decision year" in row seven (7) of the table is key to understanding how this cross-asset trade-off analysis can be used in a practical setting. Assuming we are simulating a 25 year network model, it is necessary to allow the possibility of required pipe replacement within any point in that time span, while practically still modeling from time zero (0). As such, the moving area of row eight (8) provides a scope for what the cumulative good RCI * year area is, as if the modelling decision in time zero (0) is actually being made in that corresponding future year noted in row seven (7). For example, looking at the value of 12.1812 (good RCI * year), it was calculated by taking the year one (1) value of 19.9967 and adding the year 25 value of -7.8154. Meaning, since the decision year is year one (1), the complete 25 year span of this scenario is being taken into account under the 25 year planning model. However, if the decision year is for example year 11, then only the first 15 years of this scenario are being taken into account under the 25 year planning model. The last row contains the next step in the development of a cross-asset trade-off performance measure or trigger. The assumed treatment cost is divided by the moving area, indicating the necessary monetary value needed to yield one unit of good RCI * year performance. It is important to note that the assumed treatment cost is $ 192,150, indicating only

Table 1 contains a scenario where a pavement section with a Riding Comfort Index (RCI) value of 8.607 is being partially rehabilitated due to necessary underground pipe replacement, requiring excavation.

Table 1: Partial section rehabilitation

Rehabilitation Option Table / Year	1	3	5	7	..	15	16	17	19	21	23	25
Deterioration rate		0.16985	0.16985	0.16985		0.16985	0.16985	0.16985	0.16985	0.16985	0.16985	0.16985
Top value of deterioration curve	8.607	8.2673	7.92759	7.58789		6.22907	6.05922	5.88937	5.54967	5.20996	4.87026	4.53056
Value of curve above good threshhold	2.607	2.2673	1.92759	1.58789		0.22907	0.05922	-0.1106	-0.4503	-0.79	-1.1297	-1.4694
Area per year (good RCI * year)	2.52207	2.18237	1.84267	1.50296		0.14415	-0.0257	-0.1956	-0.5353	-0.875	-1.2147	-1.4694
Cummulative +ve and -ve areas (good RCI * year)	19.9967	15.1224	10.9275	7.412		0.14415	-0.0257	-0.2213	-1.1219	-2.702	-4.9615	-7.8154
$ 192,150 (assumed treatment cost) Decision year	25	23	21	19		11	10	9	7	5	3	1
(A) Moving area (good RCI * year)	2.52207	7.05667	10.9119	14.0876		19.9967	19.971	19.7754	18.8747	17.2947	15.0352	12.1812
(A1) $/good RCI* year for decision year	76,187	27,230	17,609	13,640		9,609	9,621	9,717	10,180	11,110	12,780	15,774

cost for pipe replacement and restoration of the disturbed pavement. This is because the initial pavement section RCI value is in the excellent qualitative rating region, and there is not sufficient time within the 25 year span for the rehabilitation trigger of 4.5 RCI to come into consideration, at which point the cost would increase by $ 523,544.

Table 2 contains the corresponding information of Table 1, assuming complete reconstruction of the pavement section.

Table 2: Complete section reconstruction

Reconstruction Option Table / Year	1	3	5	7	...	15	16	17	19	21	23	25
Deterioration rate		0.123	0.123	0.123		0.123	0.123	0.123	0.123	0.123	0.123	0.123
Top value of deterioration curve	8.73	8.484	8.238	7.992		7.008	6.885	6.762	6.516	6.27	6.024	5.778
Value of curve above good threshhold	2.73	2.484	2.238	1.992		1.008	0.885	0.762	0.516	0.27	0.024	-0.222
Area per year (good RCI * year)	2.6685	2.4225	2.1765	1.9305		0.9465	0.8235	0.7005	0.4545	0.2085	-0.0375	-0.222
Cummulative +ve and -ve areas (good RCI * year)	30.2085	24.9945	20.2725	16.0425		4.0425	3.096	2.2725	0.9945	0.2085	0.048	-0.3345
$ 1,082,096 (assumed treatment cost) Decision year	25	23	21	19		11	10	9	7	5	3	1
(B) Moving area (good RCI * year)	2.6685	7.6365	12.1125	16.0965		27.1125	27.936	28.6365	29.6685	30.2085	30.2565	29.874
(B1) $/good RCI* year for decision year	405,507	141,701	89,337	67,226		39,911	38,735	37,787	36,473	35,821	35,764	36,222

Table 2 values carry the identical logic of Table 1 describe above; however the values are representative of replacing the damaged pipe and reconstructing the entire pavement section. This is the only treatment considered for the 25 year model span, hence, the cost of $ 1,082,096 is inherit to all decision years. Unlike in Table 1, the values for this alternative do not change, and are used as denominators in finalizing the development of a cross –asset trading-off performance measure, illustrated in the following Table 3.

Table 3: Decision support

Decision Guidance Table — Decision year	25	23	21	19	11	10	9	7	5	3	1
Moving area ratio ---> A / B = C	0.95	0.92	0.90	0.88	0.74	0.71	0.69	0.64	0.57	0.50	0.41
$/good RCI * year ratio ---> A1 / B1 = C1	0.19	0.19	0.20	0.20	0.24	0.25	0.26	0.28	0.31	0.36	0.44
C / C1 = D =Performance investment measure (moving area ratio) / ($/good RCI * year ratio)	5.03	4.81	4.57	4.31	3.06	2.88	2.69	2.28	1.85	1.39	0.94

The final row of Table 3 contains a proposed cross-asset trading-off Performance Investment Measure, which an experienced professional could potentially use in guiding a decision on whether to disturb only part of a pavement section due to an underlying pipe deficiency which needs immediate remedy requiring excavation, or to remedy the same but reconstruct the entire pavement section at the same time as well. The measure is a ratio, composed of two independent ratios. The first one is the moving area comparison between the two alternatives being considered, which is shown in row two (2) of the table. The second ratio is the good RCI * year unit yield per monetary value considered, shown in row three (3) of the table. Finally, row five (5) contains the values of the Performance Investment Measure. It is assumed that values above one (1) indicate that disturbing only part of the pavement under which the pipe deficiency requires remedy is likely more favorable over reconstructing the entire pavement section, with respect to maximizing network performance of both pavement and underground pipe asset classes over the 25 year planning horizon.

Figures 1 to 5 provide visual representation of the information contained in Tables 1 to 3.

Figure 1 is a visual comparison of the two alternatives' RCI values over time. The rehabilitated alternative contains an increased deterioration slope as the homogeneity of the pavement section is disturbed; thereby an increased deterioration rate is assumed for the entire section, proportional to the area of the disturbed pavement.

Figure 2 illustrates the projected RCI values above the good threshold. Partial rehabilitation of the section appears to go below that value in year 17, while reconstruction does so in year 23.

Figure 3 shows the cumulative positive and negative area values of good RCI * years for the two alternatives. Reconstructing the entire section maintains a greater positive cumulative area over the 25 year span.

Figure 4 shows the moving area curves of the two alternatives. The reconstruction alternative has a higher good RCI * year moving area irrelevant of the decision year considered.

Finally, Figure 5 shows the proposed Performance Investment Measure with respect to the decision year being considered. Other than when the decision year is one (1), the partial restoration of the section appears to be the preferred alternative.

Figure 6 contains the Performance Investment Measure values for 38 initial RCI values of the pavement section, spanning the qualitative categories of excellent, good, and fair condition ratings. In order to demonstrate its practical use it has been shown its entirety, as a result, the ability to read the actual values has been forfeited due to existing technological constraints when it comes to visualization and representation of holistic mass data in detail. None the less, the primary goal can be achieved due to all of the values below one (1) being shaded. Hence, the shaded regions represent where the reconstruction option is preferred, while the non-shaded region favors the partial rehabilitation option. In practice, the Decision Support Matrix would be developed for a range of varying treatment costs and section sizes.

The next section explores the operationalization of the above demonstrated cross-asset management process, as well as of asset management processes in general.

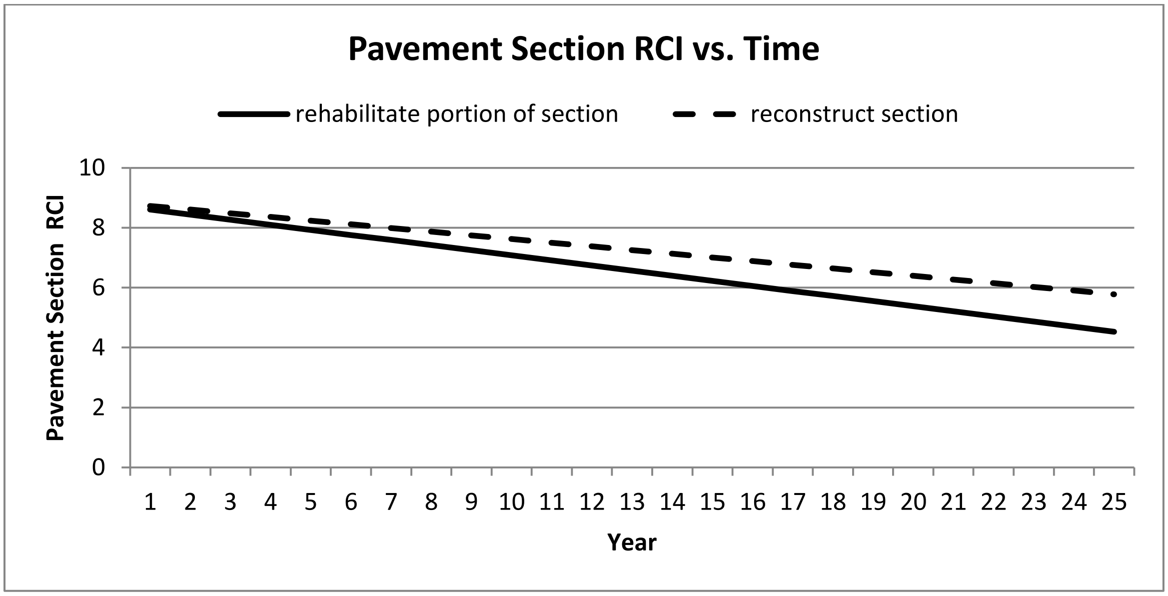

Figure 1: Pavement Section RCI vs. Time

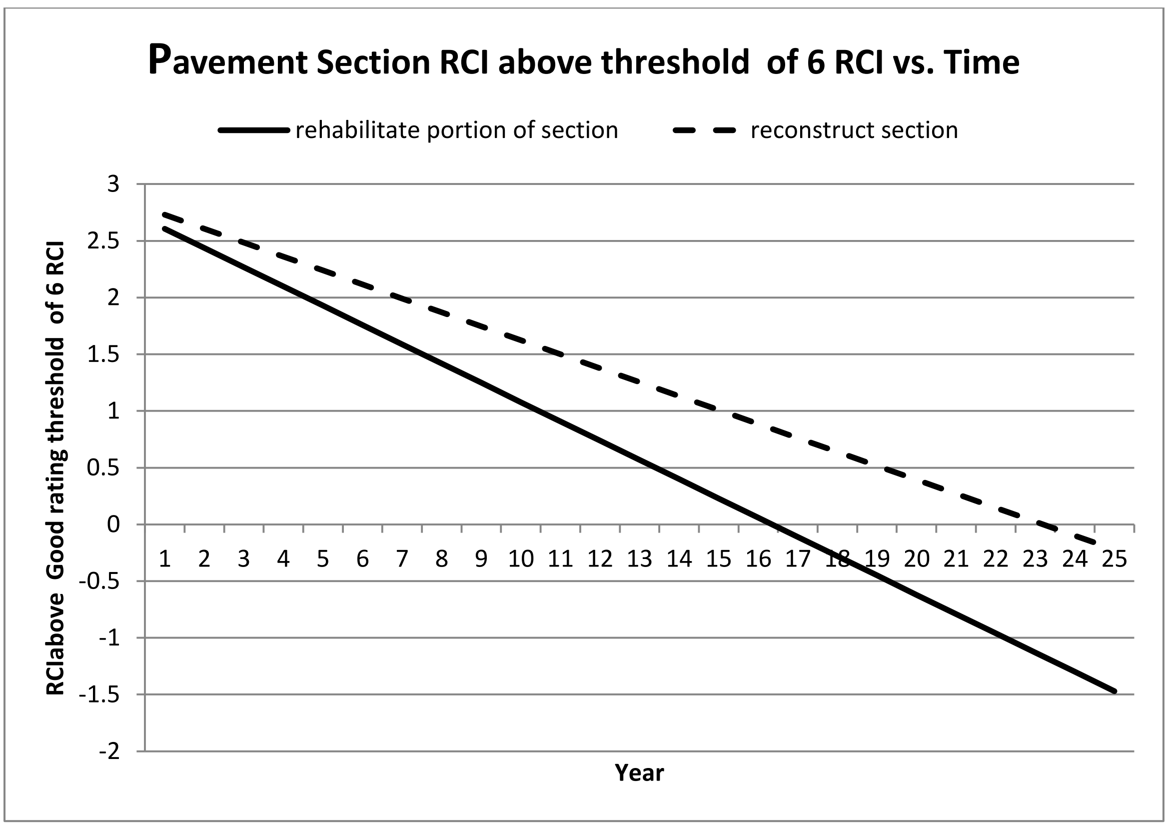

Figure 2: Pavement section RCI above threshold of 6 RCI vs. Time

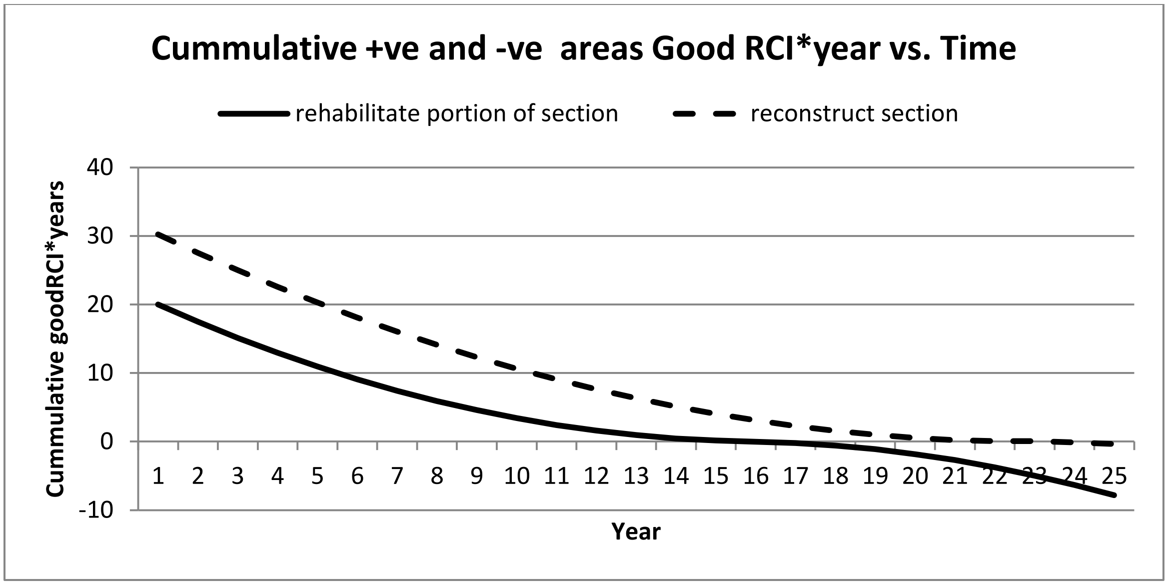

Figure 3: Pavement section RCI above threshold of 6 RCI vs. Time

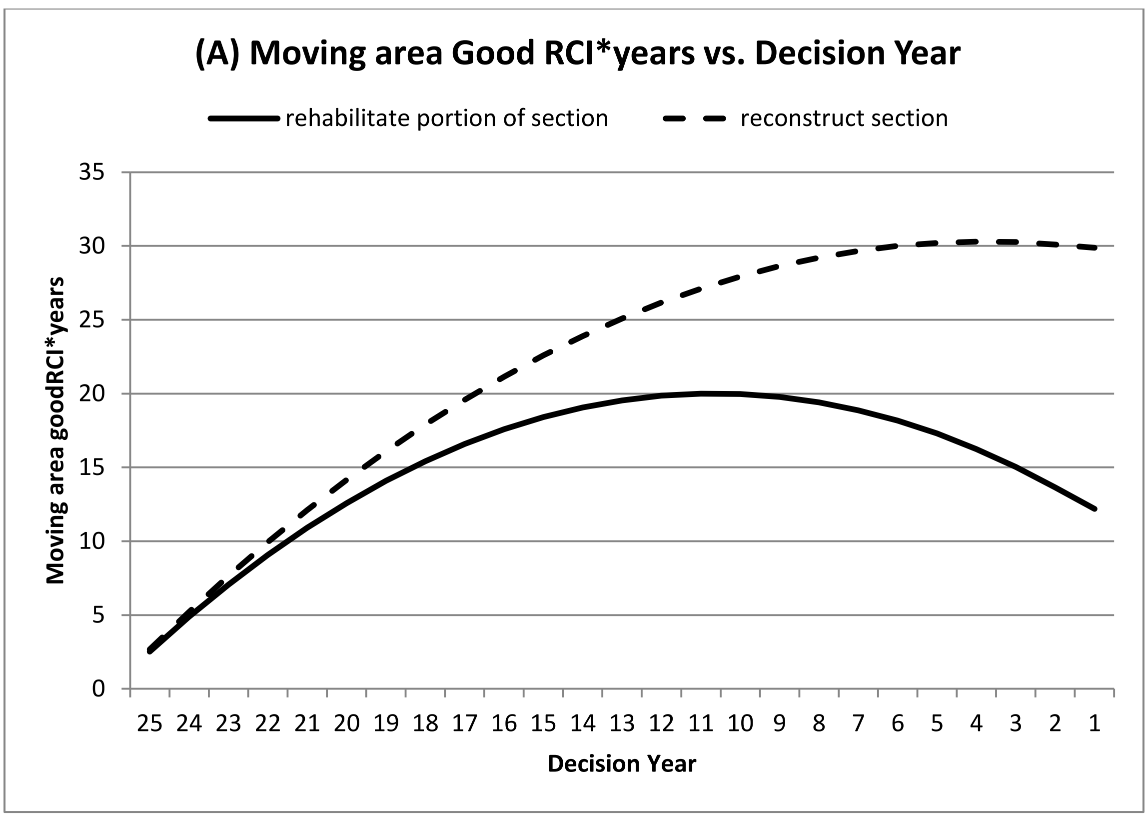

Figure 4: Pavement section RCI above threshold of 6 RCI vs. Time

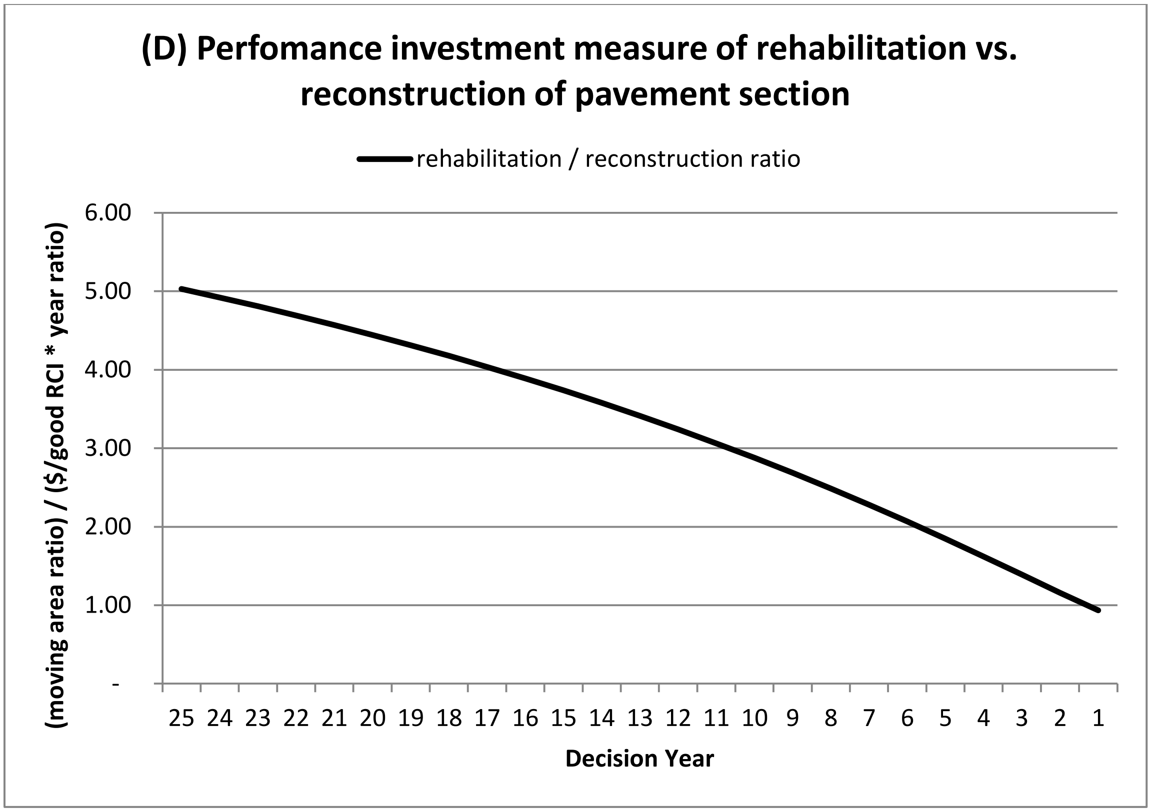

Figure 5: Pavement section RCI above threshold of 6 RCI vs. Time

	Decision year RCI Value	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
	8.607	5.03	4.92	4.81	4.69	4.57	4.44	4.31	4.18	4.04	3.89	3.74	3.58	3.41	..	3.06	2.88	2.69	2.49	2.28	2.07	1.85	1.62	1.39	1.16	0.94
Exc..	8.361	4.10	3.99	3.87	3.75	3.63	3.50	3.36	3.22	3.08	2.93	2.78	2.62	2.46	2.29	2.12	1.94	1.76	1.58	1.39	1.20	1.01	0.82	0.63	0.46	0.30
	8.238	0.90	2.59	2.51	2.42	2.33	2.23	2.13	2.03	1.93	1.82	1.72	1.60	1.49	1.37	1.25	1.12	1.00	0.87	0.75	0.62	0.50	0.38	0.27	0.24	0.35
	8.115	0.88	3.15	3.04	2.91	2.79	2.66	2.53	2.39	2.25	2.11	1.96	1.81	1.66	1.51	1.35	1.19	1.03	0.87	0.71	0.56	0.42	0.29	0.17	0.08	0.24
	7.992	0.78	0.74	2.66	2.54	2.41	2.29	2.16	2.02	1.89	1.75	1.61	1.47	1.32	1.17	1.03	0.88	0.74	0.60	0.46	0.33	0.22	0.12	0.05	0.18	0.40
	7.869	0.68	0.65	0.62	2.18	2.06	1.94	1.81	1.69	1.56	1.42	1.29	1.15	1.02	0.88	0.75	0.62	0.49	0.37	0.26	0.17	0.08	0.03	0.14	0.33	0.60
	7.746	0.59	0.56	0.53	1.86	1.74	1.62	1.50	1.38	1.25	1.13	1.01	0.88	0.76	0.64	0.52	0.40	0.30	0.20	0.12	0.06	0.01	0.00	0.04	0.15	0.34
	7.623	0.51	0.48	0.45	0.42	1.45	1.33	1.22	1.10	0.99	0.87	0.76	0.64	0.53	0.43	0.33	0.24	0.15	0.08	0.03	0.00	0.00	0.02	0.12	0.28	0.52
	7.5	0.43	0.40	0.37	0.34	1.18	1.07	0.96	0.86	0.75	0.65	0.54	0.44	0.35	0.26	0.18	0.11	0.06	0.02	0.00	0.01	0.06	0.00	0.03	0.13	0.29
	7.377	0.36	0.33	0.31	0.28	0.25	0.84	0.74	0.64	0.55	0.45	0.36	0.28	0.20	0.13	0.08	0.03	0.01	0.00	0.02	0.08	0.00	0.02	0.10	0.25	0.46
	7.254	0.29	0.27	0.24	0.22	0.19	0.63	0.54	0.46	0.37	0.30	0.22	0.15	0.10	0.05	0.02	0.00	0.01	0.04	0.10	0.01	0.01	0.08	0.22	0.41	0.65
	7.131	0.24	0.21	0.19	0.17	0.14	0.12	0.38	0.31	0.24	0.17	0.11	0.07	0.03	0.01	0.00	0.01	0.05	0.12	0.23	0.07	0.00	0.01	0.09	0.22	0.41
Good	7.008	0.18	0.16	0.14	0.12	0.10	0.08	0.07	0.18	0.13	0.08	0.04	0.01	0.00	0.00	0.03	0.07	0.15	0.26	0.09	0.01	0.01	0.08	0.20	0.37	0.59
	6.885	0.14	0.12	0.10	0.08	0.07	0.05	0.04	0.02	0.05	0.02	0.01	0.00	0.01	0.04	0.10	0.18	0.30	0.10	0.01	0.01	0.07	0.18	0.35	0.55	0.80
	6.762	0.10	0.08	0.07	0.05	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.02	0.06	0.12	0.21	0.33	0.49	0.22	0.07	0.00	0.01	0.08	0.20	0.35	0.55
	6.639	0.07	0.05	0.04	0.03	0.02	0.01	0.00	0.00	0.00	0.01	0.04	0.08	0.15	0.24	0.37	0.53	0.24	0.07	0.01	0.01	0.08	0.19	0.34	0.53	0.76
	6.516	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.11	0.18	0.28	0.40	0.57	0.25	0.08	0.01	0.01	0.07	0.19	0.34	0.52	0.74	0.98
	6.393	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.21	0.31	0.44	0.61	0.81	0.42	0.18	0.05	0.00	0.02	0.09	0.20	0.35	0.53	0.73
	6.27	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.04	0.07	0.09	0.48	0.65	0.85	0.43	0.18	0.05	0.00	0.02	0.10	0.21	0.36	0.54	0.74	0.96
	6.147	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.05	0.08	0.11	0.14	0.19	0.89	0.44	0.18	0.04	0.00	0.03	0.11	0.23	0.38	0.56	0.75	0.97	1.20
	6.024	0.00	0.00	0.01	0.02	0.03	0.04	0.06	0.09	0.12	0.15	0.20	0.25	0.12	0.17	0.04	0.00	0.04	0.13	0.25	0.41	0.59	0.79	1.00	1.23	1.47
	5.901	0.01	0.01	0.02	0.03	0.05	0.07	0.10	0.13	0.17	0.21	0.26	0.33	0.17	0.29	0.09	0.01	0.01	0.06	0.15	0.28	0.43	0.61	0.80	1.00	1.22
	5.778	0.02	0.03	0.04	0.06	0.08	0.11	0.14	0.18	0.22	0.28	0.34	0.17	0.07	0.02	0.00	0.01	0.08	0.19	0.33	0.49	0.66	0.86	1.06	1.27	1.49
	5.655	0.04	0.05	0.07	0.09	0.12	0.15	0.19	0.24	0.29	0.35	0.17	0.07	0.02	0.00	0.01	0.11	0.23	0.39	0.56	0.74	0.94	1.14	1.35	1.57	1.79
	5.532	0.06	0.08	0.10	0.13	0.17	0.20	0.25	0.30	0.37	0.16	0.06	0.01	0.00	0.01	0.04	0.08	0.47	0.65	0.84	1.04	1.25	1.46	1.67	1.88	2.10
	5.409	0.09	0.12	0.15	0.18	0.22	0.26	0.32	0.38	0.16	0.05	0.01	0.00	0.02	0.06	0.10	0.15	0.21	0.97	1.18	1.39	1.59	1.80	2.01	2.22	2.42
	5.286	0.13	0.16	0.19	0.23	0.28	0.33	0.39	0.46	0.21	0.07	0.02	0.00	0.01	0.04	0.08	0.12	0.17	0.83	1.02	1.22	1.42	1.61	1.81	2.01	2.20
	5.163	0.17	0.21	0.25	0.29	0.35	0.41	0.48	0.19	0.06	0.01	0.00	0.02	0.06	0.11	0.16	0.21	0.27	1.21	1.41	1.61	1.80	2.00	2.19	2.38	2.56
Fair	5.04	0.22	0.26	0.31	0.36	0.42	0.49	0.17	0.04	0.00	0.01	0.05	0.10	0.15	0.21	0.27	0.33	0.39	0.44	0.50	2.04	2.23	2.41	2.59	2.77	2.93
	4.917	0.28	0.33	0.38	0.44	0.50	0.14	0.02	0.00	0.03	0.09	0.15	0.22	0.28	0.35	0.41	0.47	0.53	0.58	0.63	0.68	2.70	2.87	3.03	3.19	3.33
	4.794	0.34	0.39	0.45	0.52	0.10	0.00	0.02	0.08	0.16	0.23	0.31	0.39	0.45	0.52	0.58	0.63	0.68	0.73	0.78	0.82	0.86	3.35	3.49	3.63	3.66
	4.671	0.41	0.47	0.54	0.05	0.00	0.07	0.17	0.27	0.36	0.45	0.53	0.60	0.66	0.72	0.77	0.82	0.86	0.90	0.94	0.97	1.01	1.04	3.98	4.09	4.18
	4.548	0.49	0.55	0.01	0.07	0.21	0.35	0.47	0.57	0.66	0.74	0.80	0.86	0.91	0.95	0.99	1.03	1.06	1.09	1.12	1.14	1.17	1.19	1.21	4.58	4.64
	4.425	0.56	0.06	0.34	0.56	0.72	0.84	0.93	1.01	1.06	1.11	1.15	1.18	1.21	1.24	1.26	1.28	1.30	1.32	1.34	1.35	1.37	1.38	1.39	1.41	5.26
	4.302	0.68	0.04	0.30	0.51	0.67	0.78	0.87	0.94	1.00	1.04	1.08	1.11	1.14	1.16	1.19	1.20	1.22	1.23	1.25	1.26	1.27	1.28	1.29	1.29	4.84
	4.179	0.81	0.02	0.25	0.46	0.61	0.72	0.81	0.88	0.93	0.98	1.01	1.04	1.07	1.09	1.11	1.12	1.14	1.15	1.16	1.17	1.17	1.18	1.18	1.19	4.43
	4.056	0.95	0.01	0.21	0.41	0.56	0.67	0.75	0.82	0.87	0.91	0.95	0.98	1.00	1.02	1.04	1.05	1.06	1.07	1.08	1.08	1.08	1.09	1.09	1.08	4.05
	3.933	1.11	0.00	0.18	0.36	0.51	0.61	0.70	0.76	0.81	0.85	0.88	0.91	0.93	0.95	0.96	0.98	0.98	0.99	0.99	1.00	1.00	0.99	0.99	0.99	3.68

Figure 6: Decision support matrix

3. Organizational Operationalization: Integrated Cross-Asset Investment Planning

This section focuses on discussing the organizational implications of asset management processes in general, but also aims to introduce the concept of active asset management risk.

3.1 Operationalizing Framework

Figure 7 shows a horizontal view of the asset management information flow across a managing agency, within which operationalization of asset management processes is necessary.

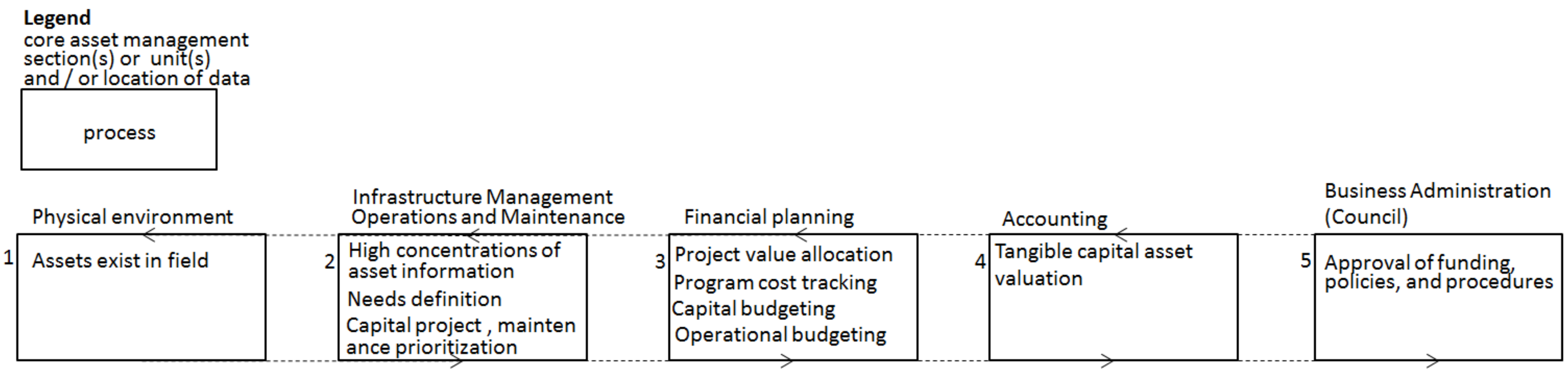

Figure 7: Operationalizing Asset Management Framework

The framework describes the general horizontal asset management process flow which takes place across an asset management agency, thereby eliminating the typical "silo" structure view. Box 1 represents the physical environment within which the tangible capital assets exist. Box 2 indicates the flow of information from the assets to Infrastructure Management sections or units. These typically contain nodes (e.g. excel spreadsheets, databases, etc.) of high information concentration, such as project lists, maintenance prioritizations, asset performance data, etc. In general, asset needs are generally converted into capital projects through collaboration with financial planning. Maintenance programs are developed and carried out by Operational Maintenance sections or units. Box 3 indicates the flow of information from Infrastructure Management sections to the Financial Planning section. Information from across the organization is aggregated as per financing policies and procedures, and used in the budget cycle process. Box 4 indicates the carrying out of tangible capital valuation and reporting as per the accounting requirements, while box 5 shows an example of the overall business administration which governs the first four boxes. For example, yearly budgets and forecasts which are created through the efforts described in boxes 1-4 are approved by Council. Once approval is obtained, the flow is reversed as allocations reach the necessary points within the organization until necessary improvements to infrastructure are carried out.

It is important to note that the Operationalizing Asset Management Framework described shows the general information flow from the assets to the funding approval authority, and back to the assets in the form of improvement treatments; it does not by any means preclude the regular micro information exchanges that may occur outside of the general process lines described within the framework.

Relying on the horizontal information flow, the following section introduces active asset management risk.

3.1 Active Asset Management Risk Framework

The goal of this section is to briefly discuss a conceptual framework of risk, not concerned with asset failure, but rather the failure of asset management processes at infrastructure managing agencies.

In general, risk is defined as the probability of failure multiplied by the consequence(s). Prior to defining risk, probability of failure and consequence need to be defined. Likewise, failure needs a definition in order to start determining its probability.

Provided multiple decades of implicit and now explicit infrastructure asset management, it is highly unlikely that a managing organization is not making the most effective decisions it is able to with the knowledge and information it possesses. Hence, defining risk as a measure of effective decision making would not provide a path for future improvements which the industry appears to be seeking when it comes to “how” to operationalize asset management processes.

In order to suggest a more appropriate definition, it may be appropriate to first check its sensitivity with respect to organizational goals. Assuming maximized asset performance is a key goal, it is important to focus in on the term “performance”. Specifically, if failure is assumed to be the lack of ability to visualize asset performance, there appears to be a direct link to a key organizational goal. Assuming asset management processes occur across an organization, then failure can further be defined as the lack of asset performance visualization according to decisions being contemplated across the organization.

This assumption connects back to Figure 7 and the operationalizing framework. The common variable across the five points illustrated is information. Hence, by analyzing the characteristics of information across the organization, the necessary elements for quantifying the probability of failure become available. The broadest three characteristics of information which can be subject to initial analysis include: nature, format and flow. Subsequently, the dynamic within each and between the engineering, finance, and administrative areas of the infrastructure managing agency, is assumed as the elementary variable of risk. Hence, by quantifying the relative degree of effort necessary to visualize asset performance at each of the five areas in the operationalizing framework, an overall system asset management process risk can be quantified.

Failure of an asset management process is assumed to be an occurrence where the future performance of an asset network cannot be quantified and imaged within a reasonable period of time, according to decisions being considered at time zero (0). Consequences of such situations are assumed to include, but not be limited to: under budgeting, over budgeting and subsequent wider societal side effects.

It is assumed that the above framing of asset management process risk may provide a formalized means of measuring and driving practical application of asset management processes, such as creating asset performance graphs in a timely manner for investment decisions being contemplated.

4. Limitations

The general limitation of this paper is inherit in the field, which is that it does not address the full portfolio of asset classes. This is important because the level of applicability of concepts such as the one presented here is likely proportional to what degree it is able to meet the demand of a managing agency.

The cross-asset trade-off method between pavements and underground infrastructure has not been applied onto a model infrastructure network.

5. Conclusions and Recommendations

Public infrastructure is an essential pillar of modern society, necessary for economic growth and social accessibility. A record quantity of it built after WWII is subject to increasing urbanization pressures. The agencies tasked with their management face a complex task of balancing asset performance and funding sources in a sustainable manner.

Infrastructure asset management planning is the driving force aimed at achieving such sustainability. Two decades of professional dedication has ensured that is seen as today’s standard of addressing infrastructure management challenges. However, progress has naturally yielded new challenges, including but not limited to:

- cross-asset trade-off analysis; and,
- operationalization of asset management processes.

With the goal of solving this new set of challenges, the paper provides explicit methodologies for cross-asset-asset trade-off analysis for bridge, roadway, sanitary, storm, and water distribution networks. From inception, the methodologies were designed to be industry ready, as they are derived from, and use information that is already readily available within managing agencies.

With respect to increasing the rate of operationalization, the paper introduces an Active Asset Management Risk Framework. It focuses on defining risk based upon the analysis of the typical horizontal information flow from the infrastructure, through the subject matter expert and financial planning areas, to the positions of funding allocation authority. Failure is defined as the inability of an organization to generate projected performance graphs in a timely manner for decisions being contemplated at time zero (0), in any area of the horizontal information flow areas mentioned.

In order to increase the ability of the industry to manage infrastructure with increasing efficiency and effectiveness, further development of cross-asset trade-off analysis methods and active asset management risk framework is recommended.

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