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DECISION-MAKING FRAMEWORK FOR INTEGRATED ASSET MANAGEMENT

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Abstract: Tackling the inefficiency and financial burdens imposed by under-performing assets is an issue that negatively impacts the country's economic development where; Canada's infrastructure 2016 report displayed 33% of the assets in critical conditions, requiring immediate actions, and a steeply growing budget deficit estimated at $123 billion. Moreover, the large number of asset intervention activities leads to detrimental social, environmental, and economic impacts on the community. Therefore, integrating the corridor intervention activities is needed to minimize the community disruption and maintain an acceptable level of service throughout the assets' lifecycle. This paper presents an integrated multi-objective asset management framework for corridor infrastructure, road, water, and sewer networks, which aids the asset managers to trade-off intervention alternatives on both single and integrated asset management levels. The multi-objective framework considers (1) condition state and (2) life-cycle costs (i.e. direct and indirect/user costs). It basically relies on a combination of meta-heuristics and goal optimization using Genetic Algorithms (GAs). The framework was applied to a 2 km stretch of Kelowna's road, water, and sewer networks where; the results showed 5% and 37% savings in the integrated system's condition state and life-cycle costs (direct and indirect costs) respectively. Furthermore, it showed a high potential for scaling up the framework to include other indicators such as; risk, reliability, spatial savings, time savings, intervention efficiency, etc., provided that sufficient information is shared among entities.

Keywords: - Integrated Asset Management, Infrastructure planning, Multi-objective Optimization, Key Performance Indicators, Decision Making, Meta-heuristics.

1. INTRODUCTION

Infrastructure projects typically carry out many challenges and risks throughout their life-cycle due to demand fluctuations, uncertainties, natural disasters occurrence, necessity, and criticality, etc. In such type of projects, crucial decisions with respect to maintenance and rehabilitation options are, not only taken at the early beginning of the life-cycle time, but they should be also revised regularly to guarantee the delivery of an acceptable Level of Service (LOS), through meeting both the tight/limited budgets, and the tough minimum acceptable physical state constraints. Thus, various alternatives need to be considered to guarantee a maximum use of expenditures and resources along with maximizing the benefits and optimally utilizing the available resources. The need for Asset Management (AM) adoption has been strengthened by the plethora of infrastructure problems (e.g. sudden system failures), as well as the deteriorating LOS, which in turn places pressure on governments to increase infrastructure expenditures for an enhanced LOS. In addition, urbanization represents another challenge besides the aging infrastructure systems. According to the United Nation Population (Osman 2015), the world is undergoing the largest wave of urban growth where; in 2008, more than 50% of the world's population were living in towns and cities and the figures are expected to grow exponentially over time. Municipal infrastructure underperformance is resulting in inefficiency and financial burden on municipalities. One-third of Canada's infrastructure is in fair, poor, and failing conditions (FCM 2016), which increases the risk of service disruption and forces the municipalities to follow a “reactive” approach rather than a “proactive” approach. Moreover, aging infrastructure systems are placing tremendous pressure on municipalities. It has been estimated that about 60% of the municipal infrastructure assets are over 55 years, 30% are over 85 years old, and the life expectancy of about 80% of our infrastructure has been already exhausted (Mirza 2009). This in return increases budget deficits and initiates the urgent need for rehabilitating/replacing the exhausted infrastructure. Canada’s municipal infrastructure deficit is estimated to be $123 billion for existing infrastructure, growing by $2 billion annually, and $115 billion for constructing new infrastructure (Mirza 2009) to satisfy a growing population, which has doubled in 40 years from 17.9 million in 1960 to reach 35.1 million in 2013 and expected to be 42.5 million by 2056 (Statistics Canada 2015).

Few municipalities have a maintenance and rehabilitation AM plan for their road, sewer and water systems (InfraGuide 2003a, b, c, 2006). Although, numerous municipalities have implemented pavement management systems, most lack maintenance and rehabilitation AM plans for their water and sewer systems. Condition assessment for water and sewer systems is challenging, given that they are buried beneath roads and require sophisticated technologies to inspect. Moreover, their service life is longer that the roads. Accordingly, InfraGuide (2003a) outlined an integrated approach to assess and evaluate the municipal road, sewer and water networks. The approach consists of five steps: a) Data inventories, b) Investigations, c) Condition assessment, d) Performance evaluation and e) Renewal plan. In the same context, InfraGuide (2006) outlined the need for integrated renewal planning of municipal road, sewer, and water systems at a network level. It emphasized the same five-step procedures mentioned in InfraGuide 2003a for the assessment and evaluation of municipal infrastructure. As well, it mentioned that the AM planning framework should include clear policy objectives and established priorities.

Elaborating on these perspectives reveals more integration aspects such as Top-down decision-making approach where; goals, objectives, and policies are the main drivers and Bottom-up management approaches where; the technical conditions of different assets and the daily aspects of maintenance and rehabilitations are the main criteria of decision-making. Thus, this paper describes a multi-objective decision-making framework for the integrated municipal infrastructure (i.e. roads, water, and sewer) to seek a near optimal maintenance and rehabilitation AM plan. The objectives could be summarized as follows:

1. Develop a multi-objective AM approach for integrated AM.
2. Build a multi-objective decision-making system for integrated AM.
3. Optimize the maintenance and rehabilitation plan for both silo (considers individual asset) and integrated AM systems.
4. Compare the silo and integrated AM systems’ results to visualize the integration savings results.

2. BACKGROUND

The concept of interventions integrations for two or more networks of co-located corridor infrastructure assets was studied by multiple scholars (Halfawy 2008, 2010, Halfawy and Figueroa 2006, Infraguide 2003a, 2003b, 2003c, 2004, 2006). Few scholars went beyond presenting conceptual frameworks and published a dedicated research on the integrated municipal maintenance and rehabilitation AM plans. For instance, Abu-Samra et al. (2016) developed a multi-objective decision-making system for multiple highways to schedules the maintenance and rehabilitation activities through minimizing the deviations for the pre-defined KPIs’ under the performance-based contracts. Likewise, Oh et al. (2011) developed a model that integrates the highway construction projects to minimize the transportation impacts on the road users. Multi-objectives optimization has grasped the attention of many researchers during the last period. For instance, Hegazy and Elhakeem (2011) developed a multi-objective optimization model to solve large-scale combinatorial bi-level optimization problems that include discrete, integer and two-level decisions. The model was applied to the buildings for scheduling the repair time of multiple building components. Moreover, De la Garza et al. (2001) developed a pavement management system that chooses the optimal maintenance and rehabilitation action plan at a network level. Numerous researches were conducted using various multi-objectives algorithms such as; linear programming, and integer programming.

The dependency and the interdependency relationships between the infrastructure systems are the main triggers behind considering the integration of the intervention activities among the different assets in the right of way. The systems’ dependency refers to the unidirectional relationship where one system relies on the other, while interdependency refers to the bi-directional relationship between the infrastructure systems (Rinaldi et al. 2001). There are various classifications for the systems' dependencies. For instance, Zimmerman (2001) classified the dependency into functional and spatial based on the operational dependency and the proximity among the systems respectively. In order to model the interdependency, numerous computational approaches have been used such as simulation, network-based analysis, etc (Ouyang 2014). The holistic AM decision-making systems have received considerable attention in the past 5 years. For example, Osman (2015) built a multi-objective goal optimization-based framework for temporal coordination of co-located infrastructure systems taking into account the risk, cost, and LOS as performance indicators. The model carried out trade-off analysis between delaying and bringing forward the intervention activities to maximize the performance of the corridor assets. Moreover, Shahata and Zayed (2016) developed an integrated risk-assessment framework for municipal infrastructure to aid the decision-makers during planning for rehabilitation projects.

3. APPROACH

The developed approach revolves through three main models as shown in Figure 1. The first model is data collection. The physical characteristics and condition data was mainly collected from two main sources as follows: (1) open source data and geographic information system (GIS) maps, and (2) municipal reports. The data was then processed for each asset category in the corridor to define the asset characteristics (i.e. physical, social, environmental, and spatial). Afterward, the output of the data collection phase was a complete asset inventory that contains sufficient information about the corridors under study. The second model is the multi-dimensional model, which is the core computational module in the decision-making system. This model features two fully-integrated models as follows: (1) integrated deterioration model, and (2) financial savings model. The mathematical processing of those two models will be discussed later in the sub-sections. Besides, the model captures three performance indicators: (1) condition, (2) life-cycle costs (LCC), and (3) user costs. Finally, the third model is the optimization model. It relies on non-pre-emptive goal optimization with priority weights and deviational variables, combined with meta-heuristic rules as discussed later in this paper.

Table 1: Sample of the road asset inventory

Corridor ID#	Asset Type	Installation/Major Rehabilitation year	Corridor Length (m)	Number of lanes	Lane Width (m)	Total Section Area (m²)	Average Annual Daily Traffic	Traffic Growth	Current Condition (%)	Number of surrounding roads	Area Type	Truck Percentage (%)	Average Speed (km/hr)
Corridor 1	Road Network	2014	300	3	3	2,700	12,000	5%	90%	2	Residential	10%	25
Corridor 2	Road Network	2009	250	4	3	3,000	8,000	5%	70%	2	Residential	10%	25
Corridor 3	Road Network	2012	200	4	3	2,400	10,000	5%	85%	1	Residential	10%	25
Corridor 4	Road Network	2007	150	2	3	900	11,000	5%	65%	3	Residential	10%	25
Corridor 5	Road Network	2009	100	3	3	900	7,000	5%	70%	2	Residential	10%	25

3.1 Data Collection Model

The data collection model relied on open-source data, GIS maps, and municipal reports to complete the required information and build the decision-making model. The required information was categorized into physical, social, environmental, and spatial. The output of this model was an asset inventory for each asset category (i.e. roads, water, and sewer). For instance, Table 1 shows a sample of the road network characteristics. The physical characteristics are represented in the installation year, corridor length, number of lanes, section area. However, the spatial characteristics are the interdependency of the asset with other assets. The spatial interdependency was considered in the maintenance costs calculations for the coordination scenarios. The environmental and social characteristics are represented through the area type, number of surrounding roads, truck percentage, etc. They were used to calculate the indirect cost implications of carrying out an intervention at a specific corridor as will be highlighted later in the next section. Similarly, the asset inventory for the water and sewer networks were developed, taking into consideration the different asset nature and characteristics.

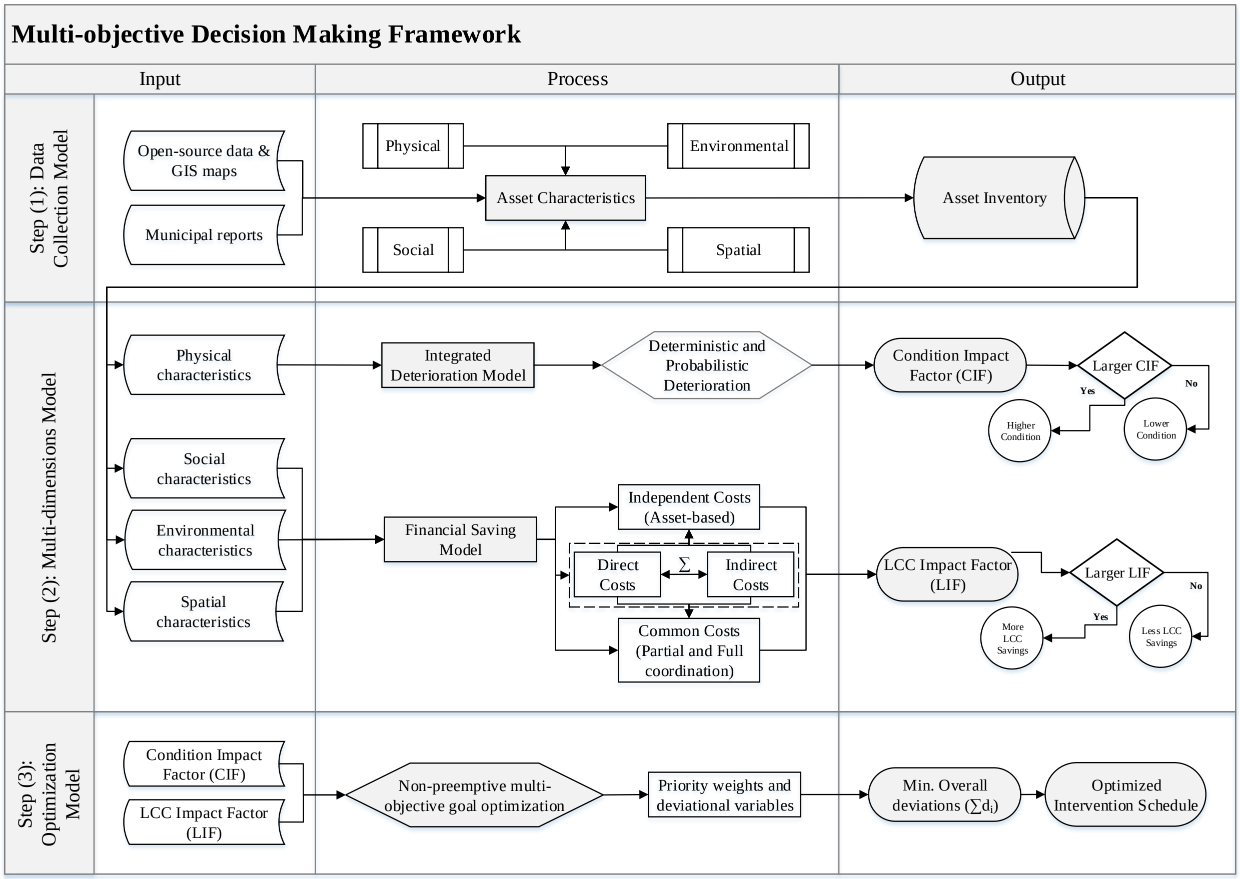
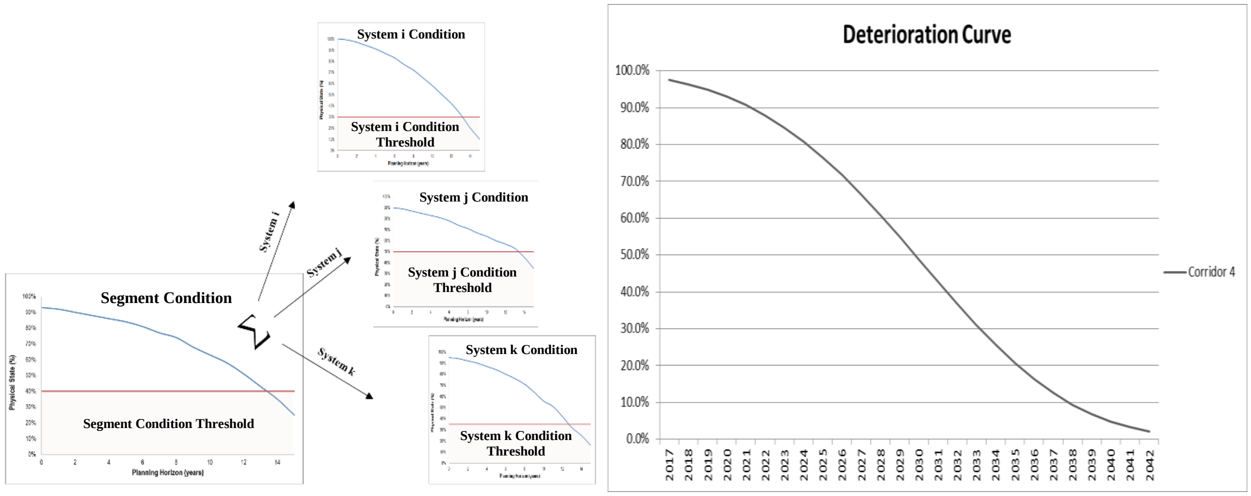


Figure 1: Multi-objective Decision-Making Framework

3.2 Multi-dimensions Model

3.2.1 Integrated Deterioration Model

The integrated segment-based deterioration model aims at calculating the condition state of the corridor, including all the n_s systems. Thus, it features n_s deterioration models for all the n_s systems and compiles their outcomes to a segment-based condition state based on the weights of importance of each system, as shown in Figure 2 (a). Due to the different service lives, deterioration patterns, surrounding conditions, etc., Markov-based deterioration model was developed for the roads (Abu-Samra et al. 2016) and Weibull-based deterioration models were built for the water, and sewer networks, given the service life for each pipe material, diameter, and the current age. The Weibull model used a pre-assumed shape and scale factors that represent the deterioration rate and characteristic life of the asset, to predict the probable deterioration model throughout the life-cycle (Kimutai et al. 2015). Based on the outcome of each deterioration model, the Condition state of each system (C_i) at each point of time is known for each coordination scenario, taking into account the maintenance/rehabilitation actions' effect on the condition state. Accordingly, the systems' condition states are compiled based on the systems' weights of importance and the corridor condition state is computed. The deterioration models have pre-set smart rules to alert the decision makers in case the condition state of any system reaches a value below the predefined threshold to undertake rapid intervention decisions prior to the increasing probability of failure as shown in Figure 2 (a). A sample of the deterioration curve of the roads network in corridor 4 is shown in Figure 2 (b).



(a) Segment Condition Amalgamation (b) Deterioration curve sample for the road of corridor 4

Figure 2: Samples of the Integrated Deterioration Model

3.2.2 Financial Savings Model

The financial savings model calculates both the direct and indirect ownership and operational costs of the infrastructure systems. The direct costs include the operation, maintenance, rehabilitation, and replacement costs, including site preparation, residents' notification, installation of traffic control systems, etc., needed throughout the planning horizon to deliver the services in an "acceptable" manner without interruption. On the other hand, the indirect costs, sometimes referred to as "Social" or "User" costs, reflect all the costs that are not directly related to the intervention (i.e. traffic disruption, vehicles or properties repair, business loss, noise disturbance, dirt and dust, environmental or health and safety issues, etc.). Those costs are subjective and rely on probabilistic approaches for predicting their amounts over the systems' service lives (Qin & Cutler, 2014). The calculations of the indirect costs were based on the model developed by Texas Department of Transportation (TDOT 2015). In order to calculate the LCC for each coordination scenario, the cost centers were divided into three categories as follows: (1) independent costs, (2) common costs centers between systems i and j, and (3) common cost centers among systems i, j, and k. Thus, the direct and indirect costs were calculated for the three categories (i.e. no, partial, and full coordination) as shown in Equations 1 through 6.

[1] $\mathrm{IDC_i} = \sum_{m=1}^{t}(Q_i * \mathrm{UC}_i)$

[2] $IIC_i = AD_i * \frac{A_i}{\sum_{i=1}^{n_S} A_i} * \left[\left((1-\mathrm{T_p}) * \mathrm{AADT} * \mathrm{UC_p}\right) + \left(\mathrm{T_p} * \mathrm{AADT} * \mathrm{UC_T}\right)\right]$

[3] $\mathrm{CDC_{ij}} = \sum_{r=1}^{p}\left[\left(Q_{ij} * \mathrm{UC}_{ij}\right)\right]$

[4] $\mathrm{CIC_{ij}} = SD_{PC} * \frac{A_{PC}}{\sum_{i=1}^{n_S} A_i} * \left[\left((1-\mathrm{T_p}) * \mathrm{AADT} * \mathrm{UC_p}\right) + \left(\mathrm{T_p} * \mathrm{AADT} * \mathrm{UC_T}\right)\right]$

[5] $\mathrm{CDC_{ijk}} = \sum_{q=1}^{s}\left[\left(Q_{ijk} * \mathrm{UC}_{ijk}\right)\right]$

[6] $\mathrm{CIC_{ijk}} = SD_{FC} * \frac{A_{FC}}{\sum_{i=1}^{n_S} A_i} * \left[\left((1-\mathrm{T_p}) * \mathrm{AADT} * \mathrm{UC_p}\right) + \left(\mathrm{T_p} * \mathrm{AADT} * \mathrm{UC_T}\right)\right]$

where:

IDC_i is the total direct costs for the independent activities of system i ($)
Q_i is the quantity of each independent activity for system i (varies according to the activity)
m is the activities counter; t is the total number of independent activities
UC_i is the unit cost for each independent activity in system i ($)
IIC_i is the total indirect costs for the independent activities of system i ($)
AD_i is the total asset duration for all the intervention activities required for system i without interruptions, assuming no coordination takes place (days)
A_i is the maintenance/rehabilitation area of system i (m^2)

i is the asset categories counter; n_s is the total number of asset categories
T_p is the percentage of trucks (%)
AADT is the average annual daily traffic representing the average number of daily vehicles (vehicles)
UC_p is the unit user cost for the passenger cars ($)
UC_T is the unit user cost for the trucks ($)
CDC_{ij} is the total direct costs for the common activities between systems i and j ($)
r is the counter of the common activities between systems i and j; p is the total number of common activities between systems i and j
Q_{ij} is the quantity of each common activity between systems i and j (varies according to the activity)
UC_{ij} is the unit cost for each common activity between systems i and j ($)
CIC_{ij} is the total indirect costs for the common activities between systems i and j ($)
SD_{PC} is the segment duration for the partial coordination scenario (days)
A_{PC} is the maintenance/rehabilitation area of all systems ns in case of partial coordination (m2)
CDC_{ijk} is the total direct costs for the common activities among systems i, j, and k ($)
Q_{ijk} is the quantity of each common activity among systems i, j, and k (varies according to the activity)
UC_{ijk} is the unit cost for each common activity among systems i, j, and k ($)
CIC_{ijk} is the total indirect costs for the common activities among systems i, j, and k ($)
SD_{FC} is the segment duration for the full coordination scenario (days)
A_{FC} is the maintenance/rehabilitation area of all systems n_s in case of full coordination (m^2)

Afterward, the LCC was calculated for the three coordination scenarios. The no coordination scenario will result in the highest LCC amount because all the common direct and indirect cost centers, either between two systems or among the three systems, will be applied n_s times, representing the number of systems. However, the partial coordination scenario will experience n_a repetitions for the common activities because there were potential activities that weren't fully coordinated. The full coordination scenario won't experience any repetitions as the systems were fully coordinated and the potentially coordinated activities were applied only once, decreasing the overall costs over the planning horizon as well as the amount/extent of disruption, which is reflected in the indirect costs. The detailed mathematical calculations could be shown in Equations 7 through 9.

[7] $LCC_{NC} = \sum_{i=1}^{n_s}(\mathrm{IDC_i} + \mathrm{IIC_i}) + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}(\mathrm{CDC_{ij}} + \mathrm{CIC_{ij}}) * n_s + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}(\mathrm{CDC_{ijk}} + \mathrm{CIC_{ijk}}) * n_s$
[8] $LCC_{PC} = \sum_{i=1}^{n_s}(\mathrm{IDC_i} + \mathrm{IIC_i}) + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}(\mathrm{CDC_{ij}} + \mathrm{CIC_{ij}}) * n_a + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}(\mathrm{CDC_{ijk}} + \mathrm{CIC_{ijk}}) * n_a \ (n_a < n_s)$
[9] $LCC_{FC} = \sum_{i=1}^{n_s}(\mathrm{IDC_i} + \mathrm{IIC_i}) + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}(\mathrm{CDC_{ij}} + \mathrm{CIC_{ij}}) + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}(\mathrm{CDC_{ijk}} + \mathrm{CIC_{ijk}})$

where:
LCC_{NC} is the life cycle costs in the no coordination case, including all the direct and indirect costs ($)
LCC_{PC} is the life cycle costs in the partial coordination case, including all the direct and indirect costs ($)
LCC_{FC} is the life cycle costs in the full coordination case, including all the direct and indirect costs ($)

3.3 Optimization Model

The optimization model utilized Genetic Algorithms (GAs) engine combined with meta-heuristic rules to minimize the optimization search space (Fogel 1998). GAs is derived from the biological systems and it is based on simulating the natural survival of the fittest concept. The solution is represented as a string of chromosomes, which consist of several genes. The genes' exchanging process within the chromosomes is carried out through mutation and crossover operations and new solutions are evaluated to replace the weaker members in the population and produce better solutions. This process continues until a near optimum solution is generated (Elbeltagi and Tantawy 2005). The system used advanced spreadsheet modeling and Evolver$_{TM}$ Version 7.0 as an optimization engine. The system combined a pre-defined set of meta-heuristics rules along with the non pre-emptive goal optimization engine to minimize the search space. Those rules could be summarized as follows: 1) Each corridor should carry out a maximum of 1 intervention every 5 years; 2) Each corridor is allowed only 5 interventions throughout the 25 years planning horizon. Afterward, the decision variables were formulated using integer programming such that; their ranges are defined according to the number of intervention activities considered in the model. Since Goal Programming

(GP) or Goal Optimization was used to overcome the multi-objective nature and conflicting goals within the optimization problem, there were no constraints as the objective is modeled through “Goal Constraints”. Thus, the objective is minimizing the sum of deviations for the desired goal values/thresholds (i.e. budget, minimal acceptable condition state). In order to combine the multi-objectives, a percentile ranking approach was used through calculating the deviation (%) from a goal rather than the absolute deviation (Schniederjans 1995). Finally, the deviational variables were mathematically defined accordingly as shown in Equations 10 through 12.

[10] $d_1^- = \frac{\sum_{i=1}^{n} C_i(CT_i) - C_i(t)}{\sum_{i=1}^{n} C_i(CT_i)}$

[11] $d_2^- = \frac{\sum_{i=1}^{n} LCC_i(t) - LCC_i(LT_i)}{\sum_{i=1}^{n} LCC_i(LT_i)}$

[12] $\mathrm{Min}(Z) = \sum_{x=1}^{m} \sum_{f=1}^{n} w_{as} w_{kl} (d_i^- + d_i^+)$

where:

CT_i is the minimal acceptable condition state (%)
t is the time when the deviation is calculated (days)
LT_i is the allowable budget at time t ($)
Z represents the minimized value of the sum of all negative (d_i^-) and positive deviations (d_i^+) for n goals
W_{as} represents the weights among the assets considered under study (%)
W_{kl} represents the deferential weights among the conflicting goals (%)
d_i represents the deviational variables (%)
f and x represent the age and assets counters respectively
m and n represent the planning horizon and total number of assets respectively

4. CASE STUDY

In order to validate the model, the system was applied to the road, water, and sewer networks of Kelowna, located in the southern interior of British Columbia, Canada. A 2 km stretch of the network was selected for analysis. The network includes 10 road sections covering water and sewer pipes of different materials. The data was collected from the open-source City of Kelowna GIS maps (City of Kelowna 2016). However, the condition rating information data was approximated to mimic the latest Canadian infrastructure report (FCM 2016). Markov and Weibull-based deterioration models were developed to forecast the future deterioration of assets. Estimated operations and maintenance costs experienced by the road, water and sewer municipalities were used to develop the LCC profile. 2% interest rate was considered in this study. The condition and LCC thresholds were defined for each asset based on previous research. The condition thresholds for roads, water, and sewer networks were assumed to be 60%, 40%, and 50% respectively. Moreover, the deferential weights (%) of the LCC and condition were assumed to be 60% and 40% respectively given the fact that municipalities are suffering from a limited budget. Finally, the assets’ weights of importance for the roads, water, and sewer networks were assumed to be 30%, 35%, 35% respectively due to the higher consequences of failure and rehabilitation cost for the water and sewer networks.

5. RESULTS AND ANALYSIS

The goal optimization engine showed promising results for the integrated AM system when compared with the silo AM in terms of less and combined interventions activities, less LCC throughout the planning horizon, and met the condition thresholds. The results of both the integrated deterioration model and the financial savings models are shown in Figures 4 and 5 respectively. As shown in Figure 4, the integrated AM results showed better results in terms of the overall condition of the 10 corridors through carrying out coordinated interventions that improve the overall condition of the corridor and not only the condition state of one asset. The difference between the silo and integrated and silo AM was 5% in favor of integrated with 30% fewer interventions along the planning horizon. The savings were much more obvious in Figure 5 where; the integrated AM showed 37% savings compared to the silo AM. This ensures the effectiveness of the integrated AM compared to the silo AM in terms of less number of intervention activities that led to less indirect costs, due to the less delay time and service disruption. It also resulted in less direct costs due to combining the common activities (i.e. traffic control devices, excavation and backfilling of areas, site reinstatement) that are carried out more than once in the silo AM. The results of the silo AM optimization showed 7.6% and 4% deviations from the LCC and condition annual pre-defined thresholds respectively, leading to a Z of 6.18% deviation, which represents the minimized value of the sum of all negative (d_i^-) and positive deviations (d_i^+) for the annually calculated deviational goals. However, the integrated AM optimization showed enhanced results compared to the silo AM where; the annual deviations from the pre-defined thresholds of the LCC and condition were 3.7% and 1.9% respectively. Besides, the goal objective of the integrated AM (Z) was 3%, which implies that the integrated AM resulted in less overall deviations from the pre-defined thresholds.

Figure 3: Sample of Kelowna GIS maps (Imagery ©2016 City of Kelowna, Infrastructure drawings map viewer)

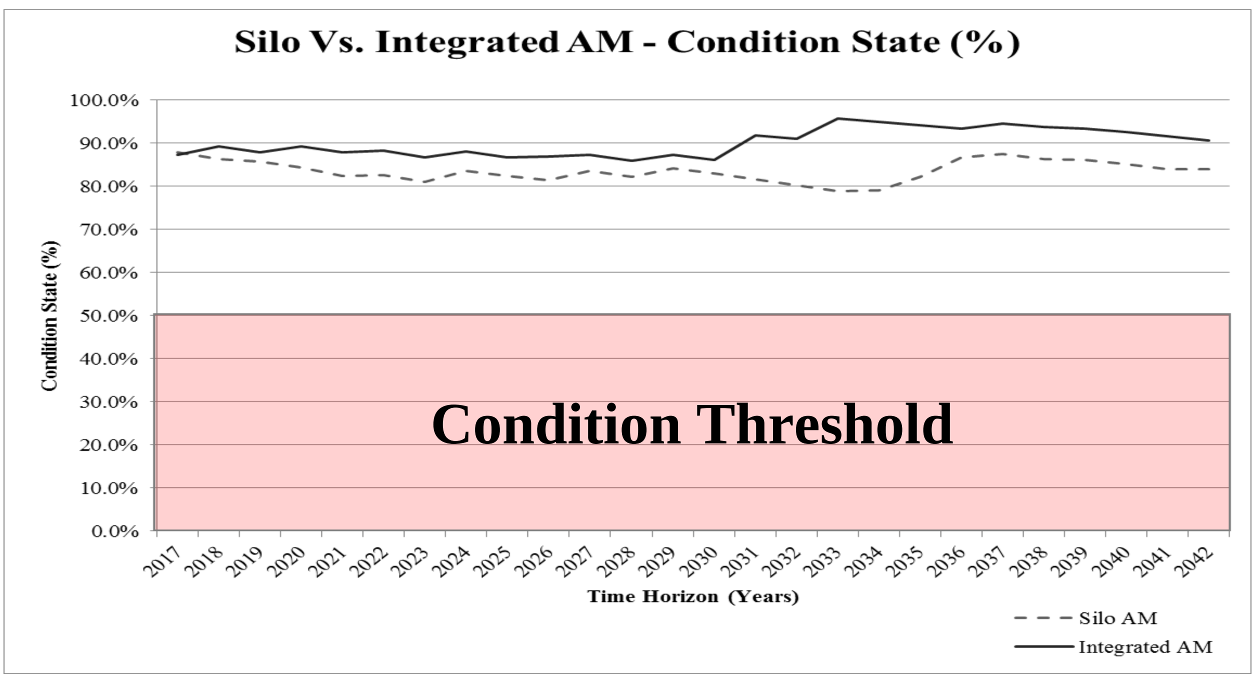


Figure 4: Silo Vs. Integrated AM Condition State Comparison

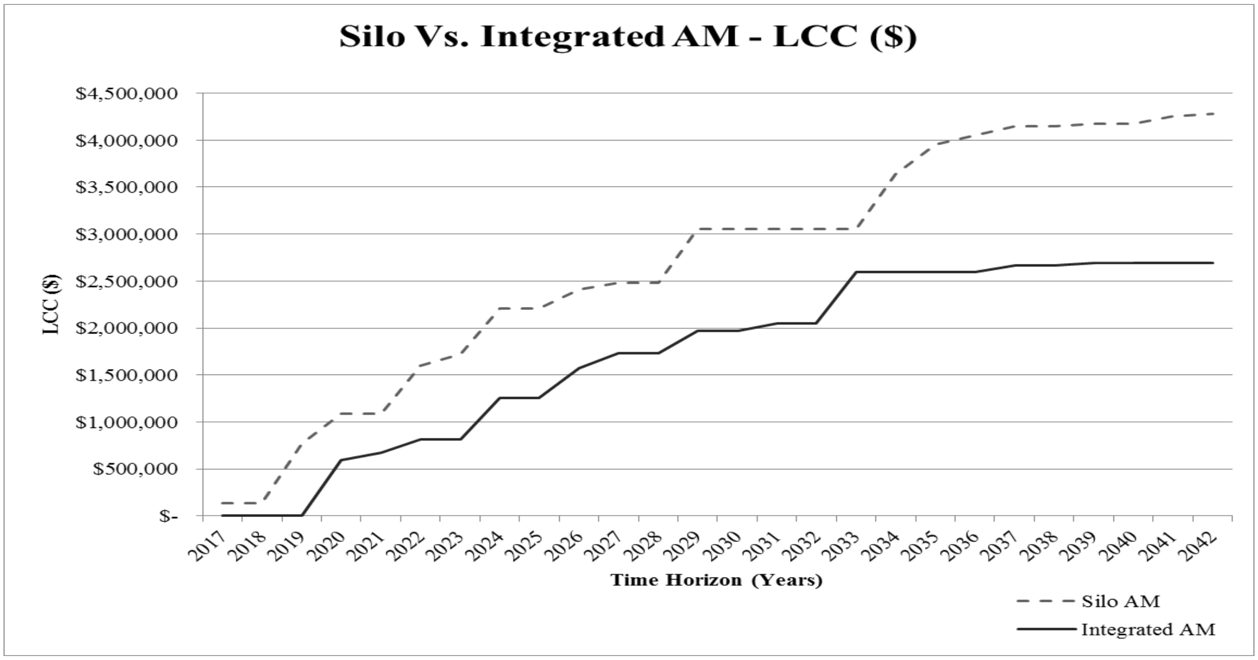


Figure 5: Silo Vs. Integrated AM LCC Comparison

6. CONCLUSIONS AND RECOMMENDATIONS

Previous research focused on developing silo AM decision-making systems for roads, water, and sewer networks. However, due to their spatial interdependencies, there are incentives towards the holistic approach to intervention actions to save time, money, and reduce disruption to end users. This paper presented a multi-objective framework for an integrated AM decision-making system while taking into account the condition and LCC for scheduling the intervention activities. An Integrated deterioration model for the roads, water, and sewer networks was developed after amalgamating their results. A financial savings model was then built to compute the direct and indirect costs for all the coordination scenarios (no, partial, and full coordination). An optimization model was also formulated using a combination of meta-heuristics and non-pre-emptive goal optimization to assess the trade-offs between bringing forward or delaying infrastructure intervention activities. This allows the decision makers to visualize the condition and financial state of each corridor separately, along with its' related assets. It also compared the results of the integrated AM with the silo AM for the corridors under study. The integrated AM showed a 5% enhanced condition state at the end of the planning horizon, and 37% financial savings due to the less direct and indirect costs resulting from the fewer interventions and hence less disruption time. Finally, the integrated AM system led to a 48% better goal objective based on the annual deviations from the condition and LCC pre-defined thresholds where; the integrated AM resulted in a 3% overall deviation compared to a 6.2% for the silo AM system.

The framework has a high potential to include more indicators that improve the decision-making process (i.e. risk, reliability, time savings, spatial savings, etc.). Further work is needed to assess the spatial savings (using GIS spatial analysis) that can improve the indirect cost estimation. Moreover, the weights selection process could be enhanced through an analytical hierarchal process (AHP) to benefit from engineering expertise while building the optimization model (Saaty 1982). Furthermore, sensitivity analysis and trade-off analysis could be carried out to consider uncertainties in intervention costs, deterioration rates, and other parameters.

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