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PERFORMANCE-BASED CONTRACTS AND MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK FOR COORDINATED INFRASTRUCTURE

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Abstract: The aging of the deteriorating infrastructure networks, coupled with declining investment rates and uncertainty, led to higher failure rates and service disruptions accordingly. Furthermore, the spatial proximity and interdependency among the corridor infrastructure (i.e. roads, water, and sewer) remains a challenging issue for asset managers, due to the assets' different deterioration mechanisms, service lives, rehabilitation strategies, etc. In the lights of those issues, this paper proposes an integrated performance-based contract and multi-objective optimization framework to ensure proper expenditures utilization, while maintaining adequate performance. The framework aids decision makers in reaching an optimal coordinated maintenance schedule. It revolves through three core models: (1) central database that contains detailed asset inventory for the infrastructure systems, (2) multi-dimensional computational models that integrate the contractual parameters with the asset management system, where five indicators namely; time, space, cost, risk, and condition were modelled for assessing the coordinated intervention plan performance over the conventional one; and (3) multi-objective optimization model that relies on a combination of mixed integer programming and goal optimization using Mosek engine to schedule the corridor interventions across the planning horizon. To demonstrate the system's functionality, the system was applied to the town of Kindersley's roads, water, and sewer networks over 25 years planning horizon. The results displayed huge savings in favor of the coordinated scenario such that; it showed 1% condition improvement, 72% time savings, 63% less space consumption, 48% less LCC, and 67% less public disruption. In summary, the developed framework is an integrated contractual and asset management solution that assists both municipalities and maintenance contractors in taking informed decisions in the pre-contract and post-contract phases.

1 INTRODUCTION

Enhancing life-cycle planning and fund allocation is increasingly becoming more vital to municipalities and utility operators to cope with the increasing challenges. Municipalities are financially overloaded due to the substantial increase in the under-performing and deteriorating assets; and the lack of enough funds to pay the increasing infrastructure deficit debt (Mirza 2009). According to 2016 Canadian Infrastructure report, Canada's infrastructure quality is ranked as "Mediocre" with a significant portion of assets in poor and very poor condition states (FCM 2016). Moreover, between 30% and 50% of assets will soon require attention or replacement, which increases the risk of municipal services' disruption. Furthermore, the estimated replacement value of the assets in very poor, poor and fair condition states for the roads, water, wastewater, and stormwater is $296.5 billion (Berz et al. 2017). Besides aging and deterioration of municipal assets, municipalities are facing other challenges that could be summarized as follows: (1) infrastructure deficit is estimated at $273 billion and is growing by $2 billion annually (Mirza 2009); (2) growing population and urbanization (i.e. the population increased from 17.9 million in 1960 to 36.7 million in 2017 and is expected to reach between 40.0 and 63.5 million people by 2063; (3) increasing demands on higher levels of services by taxpayers; and (4) low share of taxes, compared to provincial and federal governments, and huge responsibility for the largest share of public assets.

Infrastructure projects typically carries out tons of challenges and risks throughout the life-cycle due to demand fluctuations, uncertainties, natural disasters, necessity and criticality, etc. In such type of projects, crucial intervention decisions are, not only taken at the early beginning of the life-cycle but also regularly revised to guarantee delivering an acceptable level of service (LOS), meeting the tight budgets, and upholding with the minimal physical condition constraints. The need for asset management adoption has been strengthened by the plethora infrastructure problems (i.e. sudden system failures), as well as the deteriorating LOS, which in return placed tremendous pressure on the governments where they need to increase infrastructure expenditures for an enhanced LOS. Thus, enhancing life-cycle planning and fund allocation is increasingly becoming more vital to municipalities and utilities operators to cope with the increasing challenges. Coordination of intervention activities has been thoroughly considered as a part of the wider notion of the dependency and interdependency relationships among infrastructure systems. The dependency between the systems refers to a unidirectional relationship where one system relies on the other, while interdependency refers to the bi-directional relationship among the infrastructure systems (Ouyang 2014). Even though, numerous scholars have extensively studied the infrastructure interdependency within the operational phase, focusing particularly on how the system disruption propagates through related networks. But, sparse attention has been given to the interdependency occurring during undertaking interventions (i.e. repair, rehabilitation, and replacement) in terms of geographical and temporal dimensions. Moreover, the temporal dimension has not been thoroughly studied, given its' direct impact on the spatial, physical, and financial dimensions. Throughout previous decades, several scholars developed innovative funding and prioritization approaches for asset management. The relationships among numerous factors affecting assets' performance, deterioration processes, and service/physical failures are neither linear nor systematic. Consequently, the integration process across multiple co-located assets' life-cycles is complex and challenging, especially when it comes to building decision-making models for evaluating multiple investment options. To efficiently evaluate the investments, some scholars utilized spatial modeling to coordinate the corridor municipal interventions using GIS and dynamic neighborhood methodology (Amador and Magnuson 2011; Kielhauser et al. 2017). Other scholars utilized life-cycle costing (LCC) analysis, considering all direct and indirect cost categories such as; direct planning, design, acquisition, maintenance, ownership, operation of the asset (Abu-Samra et al. 2018; Osman 2015). Table 1 summarizes the most representative research efforts in single and multi-objective optimization.

Due to the increasing infrastructure deficits, extra challenges were added to the decision-making process such as; optimal utilization of the limited budgets, prioritization of municipal projects; enhancement of the network performance, reduction of service failure and disruption risks. Consequently, asset managers are continuously seeking near-optimal approaches to maximize the decisions' benefits (i.e. asset condition) and minimize their losses (i.e. LCC), which makes the problem in hand a multi-objective optimization problem by nature with conflicting objectives. Multi-objective optimization can reach a whole set of pareto near optimal solutions in one optimization run, which will require several runs to obtain the same level of information, in case of single-objective. Using a single-objective optimization, the decision-maker must express some preferences in advance such as; the goals' order or priority (i.e. maximize performance, then use it as constraint in the second run to optimize another decision-indicator such as; LCC, and so on). Preferences include assigning relative weights of importance. However, using multi objective optimization approach, one expresses preferences after running the model (Savic 2002). The application of multi-objectives optimization within the domain of infrastructure asset management has received considerable attention from researchers. Rashedi and Hegazy (2016) compared segmented GAs' and exact numerical optimization methods (GAMS/CPLEX) in the capital renewal planning of large infrastructure systems. Likewise, other scholars developed bi-level goal optimization for transportation networks, using penalty and compromise methods, to minimize the financial and performance deviations (Saad et al. 2017). While many scholars investigated multi-objective optimization to model one municipal network such as; water or road, less number of scholars attempted to use it for integrating two or more networks. Integrated asset management is still relatively limited in literature, especially, the ones with multi-objective optimization. For instance, Osman (2015) developed a framework for temporal coordination of co-located infrastructure systems taking the financial, risk, and LOS triggers into consideration while planning for systems' interventions. Likewise, Abu-Samra et al. (2018) utilized goal optimization to practically trade-off multiple competing objectives such as; LCC, risk, LOS, user-costs, and economic losses through combining all the weighted deviations from the thresholds along with their relative weights, forming an overall deviational goal. In spite of the fact that plentiful modelling computations approaches have been utilized in the last decade, some common limitations have been noticed: (1) propagation of the system disruption has not been appropriately considered as the majority of the research was focusing on the operation phase; (2) the dimension of "Time" was not considered as a key aspect that influence the asset management intervention decisions; and (3) lack of focus on holistic-based intervention for interdependent co-located infrastructure systems (i.e. roads, water and sewer). Scholars' efforts were directed towards developing decision-support systems on single-asset level. However, little research was carried out on the integrated asset management in the wider notion of optimization and decision-making. Thus, this study aims at filling this gap by developing a coordination framework that optimizes the expenditures utilization among the interdependent assets throughout the planning horizon while maintaining an acceptable LOS.

Table 1: Summary of decision-making single and multi-objective optimization research

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Abu-Samra et al. (2018)	Roads, water, and sewer	Phased network level	Multi-objective	Integrated goal optimization, dynamic and integer programming, and GAs'	Minimize deviations from the budget and performance targets
Ghodoosi et al. (2018)	Bridges	Project level	Single objective	GAs'	Minimize the equivalent uniform annual cost over the bridge life-cycle
Osman (2015)	Roads, water, and sewer	Network level	Multi-objective	Goal Optimization	Minimize the goal deviational variables
Saad el al. (2017)	Roads	Network level	Multi-objective	Bi-level goal optimization with pareto (penalty and compromise methods)	Minimize deviations from the pre-defined targets
Rashedi and Hegazy (2016)	Roads, water, and sewer	Network level	Multi-objective	Casual loop diagrams and system dynamics	Maximize performance and minimize costs
Saad and Hegazy (2015)	Roads	Network level	Single objective	Loss-aversion	Maximize the gain within the limited budget
Amador and Magnuson (2011)	Roads, water, and sewer	Network level	Multi-objective	Integrated classical time-space adjacency modelling, and mathematical optimization	Minimize the life-cycle costs and service disruption
Scheinberg and Anastasopoulos (2009)	Roads	Phased project and network level	Multi-objective	Mathematical optimization and mixed integer programming	Minimize costs and maximize condition

2 OBJECTIVES

The goal of this research is developing a coordination and optimization asset management framework under Performance-based Contracts (PBC). The framework will aid decision-makers establishing a near-optimum coordinated interventions' plan for the municipal infrastructure. In this paper, the following objectives will be achieved:

1. Identify the Key Performance Indicators (KPIs') for the PBC.

2. Design a multi-dimensional performance assessment model.

3. Establish an optimized coordinated intervention plan.

3 METHODOLOGY

The research methodology rests on three core foundations as follows: (1) integrated PBC contractual scheme; (2) multi-dimensional assessment models; and (3) multi-objective optimization for PBC-based asset management. It spins around three phases as shown in Figure 1. The 1st phase is identifying the criteria for selecting the KPIs, the KPIs' and their corresponding deterioration patterns, inspection frequencies, and degrees of importance for being inputted to the multi-dimensional performance assessment models. The 2nd phase is developing multi-dimensional performance assessment models that rest on five dimensions as follows: (1) spatial, (2) temporal, (3) financial, (4) physical, and (5) risk. Those dimensions are the contractual KPIs, as will be detailed later. Finally, the 3rd phase is building a PBC-based asset management system that functions through five main models as follows: (1) central database model that contains the data of the corridor infrastructure under study; (2) deterioration model that predicts the future condition state of each asset; (3) integrated LCC model that calculates the LCC of the systems, corridors (i.e. group of systems), and network (i.e. group of corridors); (4) multi-dimensional performance assessment models that compute the state of the pre-defined KPIs throughout the planning horizon; and (5) optimization models that function through MOSEK optimization engine and acts as a decision-support system for decision-makers.

3.1 KPIs' selection criteria phase

The KPIs' selection criteria phase aims at (1) identifying the criteria for selecting the KPIs'; and (2) defining the KPIs' along with their corresponding deterioration patterns, inspection frequencies, and degrees of importance. Given the multi-asset nature of this problem such that; different assets feature different characteristics such as; deterioration rates, useful lives, installation years, intervention costs, and physical condition implications; there is a need for careful KPIs' selection. The established KPIs' need to be indicative, specific, measurable, achievable, realistic, and timely to predict their annual performance, from economic, financial, physical, and social perspectives, before and after applying different intervention plans. Accordingly, after conducting an exhaustive literature review, a set of categories and rules were set to define the KPIs' as detailed in Abu-Samra et al. 2018. Based on those rules, four KPIs' have been chosen as follows: 1) physical; 2) financial; 3) temporal; and (4) spatial. The physical indicator represents the condition of the asset and it obtained from the asset deterioration model. In this study, a 0% represents an asset in a failing condition, and a 100% represents an asset in an excellent condition. Furthermore, financial indicator represents the ownership and operation/maintenance costs of the asset. On the other hand, temporal and spatial represent the repair time and space to keep the asset in an acceptable condition. Details on the indicators will be highlighted in the upcoming subsection.

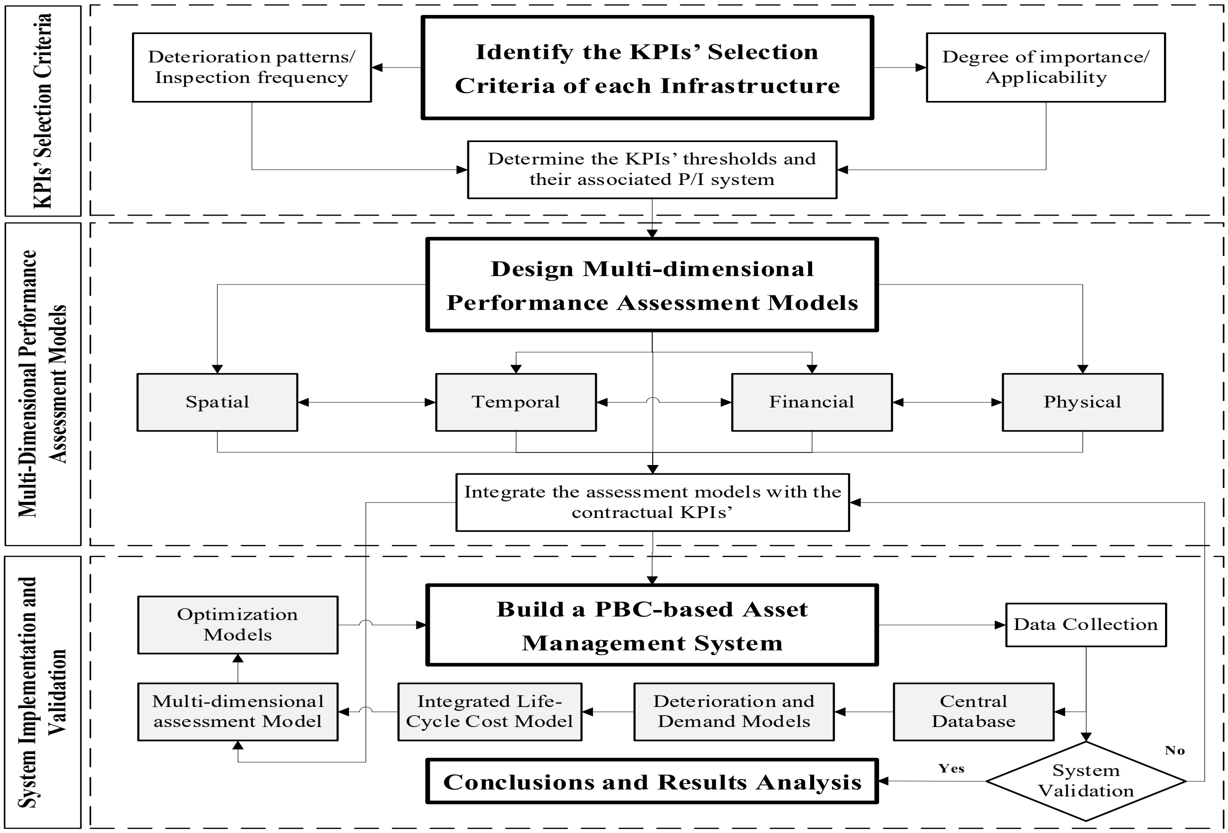


Figure 1: Integrated asset management framework

3.2 Multi-dimensional assessment models

3.2.1 Temporal model

The temporal model dynamically computes the durations of the combined, partially-combined, and conventional interventions, based on the categorized activities and their production rates. The benefit of coordinating the intervention actions is generating time savings in the corridor intervention duration compared to conventional approach. Those time savings take place because of the existence of joint activities that are shared among the three systems as well as the possibility of undertaking parallel activities rather than series ones in case proper coordination takes place (i.e. road resurfacing can occur concurrently while working on reinstating sewer laterals). As such, these activities can be undertaken only once, in case of combined approach, rather than ns, in case of partially-combined or conventional approach, where n is the number of standalone interventions and s is the number of systems (i.e. traffic control systems set up, residents notification, and site reinstatement work). Accordingly, those overlaps can be globalized through the basis of Standalone duration (SD), Parallel duration (PD), and Joint duration (JD). The SD represents the duration of the intervention activities required only for one asset and no other work can take place concurrently (i.e. installation of new sewer manholes). However, the PD represents the duration of the intervention activities that can take place concurrently. Furthermore, the JD represents the duration of the intervention actions required for two or more systems. This duration represents the activities that can take place between two or more systems concurrently (i.e. excavation of entrance and exit pits for water and sewer systems is an example of trenchless rehabilitation for both systems, traffic control devices, excavation and backfilling of common areas, site reinstatement works, etc.). Thenceforth, the activities are categorized and the potential parallel activities for each coordination scenario are defined. Afterwards, the durations for three intervention scenarios. Let Asset Standalone Duration (ASDi) represent the duration of all the intervention activities required for system i without interruptions, assuming no coordination takes place; and Corridor Coordinated Duration (CCD) represents the total duration of the entire project, assuming either partial or full coordination scenarios. Finally, the Network Coordination Ratio (NCR) is computed to reflects the potential time savings that could be attained from coordinating the intervention activities, either partially or fully, during the execution phase. The greater NCR is, the less the extent of time savings resulting from coordination. A ratio of 100% represents no possible time savings due to the absence of either joint activities or activities that can be undertaken in parallel. They could be mathematically formulated as follows:

[1] $ASD_{i_o} = SD_{i_o} + JD_{ijk_o} + \sum_{i=1}^{n_s} JD_{ij_o}\ (i \neq j)$

[2] $CCD_o = \sum_{i=1}^{n_s} SD_{i_o} + \sum_{i=1}^{n_s} PD_{ijk_o} + \left\{JD_{ijk_o} * n_a\right\} + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s} JD_{ij_o}\ (i \neq j)$

[3] $NCR\ (D_1{}^+) = \sum_{o=1}^{O}(\frac{\sum_{i=1}^{n_s} ASD_{i_o}}{CCD_o})$

where ASD_{i_o} is the standalone duration for all the systems n_s in corridor o (hours); i is the counter for the systems (number); n_s is the total number of systems (number); CCD_o is the corridor coordinated duration for all the systems n_s in corridor o (hours); n_a is the number of intervention actions that occurred at the same corridor (number); j is the counter for the systems (number); NCR is the network coordination ratio (%); o is the corridors' counter (number); and *O* is the total number of corridors (number).

3.2.2 Spatial model

The spatial intervention savings model considers the amount of space needed to be occupied while undertaking any intervention. Based on the lane rental approach, which is applied on the roads for expediting their rehabilitation works, asset managers aim at minimizing the space, time, and disruption caused by maintenance contractors while undertaking the interventions. To better understand the theory, let's assume that A_i is the amount of space needed to be utilized during the rehabilitation for system i in the case of no coordination. Therefore, the total area required in case of no coordination will be the sum of the rehabilitation areas of the three right-of-way assets (A_R+A_W+A_S), representing the area of roads, water, and sewer respectively. On the other hand, due to the spatial overlap among the systems sharing the same right-of-way, the total area required to undertake the rehabilitation for both the partially-coordinated and fully-coordinated intervention scenarios could be referred to as A_{PC} and A_C. In order to build the model, the extent and required area for each system have been separately identified and spatial interdependencies in partially-coordinated and fully-coordinated intervention scenarios have been identified to compute the above-mentioned areas (Ai, Aj, and Ak). Hence after, the duration model outcomes, ASD_{i_o} and CCDo, have been used to represent the time a specific area will be occupied for undertaking the rehabilitation. As such, the Spatio-Temporal Disruption Factor (STDF) integrates the spatial and temporal dimensions for conventional, partially-coordinated, and fully-coordinated intervention scenarios. It is obvious that the fully-coordinated scenario will consume less area as opposed to the partially-coordinated and conventional scenarios (AC<APC<ACN). This is simply because of the spatial interdependency among the co-located assets. For instance, a water or sewer pipe rehabilitation requires demolishing and reconstructing the above road section, causing duplication of work within relatively short time spans and accordingly extra nuisance to the public. Finally, a Spatio-Temporal Improvement Factor (STIF) is computed to compare the fully-coordinated and partially-coordinated intervention scenarios with the conventional one in terms of space and time savings. For instance, an STIF of "2" indicates that the considered intervention scenario consumes two times less time and space compared to the conventional intervention scenario.

[4] $STIF_{C_t}\ (D_2{}^+) = \frac{STDF_{CN_t}}{STDF_{C_t}}$

Where; $STIF_{C_t}$ is the spatio-temporal impact factor that compares the fully-coordinated network intervention scenario with the conventional intervention one in terms of space and time at point of time t (%); $STDF_{CN_t}$ and $STDF_{C_t}$ are the spatio-temporal disruption factors in the cases of conventional and fully coordinated interventions respectively at point of time *t* (%).

3.2.3 Financial model

The financial savings model calculates the direct and indirect ownership and operational costs of the infrastructure systems. The direct costs represent the costs of the intervention activities needed to be undertaken 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.). The calculations of the LCC for each intervention scenario were adopted from Abu-Samra et al. 2018. The conventional intervention scenario will result in the highest amount as all the joint direct and indirect cost centers, either between two systems or among the three systems, will be applied n_s times, dramatically increasing the direct and indirect costs. However, the partially-combined intervention scenario will experience n_a repetitions for the joint activities as there has been some potential activities that were not coordinated. Thenceforth, the combined intervention scenario will not experience any repetitions as the systems were fully coordinated and all the potentially coordinated activities were applied only once, decreasing the overall costs over the planning horizon as well as the amount/extent of disruption. Finally, the LCC Impact Factor (LIF) was calculated to compare the partially-combined or combined intervention scenarios with the conventional intervention scenario to visualize their potential cost savings. For instance, an LIF of "2" indicates that the combined intervention scenario utilizes two times less cost compared to the conventional intervention scenario.

$$[5]\ LCC_{CN_o} = \sum_{i=1}^{n_s}(\mathrm{SDC}_{\mathrm{i}_o} + SIC_{i_o}) + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ij}_o} + \mathrm{JIC}_{\mathrm{ij}_o}\right) * n_s + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ijk}_o} + \mathrm{JIC}_{\mathrm{ijk}_o}\right) * n_s$$

$$[6]\ LIF_C\ (D_3{}^+) = \sum_{\mathrm{o}=1}^{\mathrm{O}}\left(\frac{LCC_{CN_o}}{LCC_{C_o}}\right)$$

where LCC_{CN_o} and LCC_{C_o} are the life-cycle costs of corridor o for the conventional and fully coordinated intervention scenarios respectively ($); and LIF_C is the life-cycle costs impact factor of the combined network intervention scenario over the conventional intervention one (%).

3.3.4 Deterioration model

The corridor health model computes the condition of the corridor. It features n_s deterioration models for all the n_s systems and compiles their outcomes to a corridor condition state based on the weights of importance of each system. Due to their different service lives, deterioration patterns, surrounding conditions, etc., various Weibull-based deterioration models were built for the n_s systems. Based on the outcome of each integrated deterioration model, the condition state (H_i) of each system (i) at each point of time (t) is available for all the intervention scenarios, considering the intervention actions' as well as the extreme events' effects 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 preset condition thresholds that alerts the decision makers in case the condition state of any system reaches a value below the threshold to undertake rapid intervention decisions and avoid experiencing an increased probability of failure. Then, the corridor condition is computed for the conventional, partially-combined, and combined scenarios represented by C_{CN}, C_{PC}, and C_C respectively. Finally, the Condition Impact Factor (CIF) is computed to compare the partially-combined or combined intervention scenarios with the conventional intervention scenario to visualize their potential corridor condition improvement. A CIF<1 indicates that the considered intervention scenario resulted in an improved corridor condition, compared to the conventional intervention scenario, and vice versa. For instance, a CIF of "1.2" indicates that the considered intervention scenario has 20% less condition state compared to the conventional intervention scenario.

$$[7]\ CIF_C\ (\mathrm{D}_4^-) = \frac{C_{CN}}{C_C}$$

where; C_{CN} and C_C are the network condition states for the conventional and fully coordinated intervention scenarios (%); and CIF_C is the network condition impact factor of the combined intervention scenario over the conventional intervention scenario (%).

3.3 Optimization Model

The complexity of the problem on hand arises due to the spatial interdependency among the assets under study as well as the varying intervention scenarios. Thus, it would be computationally impossible to manually reach an optimal scenario due to the outsized search space. Thus, goal programming or goal optimization has been chosen for the problem in hand, given the fact that the problem features conflicting goals and multiple assets. The objective is linked to the variables through "Goal Constraints". However, the objective is clearly formulated to minimize the sum of deviations for the prescribed goal values defined by the user. To combine the objectives, a percentile ranking approach was utilized by calculating the percentage deviation from a goal rather than the absolute deviation. Finally, the deviational variables are formulated to fit the pre-defined set of KPIs, as shown in the aforementioned equations.

$$[8]\ \mathbf{Min}(\mathbf{Z}) = \sum_{\mathrm{i}=1}^{n_s}\sum_{v=1}^{V}\sum_{\mathrm{t}=1}^{T}[\mathrm{W_i} * \mathrm{W_v} * (\mathrm{d}_k^- + \mathrm{d}_m^+)]$$

[9] $\mathrm{d}_{k_t}^{-} = \sum_{i=1}^{n_s} \sum_{h=1}^{H} \frac{KPI_{h_{i_t}} - TH_{h_i}}{TH_{h_i}}$; *for all k and t*

[10] $\mathrm{d}_{m_t}^{+} = \sum_{i=1}^{n_s} \sum_{l=1}^{L} \frac{TH_{l_i} - KPI_{l_{i_t}}}{TH_{l_i}}$; *for all m and t*

[11] $\textbf{Decision variables} = \begin{bmatrix} I_{t_o} & \cdots & I_{T_o} \\ \vdots & \ddots & \vdots \\ I_{t_O} & \cdots & I_{T_O} \end{bmatrix}$

For $I_{t_o} = 0, 1, \dots 10$
$t = 1, 2, \dots T$
$o = 1, 2, \dots O$

where; Z is the summation of the deviational variables of n_s system throughout the planning horizon T (%); W_v represents the deferential weights among the conflicting goals (%); v is the KPIs' counter (number); V is the total number of KPIs (number); $\mathrm{d}_{k_t}^{-}$ is the summation of all the negative deviational variables at point of time (t) (%); and $\mathrm{d}_{m_t}^{+}$ is the summation of all the positive deviational variables at point of time (t) (%);

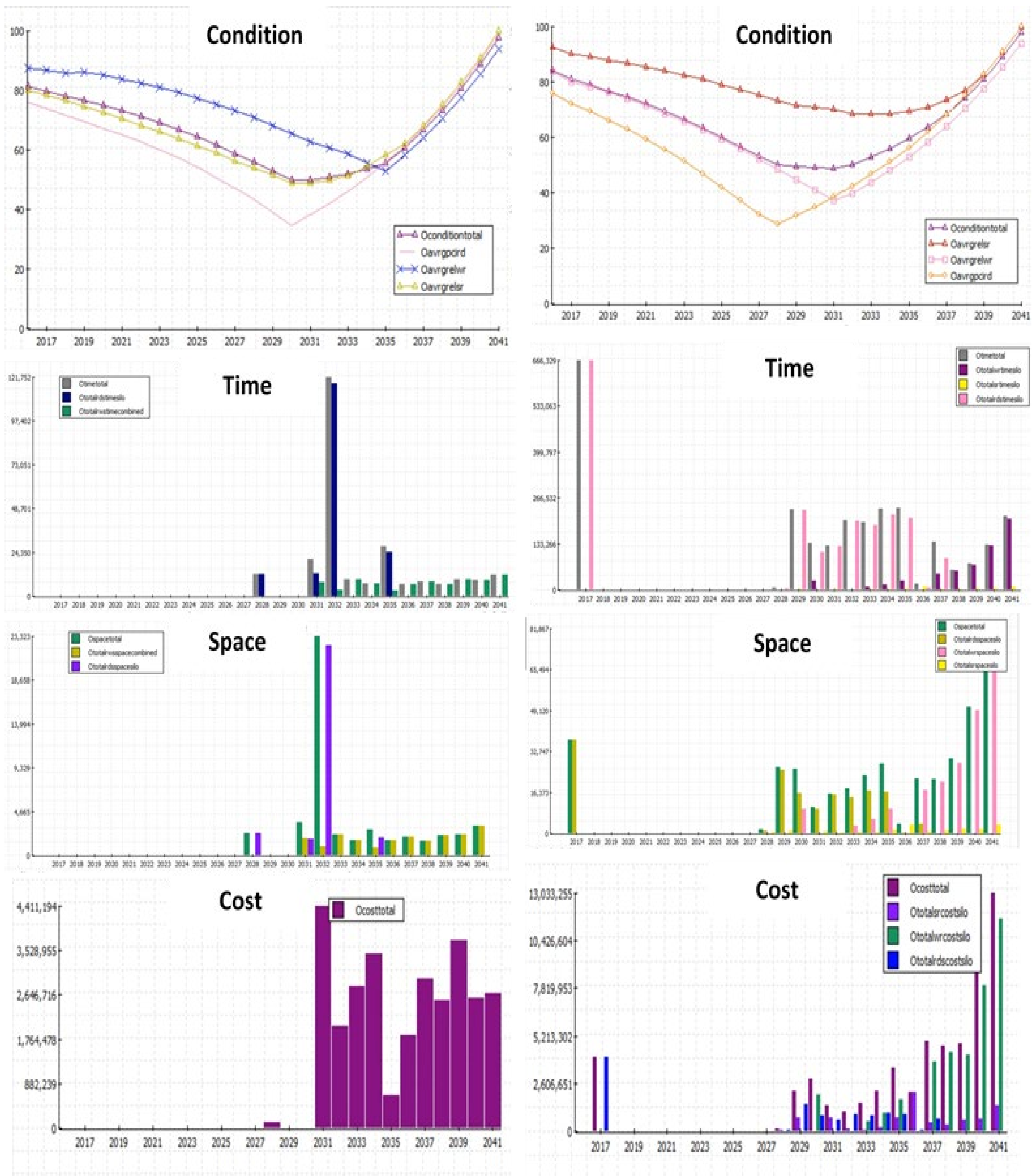
4 RESULTS AND ANALYSIS

To demonstrate the functionality of the proposed framework, the system was applied to a 53 km stretch from the town of Kindersley roads, water, and sewer networks. The network comprises 120 corridors. Time value of money has been considered with an interest rate of 2% (Bank of Canada 2018). Furthermore, the study planning horizon was 25 years. The weights of the systems were assumed according to the overall LCC of each system across 100 years, using the longest life method. The results displayed 45%, 25%, and 30% for the roads, water, and sewer systems respectively. However, those weights are subject to change according to the stakeholders' preferences (i.e. condition, replacement cost, crews' availability, etc.). The presented multi-objective goal optimization was applied to the case study and displayed encouraging results in terms of financial, temporal, condition, and spatial indicators. The model was built on REMSOFT and MOSEK optimization engine was used. The weights of importance for the financial, temporal, spatial, and physical were 50%, 10%, 30%, and 10% respectively. The optimization showed promising results for the combined intervention system as opposed to the conventional one in terms of: (1) number of interventions; (2) delay time for service disruptions; (3) combined interventions for the road, water, and sewer networks; (4) less space consumed to maintain the corridors; and (4) LCC across the planning horizon. The conventional system was modelled and optimized using the same engine. As shown in Figure 2 (a), the coordinated scenario showed to be much effective as opposed to the conventional one with 1% condition improvement, 72% time savings, 63% less space consumption, 48% less LCC, and 67% less public disruption with less number of interventions. Those savings reflect the coordination of the intervention activities where the common activities have been carried out once instead of n_a or n_s times for the partially-combined and conventional intervention scenarios. Furthermore, undertaking the combined intervention increased the number of parallel activities, which increased the temporal, spatial, and financial savings as opposed to the conventional approach in which n_s interventions are separately undertaken for each system. The results could be summarized in Table 2.

KPI	Conventional (Baseline)	Coordinated	Savings
Time (hours)	2,673,608	748,074	72%
Space (m^2)	397,069	145,467	63%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$1,529,741	48%
Average Condition (%)	66%	67%	1%
# of intervention actions	560	186	67%
Time per km per year (hours/km/year)	2,018	565	72%
Cost per km per year ($//km/year)	$55,070.62	$28,863.05	48%

Average repair length per year (km/year)	5.2	2.4	53%

Table 2: Town of Kindersley - Optimization summary results



(a) Coordinated (b) Conventional

Figure 2: Coordinated intervention savings over conventional (condition, time, space, cost)

5 CONCLUSIONS

Across the last decade, plentiful decision-making frameworks were developed frameworks for silo systems with less focus on building coordinated decision-making frameworks for collocated assets. This paper presented a coordination framework that can be used for scheduling the interventions of the municipal collocated infrastructure. It developed a set of KPIs' to aid decision-makers in taking informed decisions. Furthermore, it quantified the temporal, financial, condition, and spatial savings of the coordination decisions as opposed to the silo ones. The results of the implementation case study showed great savings in favor of the coordination over the silo one in terms of cost, time, space, and condition. Despite the capabilities and flexibility of the system, the future work is underway to address some of the limitations including but not limited to: (1) incorporating more than three infrastructure systems in the multiple-system level to maximize the coordination benefits; and (2) quantifying the public nuisance impact of undertaking a coordinated intervention as opposed to the conventional independent interventions.

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