INTEGRATED ASSET MANAGEMENT FOR CORRIDOR INFRASTRUCTURE
A WIDER ASSET MANAGEMENT PERSPECTIVE FOR AN ENHANCED LEVEL OF SERVICE

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ABSTRACT

Municipalities are facing increasing challenges due to the aging and deterioration of the infrastructure assets. There is a real need for integrating assets rehabilitation planning within and across multiple municipal departments. However, the complexity of management processes of public infrastructure assets is increasing and incorporates multiple challenges. The integration and coordination of corridor infrastructure decision-making is considered a key for optimal municipal asset management. Integrating the maintenance and rehabilitation actions is thought to save municipal money and efforts through providing a better level of service for the users. Moreover, it contributes towards minimizing the service disruption and potential user costs that result due to the service disruption. Integrated rehabilitation planning approaches incorporate the complexity of coordinating and balancing multitudes of aspects such as; a) decisions on the maintenance of existing assets versus building new assets, b) complying with more strict environmental as well as accounting regulations, c) decisions on balancing the technical, economic, social, environmental and optimal decision-making aspects, d) decisions on optimal planning at both the project and the network levels, e) interdepartmental technical and financial planning coordination, f) interdepartmental data, information, knowledge and processes coordination, g) optimal balancing of the potential risk, level of service, and available fund through the life cycle of all the assets in the organization’s portfolio. The optimal decisions for different types of co-located assets are even more challenging. Accordingly, this book presents an integrated multi-objective asset management approach for corridor infrastructure that allows asset management trade-off intervention alternatives on both silo and integrated
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asset management levels. Besides, it can be used as a planning as well as a simulation platform with unlimited number of what-if scenarios to support the decision makers in their critical decisions. The framework considered four key performance indicators as follows: (1) Physical State, (2) Life Cycle Costs, (3) User Costs, and (4) Replacement Value. It basically relies on the combination of meta-heuristics, dynamic programming and goal optimization in solving the combinatorial in nature optimization problem. In order to demonstrate the approach’s capabilities, it was applied to a case study for Kelowana’s road and water network, 20 sections. The results showed savings in the life-cycle costs and user costs throughout the planning horizon compared to the silo asset management system. The framework showed potential ability to be scaled up to include other corridor infrastructure assets such as; sewer, electricity, gas, telecom, provided that the information could be shared among these entities.
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CHAPTER 1 - INTRODUCTION

This chapter starts with a generic background about the infrastructure. Afterwards, it highlights on the some of the main challenges that are facing the municipalities’ while managing their infrastructure assets. Hence after, it provides a generic overview of the previous research in the integrated asset management and the different streamlines and perspectives that were receiving attention. Finally, it pinpoints on the objective and organization.

Background

Infrastructure is the foundation of our daily lives. The strength of this foundation enables our communities to prosper and local businesses to grow. Infrastructure development is a vital component in encouraging a country's economic growth where; Finance Canada report has recently shown that $1 billion investment in infrastructure creates 16,700 jobs and boosts the GDP by $1.6 billion (Canadian Center for Policy Alternatives (CCPA), 2009). Developing infrastructure enhances a country's productivity, consequently making firms more competitive and boosting a region's economy. Not only does infrastructure in itself enhance the efficiency of production, transportation, and communication, but it also helps provide economic incentives to public and private sector participants. The accessibility and quality of infrastructure in a region help shape domestic firms' investment decisions and determines the region's attractiveness to foreign investors.

On the other hand, looking beyond the infrastructure expectations and opting for an enhanced performance are one of the key challenges facing a plethora of municipalities across North America. Furthermore, tackling the inefficiency and financial burden imposed by underperforming infrastructure, where; one-third of Canada’s municipal infrastructure are in fair, poor and failing condition states (Canada Infrastructure, 2016), which dramatically increase the risk of service disruption and requires taking immediate corrective actions for maintaining them, is another issue for measuring countries’ economic development. Besides, ageing infrastructure systems worldwide are placing tremendous pressure on governments, through steeply growing budget deficits and urgent need for replacement where; 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 (The Canadian Council
of Public Private Partnership, 2009) to satisfy the growing population, which has doubled in 40 years from 17.9 million in 1960 to reach 35.1 million in 2013 and expecting to be 42.5 million by 2056 (Statistics Canada, 2015). Thus, it is obvious that there is an urgent need for adopting innovative and effective asset management approaches that minimize the expenditures without scarifying minimum level of services’ thresholds.

There is no one definition of integrated asset management. The following represent the different perspectives on integration:

a. Danylo and Lemer (1998) considered that the main role of an infrastructure asset management system is to work as “an integrator”, a system that can interact with and analyze the output of many different systems.

b. Shen and Spainhour (2001) emphasized that “the tools and methodologies for infrastructure lifecycle management should integrate environmental, economic, and technical issues into a total solution”.

c. “All municipalities across Canada should implement an integrated approach to assessment and evaluation of road, sewer, and water systems” InfraGuide 2003a,b,c, 2006). (InfraGuide 2003,a,b,c; 2004, 2006) recommended that the best practice for managing infrastructure networks should treat them as an integrated system. However, the different InfraGuide volumes emphasized the integrated management of co-located road, sewer and water networks.

d. Adopting integrated multi-disciplinary approaches became a key requirement for implementing efficient, and sustainable asset management programs (Halfawy 2008; Halfawy 2010; Shahata, K. and Zayed, T. 2010).

e. The Institute of Asset Management (IAM) in conjunction with British Standards Institution (BSI) published the first publicly available specification for optimized management of physical assets, (PAS 55:2004), in 2004. The 2008 update (PAS 55:2008) was developed by 50 organizations from 15 industry sectors in 10 countries. In PAS 55, Asset Management is defined as: “systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan”. (BSIgroup 2015)

f. After the widespread adoption of PAS 55 in utilities, transport, mining, process and
manufacturing industries worldwide, the International Standards Organization (ISO) then accepted PAS 55 as the basis for the development of the new ISO 55000 series of international standards. ISO 55000 published in 2014 defines Asset Management as: “coordinated activity of an organization to realize value from assets” (The IAM 2014).

Table 1: Summary of Integration Concepts in Literature

<table>
<thead>
<tr>
<th>Emphasis Given to</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrate multiple systems</td>
<td>1998</td>
</tr>
<tr>
<td>Integrate Environmental, economic, and technical issues</td>
<td>2001</td>
</tr>
<tr>
<td>(very similar to sustainability: environmental, economic and socio factors)</td>
<td></td>
</tr>
<tr>
<td>Integrate multi-disciplinary management approaches</td>
<td>2003-2015</td>
</tr>
<tr>
<td>Systematic and coordinated activities and practices as well as optimal life cycle and sustainable management of assets performance, risks and expenditures and achieving strategic plan</td>
<td>2004, 2008</td>
</tr>
<tr>
<td>Coordinated activities and policy of an organization to realize a business value</td>
<td>2014</td>
</tr>
</tbody>
</table>


From this standpoint, the mainstream of the integrated asset management research has been concentrating on a number of perspectives, which could be best summarized as follows:

1. **System complexity**: It is all about enhancing the management and balance of the factors from both micro/project level and macro/network level perspectives (Houston, 2014).
2. **Financial reporting:** The goals are optimizing to reach a near-optimum funding decision, and conducting benefit/cost analysis to carry-out various maintenance alternatives (Halfawy, 2008).

3. **Information management:** The integrated asset management represents an excellent example of the “Big Data” issue, which requires improving the data integration process across multiple departments (Michele & Daniela, 2011).

4. **Integration factors:** The integrated asset management frameworks were restricted to specific areas such as; (1) GIS-based integration systems (Halfawy, 2010), (2) Integrated risk-based decision-making (Shahata & Zayed, 2010) and (3) Integrated condition rating (Elsawah, Guerrero, & Moselhi, 2014).

5. **Conflicting perspectives:** The integrated asset management could be taken from both the community-based perspective or the municipal perspective with changing objectives (Khan, Moselhi, & Zayed, 2015).

According to (InfraGuide 2003a, b,c, 2006), only few municipalities have an integrated asset management plan for their road, sewer and water systems. While many municipalities have implemented pavement management systems, most do not have asset management plans for their water and sewer systems. Typically, these systems have a longer service life than roads, but their condition is usually not visible and needs complicated technologies to do condition assessment. The (InfraGuide 2003a) outlined an integrated approach to assessment and evaluation of 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. The (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 assessment and evaluation of municipal infrastructure. As well, it mentioned that the asset management 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 drivers of decision making. Moreover, integrating the decision making across the multiple levels of municipal, city, province, and federal decision-making, funding, and policies is not thoroughly investigated yet.
Overview

This book focused on developing an integration approach for two co-located corridor assets (roads and water networks), to explore the integration benefits from both the long-term financial planning and level of service perspectives. The book was applied on 20 sections, all-inclusive roads, and water inventory information appended in the inventory, with different ranges of lengths of sections (roads and water), different types of pipe materials, different pipe diameters, different installation years and different physical, this makes the system flexible and accounting for variability of data sets and sections. The distribution of condition states was assumed to follow the same pattern of the latest The Canadian Infrastructure Report Card (CIRC) issued in 2016 (CIRC 2016), relatively applied to 20 sections for each asset accordingly, however, the limited number of investigated sections didn’t allow an exact match of the pattern.

Objectives

Infrastructure projects typically carry out tons of challenges and risks throughout the 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 it should be also revised regularly to guarantee delivering an acceptable level of service, meeting the tight and limited budgets constraints, and meeting the tough minimal physical condition constraints. Thus, various alternatives need to be considered to guarantee a maximum use of expenditures and resources and at the same time maximum benefits and optimal resource utilization, along with meeting the extremely tight available budgets.

In this study, we will be focusing on developing a holistic asset management approach that integrates the maintenance and rehabilitation actions that is carried out for both the roads and water networks, considered to be two of the most critical corridor infrastructure assets managed by the municipalities. Accordingly, the research objectives could be best summarized as follows:

1. Build a simple asset inventory framework for the roads and water assets.
2. Develop a thorough inspection/condition assessment module for both the roads and water networks to aid the municipalities in calculating their actual conditions.
3. Establish a KPI’s selection criteria for integrating the corridor infrastructure assets and define the KPI’s selected for integration in this study.

4. Develop deterministic (regression-based) and probabilistic (Markov-based) future deterioration prediction models for the road network.

5. Develop a probabilistic (Weibull-based) future deterioration prediction model for the water network.

6. Utilize a genetic-algorithms “GAs” based optimization engine to solely run each network with an objective of minimizing the life-cycle costs through meeting the various level of service and condition thresholds.

7. Integrate the corridor infrastructure road and water networks together through the pre-defined KPIs’, and define the KPIs’ significance on the network.

8. Utilize a goal-programming (goal optimization) approach in choosing the optimal maintenance and rehabilitation plan, either integration or sole maintenance, that minimizes the overall deviations from the pre-defined KPIs’ goals.

**Organization**

This book is organized and distributed into 9 chapters as follows:

**Chapter 1 – Introduction:** Chapter 1 provides a generic background about the book and highlights on the focal challenges that are facing the municipalities’ while managing their infrastructure assets.

**Chapter 2 – Background:** Chapter 2 highlights on the very recent publications representing the state-of-the-art in the area of integrated infrastructure management. It provides an overview of the different streamlines and perspectives that were receiving attention recently.

**Chapter 3 – Research Methodology:** Chapter 3 provides an overview of the research methodology, stating the tools and techniques/methods used to meet the pre-defined objectives.

**Chapter 4 – Research Framework:** Chapter 4 enlightens the proposed research framework for the municipalities to integrate the maintenance and rehabilitation actions in order to meet their goals, either acceptable level of service or minimum acceptable condition threshold, with the minimal life-cycle costs.
Chapter 5 – Pavement Management System: Chapter 5 focuses on the road networks, as the 1st corridor asset considered under the study, and deeply discuss the silo framework developed for reaching the pre-defined asset-based KPIs’.

Chapter 6 – Water Management System: Chapter 6 focuses on the water networks, as the 2nd corridor asset considered under the study, and deeply discuss the silo framework developed for reaching the pre-defined asset-based KPIs’.

Chapter 7 – Integrated Management System: Chapter 7 discussed the KPIs’ selection criteria, the selected KPIs’, and the integration framework to amalgamate the two corridor assets under study, through pre-defined KPIs’, and result in an optimum maintenance and rehabilitation plan that recommends the best time and maintenance strategy that meets the combined KPIs’ goals for the two assets collectively.

Chapter 8 – Validation and Analysis: Chapter 8 verifies the proposed integration framework on a case study to show the reimbursements of integrating the maintenance and rehabilitation actions versus silo maintenance and rehabilitation system plans. Besides, it discusses the results of the silo and integrated approach to optimization and conducts some analysis (i.e. sensitivity analysis).

Chapter 9 – Findings and Conclusions: Chapter 9 concludes the book with some key findings and contributions to the body of knowledge the authors came up with throughout the book.
CHAPTER 2 - BACKGROUND

This chapter highlights on the very recent publications representing the state-of-the-art in the area of integrated infrastructure management. It provides an overview of the different streamlines and perspectives that were receiving attention recently. The following four journal publications by are summarized in the following sections: (1) Coordination of urban infrastructure reconstruction projects, (2) Integrated Risk-Assessment Framework for Municipal Infrastructure, (3) Integrated rehabilitation planning of urban infrastructure systems using a street section priority model Optimized municipal right-of-way capital improvement planning and (4) Optimized Holistic Municipal Right-of-Way Capital Improvement Planning using the criticality and physical state.

Coordinated Infrastructure Rehabilitation (Osman, 2015)

Introduction

The need for Asset Management (AM) adoption has been strengthened by the plethora infrastructure problems (i.e. Sudden system failures), as well as the deteriorating Level of Service (LOS), which in return placed tremendous pressure on the governments; where they need 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, the world is undergoing the largest wave of urban growth; wherein 2008, more than 50% of the world’s population were living in towns and cities and is expected to exponentially swell throughout the upcoming years.

Accordingly, Asset managers need to utilize a holistic approach in their decision-making process rather than the typical one. However, they have to consider the fact that dealing with distinctive systems with different useful lives, deteriorating mechanisms, maintenance schedule, and rehabilitation/replacement method is perplexing and requires huge efforts to persuade reluctant to share entities to integrate their information and coordination their actions together. Proper coordination of the infrastructure intervention activities will result in the following:

1. Minimized community disruption
2. Minimized Life-Cycle Costs (LCC) and maximized LOS across various infrastructure systems rather than making sub-optimal decisions for each system separately
3. Much more efficient tendering for the construction works
4. Attractive for more contractors due to the ability to package construction works in larger projects, especially for small communities

Besides the coordination of intervention activities, the dependency and interdependency relationships between infrastructure systems represent the broader notion. The interdependency refers to the bi-directional relationship between the infrastructure systems where it could be classified to functional and spatial depending on the operational dependency and the proximity between systems respectively. However, others classified the interdependency to physical, cyber, geographical and logical.

In spite the fact that plentiful modeling computations approaches have been utilized in the last decade, some limitations have been noticed as follows:

1. The propagation of the system disruption hasn’t been appropriately considered as the vast majority of the research was focusing on the operation phase.
2. The dimension of “Time” wasn’t considered as a key aspect that influences the AM intervention decisions.
3. The lack of focus on holistic-based intervention for interdependent co-located infrastructure systems (i.e. roads, water and sewer).

Objectives

The paper aims at developing a framework for temporal coordination for co-located infrastructure systems taking the economic (LCC), risk and LOS triggers into consideration while planning for systems’ interventions. The trade-off between delaying and bringing forward the intervention activities has been conducted using “Goal Optimization” approach based on the objectives/constraints of other co-located systems.
Framework

*Single-system heuristic*

The framework advocates the transition from an “asset stewardship” approach, which is condition and cost centric, to an “asset serviceability” approach, which considers the cost, LOS, and risk exposure. Accordingly, there is an optimal time for intervention based on the cost, LOS and risk exposure considerations, indicated as TIC, TIL and TIR respectively, as shown in Figure 1. However, in most cases, TIC≠TIL≠TIR, which obligates the asset managers to undertake a thorough trade-off analysis between the three objectives. In addition, it has been observed that small deviations around the long-living infrastructure systems’ TIC have a negligible effect on the conquered objective. Thus, this seconds the asset serviceability approach with the fact that the optimal intervention strategies are governed by the LOS and risk exposure not the condition and cost.

![Figure 1: Optimal interventions time for LCC, LOS and risk for a single infrastructure system](image)

In the lights of the above-mentioned objectives, the framework assumes three possible intervention coordination scenarios, which opts at including both the temporal grouping impact and public disruption due to the construction works, as follows:

1. **No Coordination**: The intervention time is optimally chosen for each infrastructure separately resulting in the maximum number of public disruptions (i.e. n number of disruptions for n number of infrastructure systems).
2. **Partial Coordination**: The intervention time for at least two infrastructure systems is equal while the intervention time for the other infrastructure systems is not (i.e. d number of disruptions for n number of infrastructure systems; where 1<d<n).
3. **Full Coordination:** The intervention time for all the infrastructure systems is taken equal resulting in the least number of public disruptions (i.e. 1 disruption for n number of infrastructure systems).

The challenge for the asset managers remains with the need for trade-off intervention triggers for LCC, LOS and risk. Three cases, with a total of six possibilities, are enumerated in Table 2. In cases B and C, the asset manager is faced with a trade-off between two objectives (LOS and risk). Thus, the cost premium (CP) should be computed as the difference between the LCC at the time of intervention and the optimal time of intervention (TIC) as shown in Equation 1. However, for cases A and B, the community will receive an LOS value-added (LVA), which is the difference between the LOS at the time of intervention and the minimum acceptable LOS (TIL) as revealed in Equation 2. Finally, for cases A and C, the community will receive a risk value-added (RVA), which is the difference between the risk exposure at the time of interventions and the maximum acceptable risk threshold (TIR) as highlighted in Equation 3.

**Table 2:** Optimal intervention time cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Conditions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>Cost first</td>
<td>( TIC_i \leq TIR_i \leq \text{TIL}_i ) or ( \text{TIC}_i \leq \text{TIL}_i \leq TIR_i )</td>
</tr>
<tr>
<td>(B)</td>
<td>Risk first</td>
<td>( TIR_i \leq TIC_i \leq \text{TIL}_i ) or ( \text{TIR}_i \leq \text{TIL}_i \leq TIC_i )</td>
</tr>
<tr>
<td>(C)</td>
<td>LOS first</td>
<td>( \text{TIL}_i \leq TIC_i \leq \text{TIR}_i ) or ( \text{TIL}_i \leq TIR_i \leq TIC_i )</td>
</tr>
</tbody>
</table>

\[
CP_i = C_i(TI_i) - C_i(TIC_i) \quad \text{Equation 1: Cost premium (CP)}
\]

\[
LVA_i = L_i(TI_i) - C_i(TIL_i) \quad \text{Equation 2: LOS Value-Added (LVA)}
\]

\[
RVA_i = R_i(TI_i) - C_i(TIR_i) \quad \text{Equation 3: Risk Value-Added (RVA)}
\]
Multiple systems coordination

The sizeable search spectrum for the multiple systems initiates the need for an optimization approach, which make the application of the heuristic approach no longer valid. Imagine n adjacent infrastructure systems with an analysis window of t year, the number of possible solutions will be $n \times n^t$. Given the fact that the framework is dealing with three different objectives, goal optimization has been used to structure the optimization problem with an objective of minimizing any deviations from the set goals. The reasons why the goal optimization, sometime referred to as “Goal Programming (GP)”, is its’ capability in handling ample conflicting goals. In the GP terminology, a set of goals (G_i); where i = 1, 2, 3, ..., n, need to be simultaneously achieved. As shown in Equation 4, the objective function is formulated to minimize the sum of deviations from predetermined goal values.

$$\text{Min}(Z) = \sum_{i=1}^{n} w_{kl} p_k (d_i^- + d_i^+)$$  \text{Equation 4: GP objective function}

In the pre-emptive GP formulation, $d_i$ are referred to as “Deviational Variables”. In case the goals have different priorities, “Priority Factor ($p_k$)” is utilized for ranking purposes, as it ensures that the next objective cannot be considered unless all deviations from goals of higher priority have been fully eliminated. The deviational variables within each priority level are differentiated using the “Differential Weights ($w_{kl}$)”, to account for different levels of importance among the conflicting goals. One of the interesting characteristics of GP is that there are no decision variables in the objective function. However, the decision variables are linked with the objective function through “Goal Constraints”, which makes it a priori multi-objective optimization method; where objectives’ preferences need to be defined prior to the solution.

For the case of multiple infrastructure systems with multiple objectives, a percentile ranking approach is utilized, due to the fact of the objectives conflicting units, through computing the goal deviation percentage rather than the absolute deviation. The goals could be summarized as follows:

1. Deviation below the minimum acceptable LOS (Equation 5)
2. Deviation above a risk threshold (Equation 6)
3. Deviation below an LVA (Equation 7)
4. Deviation below an RVA (Equation 8)
5. Overall CP due to the deviation from the minimum possible LCC for all infrastructure systems (Equation 9)

\[ d_1^- = \frac{\sum_{i=1}^{n} L_i(TIL_i) - L_i(t)}{\sum_{i=1}^{n} L_i(TIL_i)} \quad \text{Equation 5: LOS deviation} \]

\[ d_2^+ = \frac{\sum_{i=1}^{n} R_i(t) - R_i(TIR_i)}{\sum_{i=1}^{n} R_i(TIR_i)} \quad \text{Equation 6: Risk threshold deviation} \]

\[ d_3^- = \frac{\sum_{i=1}^{n} LVA_i - L_i(t)}{\sum_{i=1}^{n} LVA_i} \quad \text{Equation 7: LVA deviation} \]

\[ d_4^- = \frac{\sum_{i=1}^{n} RVA_i - R_i(t)}{\sum_{i=1}^{n} RVA_i} \quad \text{Equation 8: RVA deviation} \]

\[ d_5^+ = \frac{\sum_{i=1}^{n} C_i(t) - C_i(TIC)}{\sum_{i=1}^{n} C_i(TIC)} \quad \text{Equation 9: CP (LCC deviation)} \]

The aforementioned positive and negative deviation variables are summed together using non-pre-emptive goal optimization through assigning differential weights to each deviation variable to represent the conflicting objectives importance as shown in Equation 10.

\[ \text{Min}(Z) = w_1 d_1^- + w_2 d_2^+ + w_3 d_3^- + w_4 d_4^- + w_5 d_5^+ \quad \text{Equation 10: GP objective function} \]

**Intervention impacts’ quantification**

In order to better understand the advantages of temporal coordination, quantifying the impact of disruption from both the time and cost perspective has been conducted. Thus, the model considered the disruption impact, through a number of performance measures, as a function of the following:

**Intervention duration**

Coordinating infrastructure construction activities results in a minimized overall time for the coordinated project compared to the no coordination scenario. These time savings are due to the following: (1) The possibility of undertaking parallel activities rather than in series (i.e. road resurfacing and reinstating sewer laterals), and (2) Common activities among the infrastructure systems can be shared (i.e. traffic control systems, residents’ notification, etc.). Accordingly, the framework introduced two types of durations “Independent Duration (ID)” and “Common Duration (CD)”. As shown in Figure 2, ID\(_i\) represents the tasks for a certain infrastructure system \(i\) in which no other tasks can take place concurrently (i.e. new sewer manholes installation). On the other hand, the CD\(_{ij}\) represents the activities that can take place
among any two-infrastructure systems i and j concurrently (i.e. excavation for entrance and exit pits for water and sewer rehabilitation). Similarly, CD_{ijk} represents the common duration for construction activities in the three infrastructure systems i, j and k (i.e. site reinstatement works). As a result, the “Total Duration (TD)” for all the construction activities for system i, excluding the interruptions, could be computed as shown in Equation 11. In addition, the “Total Duration for the entire Project (PD)”, assuming full coordination among the three infrastructure systems, could be calculated as exposed in Equation 12. Finally, a “Project Coordination Ratio (PCR)”, which represents the time savings in the project execution due to applying the full coordination scenario, is computed as shown in Equation 13. The greater the PCR, the smaller the time savings will be achieved and vice versa.

![Temporal overlap during coordinated construction](image)

**Figure 2:** Temporal overlap during coordinated construction

$$TD_i = ID_i + CD_{ijk} \sum_{i=1}^{n_s} CD_{ij}(i \neq j)$$  \hspace{1cm} \text{Equation 11: Total activities Duration (TD)}

$$PD = CD_{ijk} + \sum_{i=1}^{n_s} \sum_{j=1}^{n_s} CD_{ij}(i \neq j) + \sum_{i=1}^{n_s} ID_i$$  \hspace{1cm} \text{Equation 12: Entire Project total Duration (PD)}

$$PCR = \frac{PD}{\sum_{i=1}^{n_s} TD_i}$$  \hspace{1cm} \text{Equation 13: Project Coordination Ratio (PCR)}

**Spatial intervention extent**

The spatial overlap represents the amount of space that needs to be occupied by the construction works. In the “No coordination” scenario, the total amount of space needed will be the summation of the three infrastructure systems ($A_R, A_S, A_W$). However, the total area (AP) in the “Full coordination” scenario should be less than the summation of the space needed in case of no coordination scenario, due to the spatial overlap among the construction activities, as highlighted in 3. Accordingly, the framework calculates the “Disruption Impact Factor (DIF)” for various coordination scenarios are calculated as shown in Equations 14 and 15. DIF
is similar to the concept of lane renting in highway construction contracts as a gesture to expedite the highway reconstruction and minimize the amount of space and time occupied by the contractors. Finally, a “Spatio-Temporal Improvement Factor (STIF)” is computed, as shown in Equation 16, to consider the impact of both the time and space savings during a coordinated reconstruction project. The higher the factor, the more time and space savings are accomplished and vice versa.

**Figure 3: Spatial overlap during coordinated construction**

\[
DIF_{NC} = \sum_{i=1}^{n_s} TD_i \times A_i \quad \text{Equation 14: Disruption Impact Factor (DIF) for no coordination scenario}
\]

\[
DIF_{FC} = PD \times AP \quad \text{Equation 15: Disruption Impact Factor (DIF) for full coordination scenario}
\]

\[
STIF = \frac{DIF_{NC}}{DIF_{FC}} \quad \text{Equation 16: Spatio-Temporal Improvement Factor (STIF)}
\]

**Intervention efficiency and effectiveness**

Anecdotal evidence and common logic suggest that non-coordinated construction activities cause more discomfort and disruption to the surrounding communities compared to spaced construction activities. In the lights of this negative impacts, many road agencies have implemented some measures such as; pavement moratoriums and pavement cutting fees to discourage excavating within 3-6 years of a road reconstruction. Subsequently, the concept of intervention efficiency has been introduced to consider the amount of time spent on disruptive activities as a percentage of the “Total Disruption Time (TDT)” until all the infrastructure systems are restored. In the no coordination scenario, an “Inter-Disruption Time (IDT)” takes place between the end of one intervention and the start of the second one, as shown in Figure 4. The nuisance to surrounding communities’ increases as the IDT decreases because of the ample disruptions within a small time frame. Therefore, the “Intervention Efficiency Factor
The “Intervention Effectiveness Factor (IFF)” considers the amount of time spent without any disruptive intervention activities taking place once the intervention program is fully completed, which is dependent on the time of the next major intervention, as shown in Equation 18. The time for the next major intervention depends on the following: (1) Deterioration rate of the infrastructure system, (2) Effectiveness of the infrastructure rehabilitation (i.e. improvements in the condition state), and (3) Presence of any other overriding intervention triggers such as; risk and LOS. Likewise, the larger IFF values represent superior effectiveness and vice versa.

\[ IEF = 1 - \sum_{i=1}^{n_s} \frac{T_D_i}{T_D} \]  
Equation 17: Intervention Efficiency Factor (IEF)

\[ IFF = 1 - \frac{T_D}{T_D + ROT} \]  
Equation 18: Intervention Effectiveness Factor (IFF)

Assumptions/limitations

1. The same extent of disruption per time is assumed for all the intervention types, which doesn’t account for some trenchless technologies used for buried infrastructures.

2. The intervention results in the asset returning back to a pristine condition state, neglecting the fact that many pavement intervention types (i.e. non-structural overlay, crack and fog seals for specific distresses) don’t necessarily result in an asset in “Excellent” condition state.