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Optimized phased planning for dynamic rehabilitation of integrated municipal infrastructure

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ABSTRACT

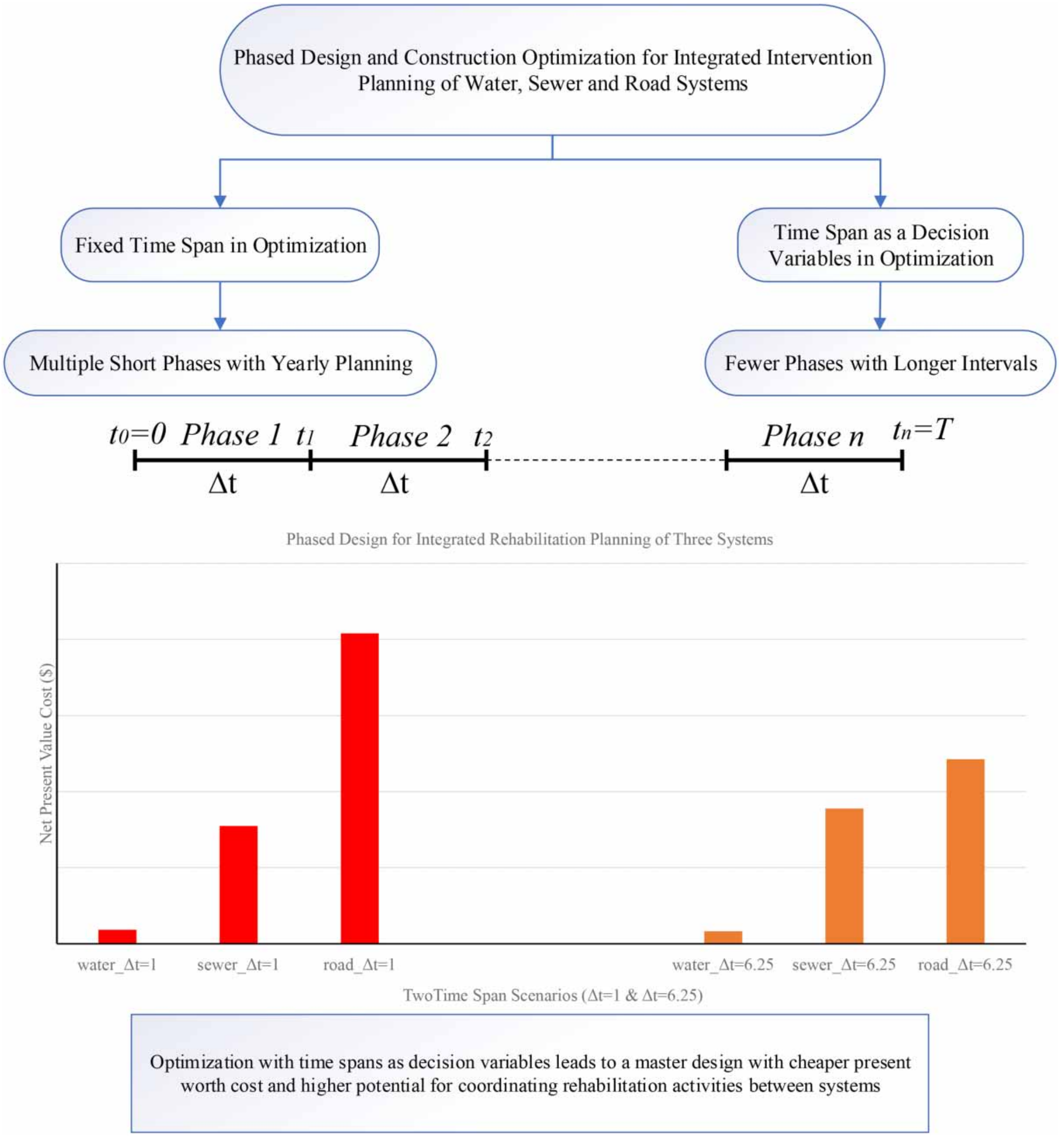
Phased planning for municipal infrastructure is based on the time-dependent status of multiple networks, which is in contrast to the traditional approach, where one-phase construction and a single status are considered for planning system activities. This study integrates and optimizes the corridor-wise intervention planning of water, sewer, and road networks where the number of equally long phases and intervention decisions are among the decision variables showing the extent to which phase number optimization can impact the cost and coordination of the interventions in interdependent systems. Optimizing the phase number for municipal infrastructure optimization within an evolutionary algorithm is a challenging task due to the evolutionary recombination between numerous planning solutions with different decision variable lengths. A multi-phase design and construction approach is developed for the rehabilitation of the system in a real case study in Montreal, Canada. The study involves 20 corridors in which a street section is co-located with water and sewer pipes. A metaheuristic single-objective optimization engine is employed to minimize the total net present value of intervention plan costs for the whole integrated system. The results show that phased optimization could bring about a 25% cost saving for the rehabilitation master plan and coordinated multi-systems intervention activities.

Key words: deterioration, intervention activities, metaheuristic optimization, phasing design and construction, renewing co-located urban infrastructure systems

HIGHLIGHTS

- Phasing design and construction in water, road, and sewer systems' rehabilitation planning.
- Spatially interdependent urban infrastructures.
- Dynamic intervention planning and construction scheduling.
- Deterioration rates for pipes and pavements.
- Optimization and coordination scenarios for different networks' intervention activities.

GRAPHICAL ABSTRACT



NOMENCLATURE

α	Scale factor
β	Shape parameter
Δt	Time span
γ	Location parameter
Γ	Rehabilitation program
A	Area of corridor
$C_{F_{np}}$	Percentage full coordination for the scenario of n_p for a, b, and c systems
$C_{p_{np}}$	Percentage partial coordination for the scenario of n_p
C_{det}	Cost of leakage detection
C_{rep}	Replacement cost of pipes
C_{repair}	Repair cost
C_{res}	Resurfacing cost
C_{sur}	Surface overlay cost
$\mathrm{Cost}_{i,s,p}$	Cost of corridor i for the system s in phase p

D	Diameter
$HR_{\min,i,s}$	Health reliability threshold of element i of the system s
HR_{pipe_i,t_j}	Health reliability of pipe i at the time j
HR_{pipe_i,t_p}	Health reliability of pipe i at the pristine time
HR_{road_i,t_j}	Health reliability of pipe i at the time j
k	Leakage emitter value
L_c	Length of corridor
n_c	Number of corridors
n_p	Number of phases
n_s	Number of systems
p	Phase indicator
r	Type of intervention
R	Discount rate
s	System indicator
T	Planning horizon year
U_{rep}	Unit cost for pipe replacement
U_{res}	Unit cost for road resurfacing
U_{sur}	Unit cost for road surface overlay
w	Number of weeks
$X_{i,a,p}$	Intervention decision in corridor i for the system a in phase p
$Y_{i,b,k}$	Rehabilitation decision in corridor i for the system b in phase p
$Z_{i,c,k}$	Intervention decision in corridor i for the system c in phase p

1. INTRODUCTION

The well-being and economic growth of societies worldwide are significantly influenced by urban infrastructure systems. As an example, an investment of $1 billion in infrastructure not only creates 16,700 jobs but also enhances the gross domestic product (GDP) by $1.6 billion, as reported by Finance Canada. However, these systems are continuously exposed to degradation due to aging, excessive use, and natural hazards (De Iuliis *et al.* 2019; Liu & Song 2020), leading to deteriorated infrastructures in numerous municipalities globally. A notable example is the state of Canada's municipal infrastructures, where one-third is categorized as being in fair, poor, or failing condition (Abu-Samra *et al.* 2018). Consequently, comprehensive renewal plans, encompassing repair and rehabilitation interventions, become imperative to effectively and economically preserve the value and performance of infrastructure assets.

Both qualitative and quantitative approaches for solving engineering and environmental problems can be found in the literature. Among qualitative approaches, observation methods, surveys, questionnaires, and various planning documents are essential for solving a problem (Sukri *et al.* 2023). Quantitative approaches use complex mathematical models including differential equations, artificial intelligence, and optimization algorithms (Feng *et al.* 2022; Bachtiar *et al.* 2023; Khalaf *et al.* 2023; Moayedi *et al.* 2024). The focus of the current study is on using a quantitative approach for solving complex intervention planning of urban infrastructure systems.

Over the past two decades, attention has significantly increased toward system thinking approaches for addressing asset management challenges, including rehabilitation, maintenance, and operation planning (Kerwin & Adey 2021; Okwori *et al.* 2021; Daulat *et al.* 2022). These approaches involve the strategic coordination and integration of infrastructural activities across various interdependent systems to achieve cost savings, sustainability, and reliability. Capital renewal plans pose a complex, dynamic, and multi-criteria decision-making challenge for asset managers. Researchers have frequently turned to optimization algorithms as preferred tools for addressing asset-related issues (Amador & Magnuson 2011; Rashedi & Hegazy 2015; Rashedi & Hegazy 2016; Van Dijk & Hendrix 2016; Alinizzi *et al.* 2018). The dynamic nature of these problems, where infrastructure properties such as physical states and design factors (like customer demands) evolve over time, calls for the use of dynamic optimization approaches, such as dynamic programming. Consequently, this work developed a phased design and construction approach that employs optimization models, offering a more adaptive solution compared with static approaches.

Static conventional planning involves the creation of a master plan for the rehabilitation and replacement of urban infrastructures based on the network performance at the end of the planning horizon. It is typically assumed that the generated plan is constructed and designed in a single phase. However, it has become evident that this approach does not align well with practical issues and uncertainties including network developments and population growth. Instead, the design period is often divided into multiple phases, each with a specific duration. Planning and construction should then be carried out through multiple planning criteria (e.g., physical health condition of elements such as pipes and asphalts' deterioration statuses at the end of every phase) and equally spaced phases, as illustrated in Figure 1. Table 1 presents examples from the literature that have employed the multi-phase design and construction approaches to address asset management problems.

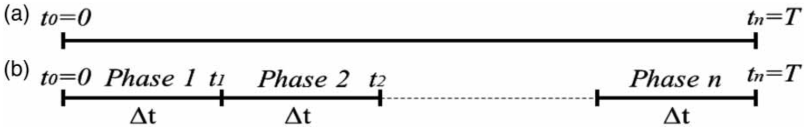


Figure 1 | (a) Traditional approach and (b) phased approach for the design and construction periods.

Table 1 | Studies proposing the multi-phase approach in multi-utility and single-utility optimal intervention planning of interdependent urban infrastructure systems

Reference	Asset systems	Problem type	Objectives	Planning horizon year	Interval duration (years)	Interval duration is variant in optimization?	
						Yes	No
Amador & Magnuson (2011)	Road, sewer, storm, water	Maintenance and rehabilitation	Maximizing pipe and pavement condition	50	1		√
Carey & Lueke (2013)	Road, sewer, water	Maintenance, rehabilitation, and renovation	Maximizing condition of system components	5	1		√
Creaco *et al.* (2014)	Water	Design, upgrade, and expansion	Maximizing minimum-pressure surplus and minimizing cost	100	25		√
Rashedi & Hegazy (2015)	Buildings	Repair, rehabilitation, or replacement	Minimizing network deterioration	5	1		√
Creaco *et al.* (2015)	Water	Design and expansion	Maximizing minimum-pressure surplus and minimizing cost	100	20		√
Van Dijk & Hendrix (2016)	Water	Replacement	Minimizing the replacement and pipe failure costs	30	1		√
Alinizzi *et al.* (2018)	Road and water	Operation and maintenance	Minimizing the intervention cost and maximizing its benefits	15	1		√
Abu-Samra *et al.* (2018)	Water and road	Rehabilitation and replacement	Minimizing and intervention cost	25	1		√
Minaei *et al.* (2019)	Water	Design and rehabilitation	Maximizing reliability and minimizing cost	25	5		√
Minaei *et al.* (2020)	Water	Design, upgrade, expansion	Maximizing reliability and minimizing cost	60	20		√
Kammouh *et al.* (2021)	Highway, railway, water	Maintenance, removal and upgrading	Minimizing operator and social costs	18	1		√
Dell'Aira *et al.* (2021)	Water	Rehabilitation and design	Minimizing cost and maximizing resilience	100	25		√
Pachos *et al.* (2022)	Water	Leakage control, pipe repair, water efficiency, and metering	Minimizing capital and operating costs, maximizing system service resilience, reliability, and desired level	50	5		√
Minaei *et al.* (2023)	Water, sewer, road	Rehabilitation and replacement	Minimizing cost and cascading failure chance, and maximizing hydraulic reliability	25	5		√

Such approaches can be applied to systems when the focus is either on one system (single utility) or more than one system (multi-utilities).

As indicated in Table 1, researchers have used the phased design and construction approach in addressing both multi-utility and single-utility asset management problems. Nevertheless, it is noteworthy that the phase duration has consistently been treated as a fixed parameter in optimization problems and typically ranges from 1 to 25 years.

Looking at the different number of phases and their durations found in the literature, the question of whether the number of phases (and consequently their duration) is suitable to be treated as a decision variable to produce optimal master plans arises, and furthermore, what could be their role in the rehabilitation strategies for the renewal plans? Is it better to upgrade the networks in many short phases by implementing minor rehabilitation actions (e.g., leakage repair for pipes and surface overlay of pavements) or a few longer phases by major rehabilitation actions (pipe replacement or resurfacing of pavements)? This study aims to explore this research gap in the literature by solving a real-world rehabilitation problem in Montreal City, Canada, for three interdependent urban systems, which are the water, sewer, and road networks. The case study was first presented by Abu-Samra *et al.* (2020). They addressed a rehabilitation problem encompassing water, sewer, and road networks within an asset management framework. Our work uses their case study with a minor change through reconstructing water leakages in pipes. The approach will demonstrate the benefits of phased design optimization when applying minor and major rehabilitation actions on the three interdependent networks. Abu-Samra *et al.* (2020) work's approach involved a phased planning method, dividing a 25-year planning horizon into 25 one-year phases. The present study formulates a dynamic optimization programming model, treating the phase duration as a decision variable, for the rehabilitation planning of interdependent urban infrastructures. Results from the new methodology are compared with those in the referenced work, resulting from fixed phase planning, to understand the role of phase duration in achieving optimal results.

The primary contribution of this paper is the introduction of variable phase numbers within the framework of phased intervention planning for three urban infrastructure systems. This dynamic approach addresses a significant gap in the literature concerning the integrated management of interdependent infrastructure systems. Our method represents a novel advancement in phased planning optimization, enhancing the phased design and construction strategy for interdependent systems. Additionally, the genetic algorithm employed has been specifically developed to manage three-dimensional solutions of varying sizes within the mating pool.

2. METHODOLOGY

2.1. Deterioration, intervention activities, and cost

The three systems of water, sewer, and road networks (WN, SN, and RN, respectively) include elements with various service life periods. Figure 2 shows the conceptual deterioration rates for pipes and pavements. As observed, these elements could function as long as they meet the health-specified threshold; hence, the timing of the rehabilitation should be optimized to keep them consistently in good health status.

To model the deterioration patterns of the pipes and pavements, the following equations are used (Abu-Samra *et al.* 2020):

$$\mathrm{HR}_{\mathrm{pipe}_i,t_j} = \mathrm{HR}_{\mathrm{pipe}_i,t_p} * e^{-(((\mathrm{Age}_{\mathrm{pipe}_i,t_j}-\gamma)/\alpha))^{\beta}} \tag{1}$$

$$\mathrm{HR}_{\mathrm{road}_i,t_j} = [0.033 * (\mathrm{Age}_{\mathrm{road}_i,t_j})] - [2.688 * \mathrm{Age}_{\mathrm{road}_i,t_j}] + \mathrm{HR}_{\mathrm{road}_i,t_0} \tag{2}$$

Equation (1) represents the Weibull functional form where $\mathrm{HR}_{\mathrm{pipe}_i,t_j}$ represents the health reliability of pipe i, $i = 1{:}n_c$ where n_c is the number of corridors (every corridor represents a segment in the network including a WN pipe beside an SN pipe on which there is an RN pavement) at the times of t_j, $j = 0{:}\,tn$ (shown in Figure 1); $\mathrm{HR}_{\mathrm{pipe}_i,t_p}$ stands for the health reliability of pipe i at the pristine time (usually considered 100%); $\mathrm{Age}_{\mathrm{pipe}_i,t_j}$ is the age of pipe i at the time t_j; α and β are the scale factors (years, defined based on the service life span of pipes depending on the type of materials which could be PVC, cast iron, cement, etc.) and shape parameter (>0); the third parameter of Weibull probability distribution, location parameter (γ) is equal to 0 in this study.

Equation (2) represents a nonlinear deterioration mathematical model where $\mathrm{HR}_{\mathrm{road}_i,t_j}$ stands for the health reliability of road i at the time t_j; $\mathrm{Age}_{\mathrm{road}_i,t_j}$ is the age of road i at the time t_j (the reference is year 0); and $\mathrm{HR}_{\mathrm{road}_i,t_0}$ is the health reliability of road i at the year 0.

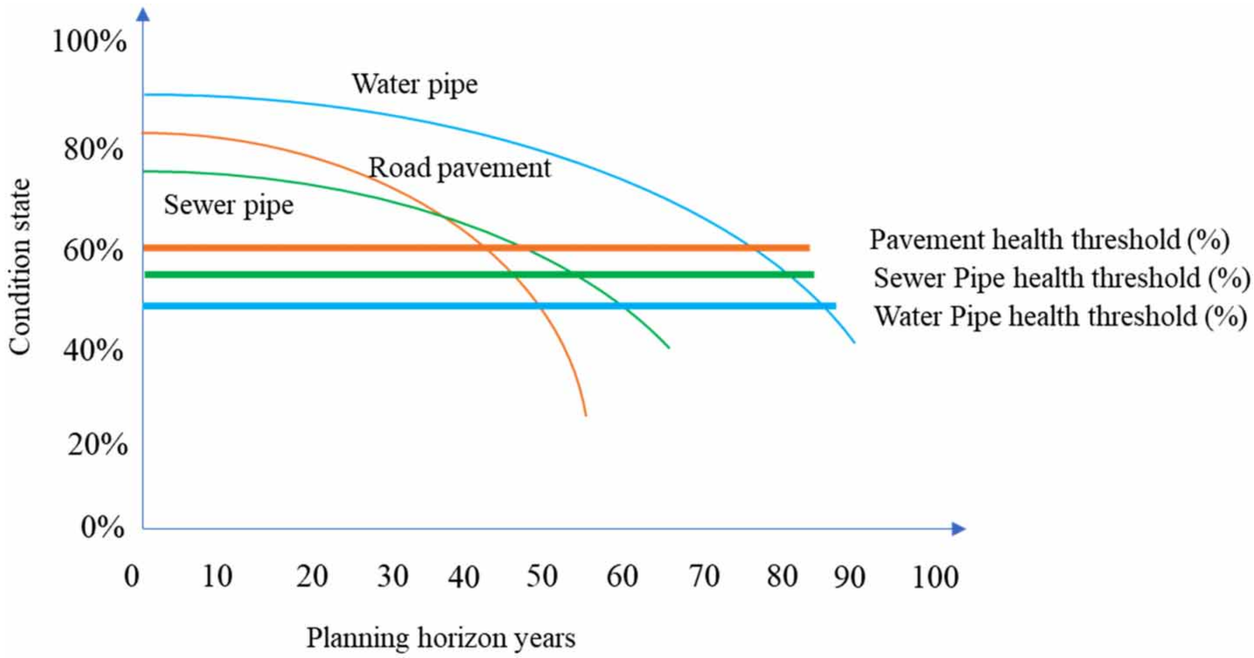


Figure 2 | Deterioration graphs of a pipe and pavement segment over time.

Based on the health condition of every element at a time, different decisions for interventions can be made. The current health condition of the element could be satisfactory when its deterioration over a target phase does not cause a complete failure (health reliability < threshold); hence, a decision for no intervention could be made; otherwise, rehabilitation activities should be pursued. In the current study, the interventions on the elements could be minor or major actions shown in Table 2. Every action has its impact value for upgrading the physical status of pipes and road pavements. Health improvements after minor actions depend on the current condition of the elements. For example, repairing cracks in water pipes with current reliability of 90% would not give the same improvement if the current reliability is 10%. However, for the sake of simplicity, it is assumed to be 10% for minor interventions regardless of the initial reliability and 100% for major interventions (Abu-Samra *et al.* 2020).

The mathematical cost models for calculating the leakage repair and pipe replacement costs are shown by Equations (3) and (4). The mathematical models for calculating the costs of road resurfacing and surface overlay are obtained by Equations (5) and (6). The main assumptions for calculating the costs consist of neglecting other associated costs for every project activity, like site reinstatement, traffic control systems, residence notifications, etc.

$$C_{\text{repair}} = [94 - 0.3 * D(\text{mm}) + 0.01 * D(\text{mm})^2] * [1.5 + 0.11 * \log_{10}(k)] \tag{3}$$

$$C_{\text{rep}} = U_{\text{rep}} * L_{\text{c}} \tag{4}$$

$$C_{\text{res}} = U_{\text{res}} * A(\text{m}^2) \tag{5}$$

$$C_{\text{sur}} = U_{\text{sur}} * A(\text{m}^2) \tag{6}$$

Table 2 | Intervention actions and their impacts on the health reliability of the elements for the three types of assets: water, sewer, and road

Asset type	Major	Reliability improvement (%)	Minor	Reliability improvement (%)
Road	Resurfacing	100	Surface overlay	10
Water	Pipe replacement	100	Leaks repair	10
Sewer	Pipe replacement	100	Leaks repair	10

C_{repair} is the repair cost (in € and rounded to two decimal places) of a leak with emitter value k (with flow in L/s and pressures in meters of piezometric head) in a pipe of diameter D (mm). The cost of leak detection varies inversely with the size of the defect. Smaller leaks will have a higher detection cost, while larger leaks will have a lower detection cost. The cost function for leak repair is captured from Mottahedin *et al.* (2023) are used when the intervention decision for a pipe is repair (minor action) and not replacement (major action), which are given by

$$C_{det} = 2,400 * e^{-28 * k} \tag{7}$$

$$C_{leak} = C_{det} + C_{repair} \tag{8}$$

$$k = k_0 * e^{0.25 \frac{w}{260}} \tag{9}$$

The replacement cost of a pipe will depend on the diameter of the pipe with C_{rep} as the replacement cost in €/m (note: the prices with € in this study are changed to CAN$ with the exchange rate of 1.44 Canada dollar/€), and L_c is the length of corridor in m. As regards the leak, the k value grows with time based on Equation (9), where k_0 is the initial value of the k coefficient and w is the number of weeks since the start of the work. It is assumed that after pipe replacement, the pipe does not leak until the last phase, and therefore, the k value becomes 0; in the repair case, the k value neither gets to 0 nor grows and its value becomes constant over the target phase.

Regarding the road costs, C_{res} and C_{sur} represent the resurfacing and surface overlay costs for road pavements, respectively, where U_{res} and U_{sur} are unit costs for the two mentioned activities in the area of interest (CAN$/m^2), and A is the area of the corridor (m^2).

2.2. Optimization modeling

The current study's optimization problem is formulated with one objective to minimize the net present value of asset rehabilitation costs. The reliability is the surrogate of the physical health conditions of the three systems' elements, which are pipes in the WN and SN, and road pavements in RN. Equations (10)–(12) define the structure of the optimization problem:

$$\text{Minimize}\left(\sum_{s=1}^{n_s}\sum_{p=1}^{n_p}\sum_{i=1}^{n_c}\frac{\text{Cost}_{i,s,p}(\Gamma_{i,s,p}(r))}{(1+R)^{(p-1)\Delta t}}\right) \tag{10}$$

$$r_{i,s,p} \in \{0, 1, 2\},\; i = 1{:}n_c,\; s = 1{:}n_s,\; p = 1{:}n \tag{11}$$

Subject to:

$$\Delta t = \left(\frac{T}{n_p}\right),\; n_p = 1, 2, 3, \;\ldots, T$$

$$\text{Constraint} = \sum_{s=1}^{n_s}\sum_{p=1}^{n_p}\sum_{i=1}^{n_c} f(r_{i,s,p}) = \begin{cases} 1, & \text{HR}_{i,s,p} < \text{HR}_{\min,i,s} \\ 0, & \text{HR}_{i,s,p} \geq \text{HR}_{\min,i,s} \end{cases},\quad i = 1{:}n_c,\; s = 1{:}n_s,\; p = 1{:}n \tag{12}$$

where n_s represents the number of systems (three in this work), s, n_p, p, i, and n_c are the indices for the system, the number of phases, the phase and corridor indicators, and the number of corridors, respectively; $\text{Cost}_{i,p,s}(\Gamma_{i,p,s}(r))$ stands for the cost of rehabilitation program Γ applied on the element of the system s in the corridor i and phase p where r and R are the type of interventions (as explained in Table 2) and the interest rate of the area, respectively; $HR_{i,s,p}$ is the health reliability of element i of the system s in phase p; Δt and T are the duration of an interval and the planning horizon year, respectively; $\text{HR}_{\min,i,s}$ is the health reliability threshold of element i of the system s; $r_{i,s,p}$ represents the type of intervention for the element i of the system s in phase p where it could take on 0 meaning do nothing, 1 meaning minor action, and 2 meaning major action. Accordingly, current solutions for the optimization problem provide optimal decisions for the clients in terms of selecting the best timing and type of intervention activities on every element.

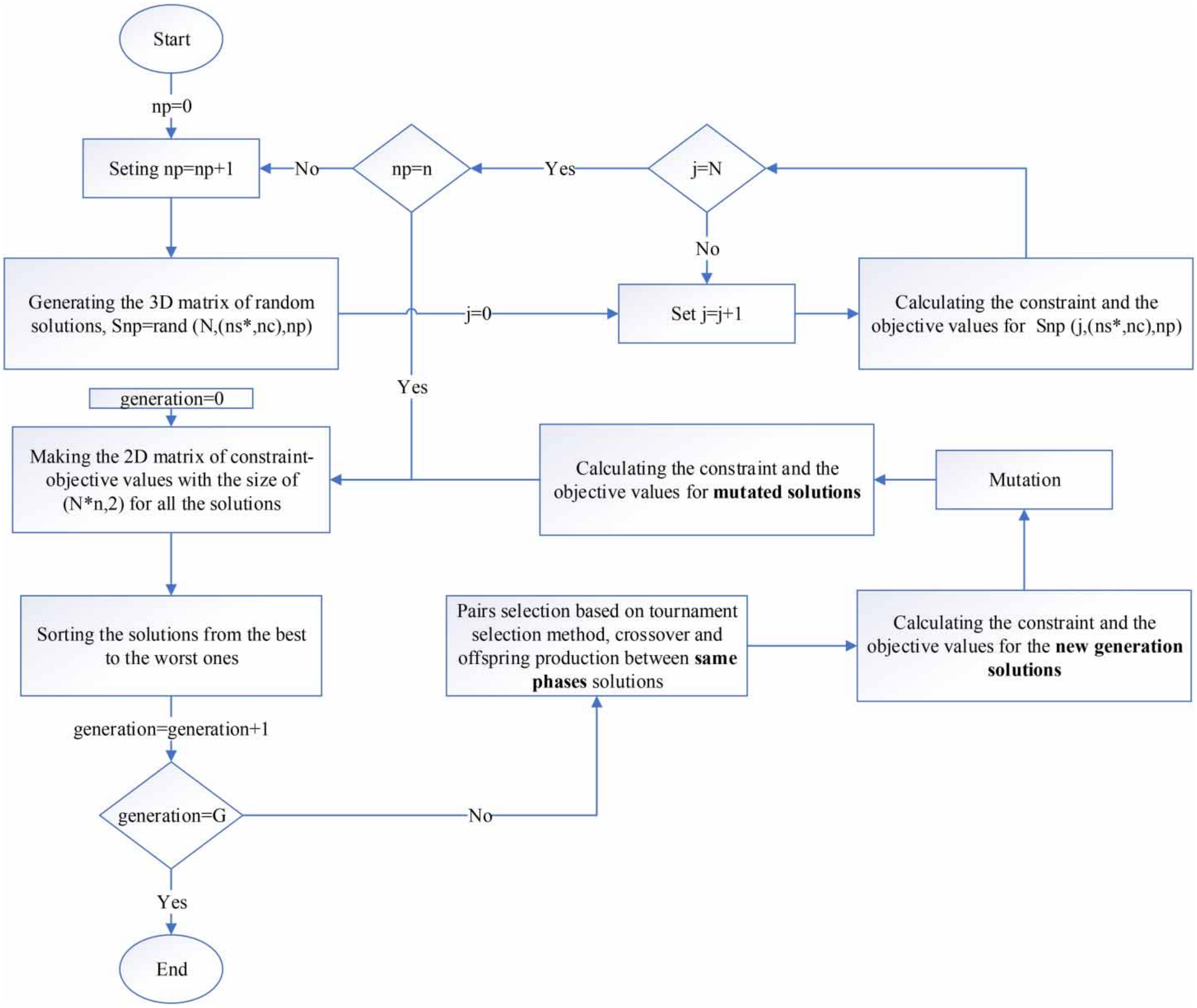


Figure 3 | Process in genetic algorithm optimization for phased design and construction intervention planning of the three systems: water, sewer, and road network where n_p: number of phases, Sn_p: solutions for the n_p scenario, N: population size, n_s: number of systems, n_c: number of corridors, n: maximum number of phases, and G: maximum number of generations.

As regards the constraint of the optimization, except for meeting the health threshold in every phase of the optimization, there is a practical consideration such that in every corridor, once a major action has been taken on an element, the element does not get renovated by the major action again (for example, multiple pipe replacements is not possible over the phases).

In Figure 3, a further explanation of the genetic algorithm optimization with the concept of phased design and construction is shown. The first step involves producing various possible scenarios for the number of phases, ranging from 1 to 25. For each scenario, a random population is generated in the form of a three-dimensional matrix, where the rows, columns, and the third dimension represent the number of solutions, corridors, and phases, respectively. After calculating the objective and constraint values for every solution across all phase scenarios, the pool of initial populations is formed and ready to be processed by the different steps of GA optimization: sorting, pair selection, crossover, and offspring production, followed by calculating new generation solutions. The GA in the current study has been developed in such a way that every solution in the pool can only be mated with another solution having the same number of phases.

2.3. Coordination scenarios

Abu-Samra *et al.* (2020) proposed three approaches for coordinating the infrastructural activities between the three systems of water, sewer, and road. The approach assumes that in every corridor, the intervention activities of different

Table 3 | List of coordination scenarios (*Source:* Abu-Samra *et al.* (2020))

Intervention scenario	Water System	Sewer System	Road System
Full coordination	I	I	I
Partial coordination	I	I	No
	I	No	I
	No	I	I
Conventional (no coordination)	I	No	No
	No	I	No
	No	No	I

Note: I = intervention; and No = no intervention.

systems could be coordinated to minimize the asset management costs by synchronizing activity for different systems (Table 3).

This issue has been investigated in the current study through the equations of (13) and (14):

$$C_{p_{n_p}} = \frac{\sum_{k=1}^{n_p}\sum_{a=1}^{n_s}\sum_{b=1}^{n_s}\bigcup_{i=1}^{n_c}(X_{i,a,p}\cap Y_{i,b,p})}{n_c \times n_p} \quad a = \text{water},\quad b = \text{sewer} \tag{13}$$

$$C_{F_{n_p}} = \frac{\sum_{k=1}^{n_p}\sum_{a=1}^{n_s}\sum_{b=1}^{n_s}\sum_{c=1}^{n_s}\bigcup_{i=1}^{n_c}(X_{i,a,p}\cap Y_{i,b,p}\cap Z_{i,c,p})}{n_c \times n_p} \quad a = \text{water},\quad b = \text{sewer},\quad c = \text{road} \tag{14}$$

where $C_{p_{n_p}}$ is the percentage of partial coordination for the scenario of n_p; a and b represent two different systems (e.g., water and sewer); $X_{i,a,p}$ stands for the intervention decision in the corridor i which could be nothing, minor or major action for the system a in phase p; $Y_{i,b,k}$ stands for the rehabilitation decision in corridor i for the system b in phase p; $X_{i,a,p} \cap Y_{i,b,p}$ could be either 1, if there are common intervention decisions for both systems a and b, or 0 if there is no intervention decision at least for one system. $C_{F_{n_p}}$ is the percentage of full coordination for the scenario of n_p where a, b, and c represent different systems (e.g., water, sewer, and road); $Z_{i,c,k}$ represents the intervention decision in corridor i for the system c in phase p; $X_{i,a,p} \cap Y_{i,b,p} \cap Z_{i,c,p}$ could be either 1, if there are common intervention decisions for all three systems, or 0, if there is at least one 'do nothing' for a system.

3. CASE STUDY

To demonstrate the functionality of the methodology, the proposed optimization approach is applied to a 9 km stretch from the city of Montreal's roads, water, and sewer networks (Abu-Samra *et al.* 2020). The network comprises 20 corridors, each of which has pipes and roads with different properties shown in Table 4. The total number of decisions for intervention actions in 'no coordination', 'partial coordination' and 'full coordination' scenarios in a corridor are 9, 27, and 27, respectively, while there are 25 decisions on the number of phases within the planning horizon period. Therefore, for 1, 2, …, and 25 phase scenarios, the number of solutions are equal to $(9+27+27)^{20}$, $2 \times (9+27+27)^{20}$, and $25 \times (9+27+27)^{20}$, respectively; hence, the search space size is equal to $325 \times (9+27+27)^{20}$.

The infrastructure stretch is conceptualized in Figure 4 (manhole to manhole represents one corridor) and the assumed interest rate is 2%. The dataset scale/size, in terms of the number of corridors, is scaled down several times to enable the use of optimization techniques. It is worth noting that the condition status of the 20 corridors was assumed to represent the overall network condition status of each system; other information on the case is shown in Table 4. The unit costs for road resurfacing and surface overlay are about 85 and 33 $/m^2, respectively. The unit costs for pipe replacements are shown in Table 5.

In the database, there are some missing values for the parameter k, which were reconstructed stochastically and validated for every pipe based on literature values (Mottahedin *et al.* 2023).

Table 4 | Sample from the central database for Montreal's infrastructure systems (Abu-Samra *et al.* 2020)

General		Road network				Water network			Sewer network		
Corridor ID no.	Corridor length (m)	Number of lanes	Lane width	Section area (m^2)	Current condition (%)	Year of installation	Pipe diameter (mm)	$k(\times 10^{-4})$	Year of installation	Pipe diameter (mm)	$k(\times 10^{-4})$
1	370	3	3	3,330	90	1953	450	8.00	1920	600	3.60
2	370	4	3	4,440	70	1982	150	0.15	1900	525	4.10
3	452	4	3	5,424	85	1976	250	8.10	1893	375	27.70
4	393	2	3	2,385	65	1958	200	14.00	1950	300	0.67
5	419	3	3	3,771	70	1965	150	2.70	1960	250	7.50
6	766	4	3	9,192	90	1991	100	2.90	1970	150	7.90
7	451	4	3	5,412	70	1992	500	427.10	1980	200	7.70
8	311	2	3	1,866	85	1977	500	2.90	1990	450	6.50
9	425	4	3	5,100	65	1982	350	2.20	2000	200	0.73
10	783	4	3	9,396	70	1991	500	0.10	1975	525	0.39
11	318	3	3	2,862	90	1972	500	0.09	1943	375	0.68
12	162	4	3	1,944	70	1960	250	8.70	1955	300	3.40
13	498	4	3	5,976	85	1979	250	5.00	1965	250	8.70
14	686	4	3	8,232	65	1953	100	5.20	1975	150	8.40
15	207	2	3	1,242	70	1960	450	3.30	1985	200	0.91
16	715	3	3	6,435	90	1977	200	3.10	1905	450	10.80
17	270	2	3	1,620	70	1986	150	14.90	1965	200	10.40
18	217	2	3	1,302	85	1992	350	8.70	1968	600	15.10
19	519	2	3	3,114	65	1975	300	4.00	1978	525	18.80
20	560	4	3	6,720	70	1987	150	0.85	1982	600	6.90

The rehabilitation is planned for a planning horizon of 25 years ($T = 25$) and the threshold values are considered 50 and 65% for the pipes and pavements for the whole period, respectively (Abu-Samra *et al.* 2020). At the year 0, the health reliability values for WN, SN, and RN are 83, 69, and 76%, respectively. The condition health of the sewer is considered the most critical because the sewer pipes in corridors 1, 2, 3, and 16 have a health reliability measure below the threshold. The pipe material is polyethylene with a service life of 100 years and the pavements including asphalts, basements, and sub-basements have a 25-year life span.

4. RESULTS

The adapted optimization algorithm is an improved version of the genetic algorithm (GA) to adaptively handle constraints where parameters like crossover and mutation rate were tuned after test optimization runs (Minaei *et al.* 2020). The optimization converged after 500,000 function evaluations where the population size is 1,000 and the number of generations is 500. Figure 5 shows the convergence trend while the numerical results are depicted in Figure 6.

Figure 6(a) displays the optimization outcomes, with the optimal phasing favoring a design of four phases, each lasting 6.25 years (or 6 years and 3 months). This configuration results in an integrated rehabilitation plan totaling approximately $21.03 M in net present value cost. It is evident that the scenario with $n_p = 1$ incurs the minimum cost; nonetheless, the corresponding solution proves infeasible since initiating the rehabilitation plan in year 0 fails to maintain the health condition of elements above the relevant thresholds for the duration of 25 years.

Figure 6(b) illustrates how the number of phases impacts the coordination of rehabilitation activities across different systems. Generally, corridors have a higher chance of partial coordination compared with full coordination. Moreover, fewer phases increase the likelihood of coordinating activities in corridors compared with scenarios with a higher number of

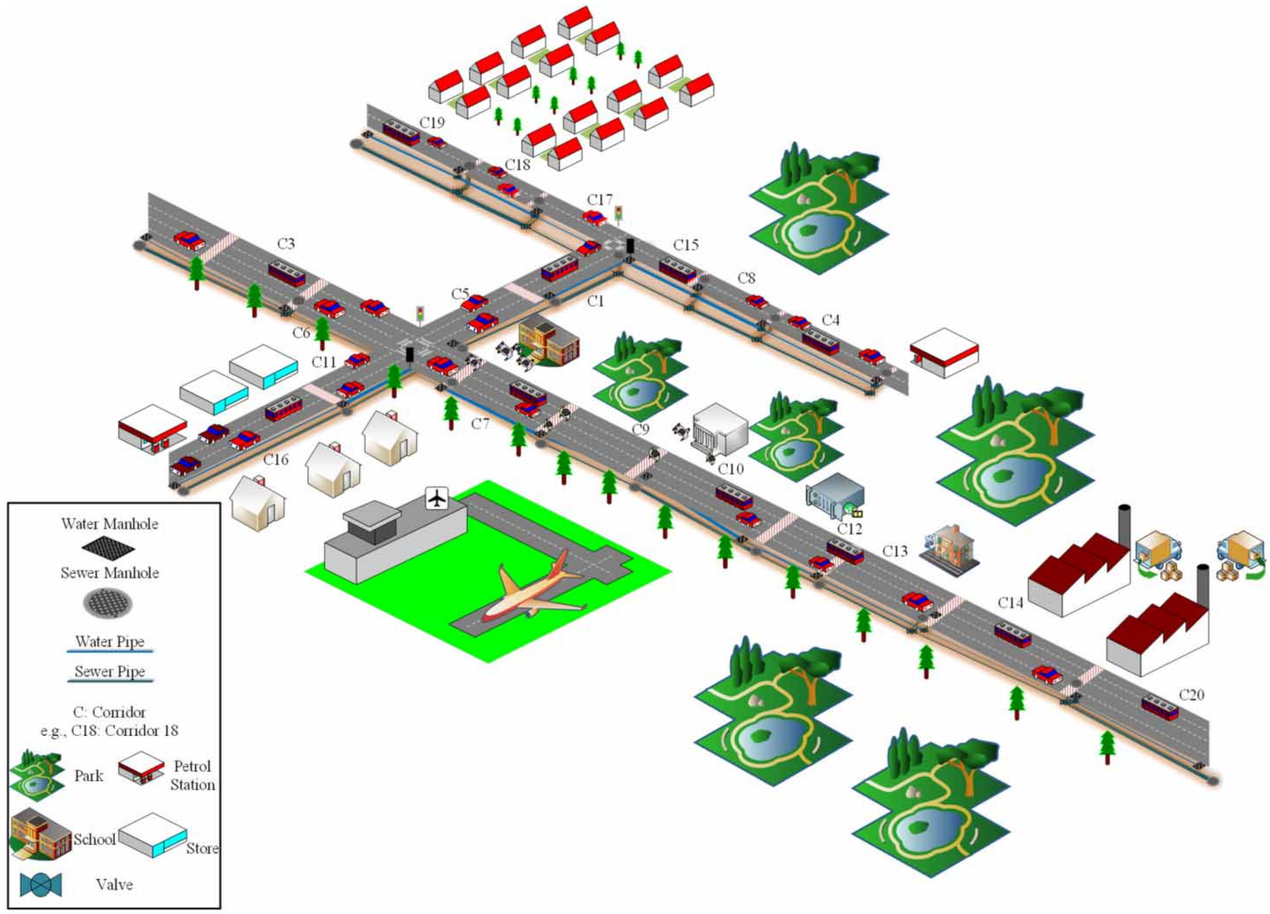


Figure 4 | Conceptualized 9 km stretch from the city of Montreal's urban infrastructure systems, with different corridors, including water and sewer pipes as well as streets.

Table 5 | Unit cost list for different pipe replacement

Diameters (mm)	Unit cost ($/m)
100	179
150	397
200	701
250	1,092
300	1,570
350	2,133
375	2,447
450	3,519
500	4,343
525	4,787
600	6,248

phases. For instance, planning with just one phase results in numerous corridors undergoing rehabilitation actions in year 0, as intervention decisions are based on the health status of systems at year 25. However, aside from the planning horizon, this issue also depends on the initial health conditions of elements from different systems within each corridor. For instance, if a

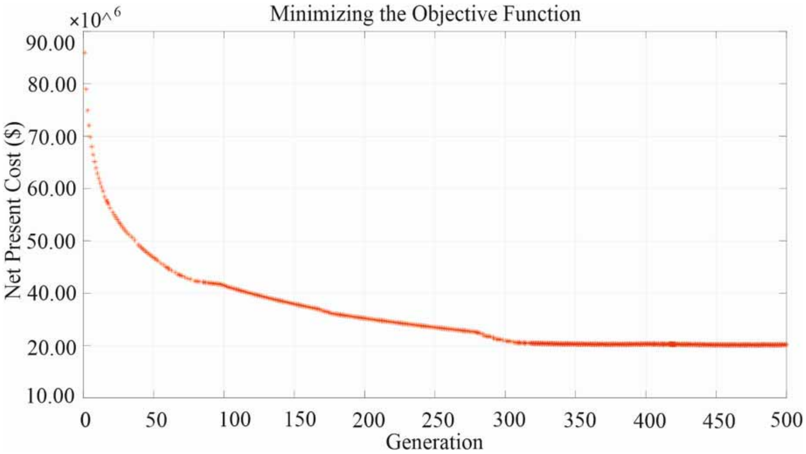


Figure 5 | Optimization convergence trend.

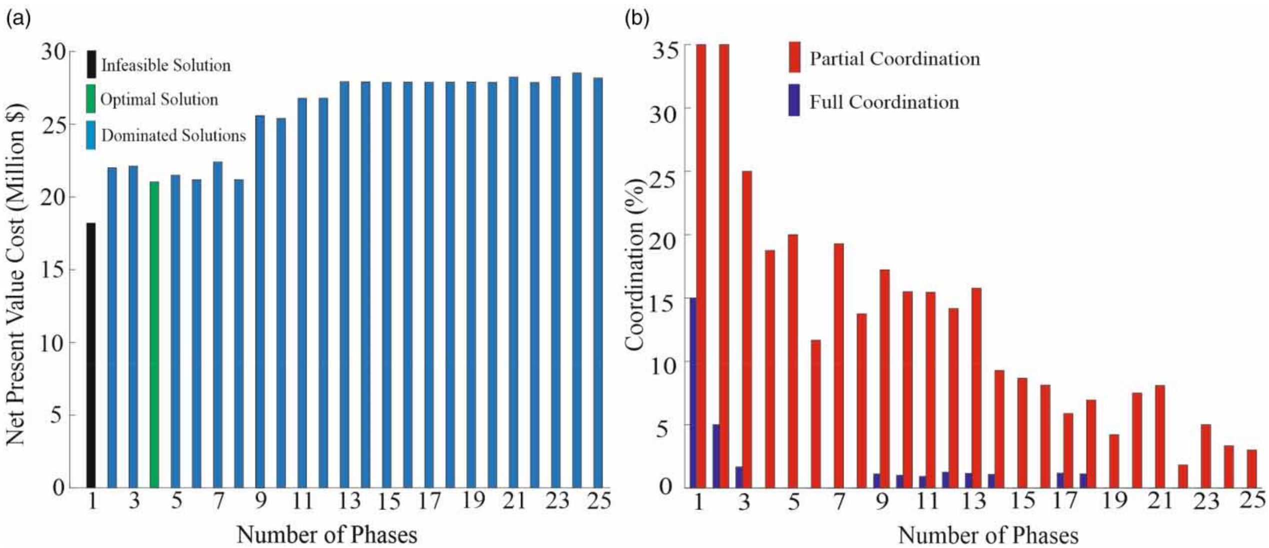


Figure 6 | Optimization solutions and coordination capacities against different numbers of phases.

corridor contains a sewer pipe with 100% health reliability but poor conditions in its water pipe and street section, full coordination might become unlikely, while partial coordination is more probable.

As evident, the coordination potential of scenario $n_p = 4$ stands at approximately 18% (number of corridors with coordinated activities/maximum possible number of coordinations in all corridors). Consequently, while scenario $n_p = 4$ proves optimal in terms of minimizing the cost of an integrated rehabilitation plan, it falls short in terms of coordinating activities. This limitation arises from the formulation of the cost model in this study, which does not incorporate social and environmental costs. While this is a significant assumption and simplification, the consideration of the number of phases as a decision variable in the optimization process (a novelty in the current study) remains crucial for attaining an optimal solution.

The detailed scheduling of the rehabilitation plans for the optimal solution, $n_p = 4$ and the reference work's number of phases ($n_p = 25$) are shown in Table 6.

Comparing the result obtained in the current study (when the number of phases is among the optimization decision variables) with the reference case (with a fixed number of 25 phases, each with a one-year interval) shows that the number of phases plays a critical role in cost saving of the whole rehabilitation project such that around \$7 M saving is achieved

Table 6 | Optimum infrastructures' rehabilitation planning and comparison with the reference one

	$n_p = 25$ (Abu-Samra *et al.* 2020)						$n_p = 4$ (optimum, current study)					
	Water		Sewer		Road		Water		Sewer		Road	
Year	Maj (M)	Min (K)	Maj (M)	Min (K)	Maj (M)	Min (K)	Maj (M)	Min (K)	Maj (M)	Min (K)	Maj (M)	Min (K)
0	0	0	7.70	0	0	616.21	0	0	7.71	0	4.55	0
1	0	0	0	0	0	1,109.83	N/A	N/A	N/A	N/A	N/A	N/A
2	0	0	0	0	0	592.28	N/A	N/A	N/A	N/A	N/A	N/A
3	0	0	0	0	0	0.00	N/A	N/A	N/A	N/A	N/A	N/A
4	0	0	0	0	0	1,615.06	N/A	N/A	N/A	N/A	N/A	N/A
5	0	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A
6	0	0	0	4.93	0	1,005.18	0	0	0.69	0	1.10	631.77
7	0	0	0	0	0	952.04	N/A	N/A	N/A	N/A	N/A	N/A
8	0	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A
9	0	0	0	0	0	2,061.09	N/A	N/A	N/A	N/A	N/A	N/A
10	0	0	0	0	0	391.63	N/A	N/A	N/A	N/A	N/A	N/A
11	0	0	0	0	0	1,485.47	N/A	N/A	N/A	N/A	N/A	N/A
12	0	0	0	4.40	0	861.82	0	8.81	0.48	3.82	5	0
13	0	0	0	3.74	0	0	N/A	N/A	N/A	N/A	N/A	N/A
14	0	2.75	0	0	0	1,761.30	N/A	N/A	N/A	N/A	N/A	N/A
15	0	0	0	0	0	457.85	N/A	N/A	N/A	N/A	N/A	N/A
16	0	0	0	0	0	1,345.44	N/A	N/A	N/A	N/A	N/A	N/A
17	0	4.79	0	0	0	780.58	N/A	N/A	N/A	N/A	N/A	N/A
18	0	0	0	7.34	0	0	N/A	10.32	N/A	3.03	0.86	0
19	0	0	0	3.33	0	1,690.82	N/A	N/A	N/A	N/A	N/A	N/A
20	0	2.61	0	0	0	3,212.70	N/A	N/A	N/A	N/A	N/A	N/A
21	0	2.37	0	0	0	471.75	N/A	N/A	N/A	N/A	N/A	N/A
22	0	2.81	0	2.82	0	1,439.60	N/A	N/A	N/A	N/A	N/A	N/A
23	0	4.24	0	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A
24	0	4.17	0	6.53	0	1,445.13	0	0	0	0	0	0
Sum.	0	23.75	7.70	33.10	0	20,405.85	0	18.40	8.88	6.85	11.50	631.77
TNPVC	**$28.16 M (CAD)**						**$21.03 M (CAD)**					

Maj, major; Min, minor; Sum.: this is the summation of net present value costs of every year cost; TNPVC, total net present value cost (the summation of total costs of water, sewer, and road rehabilitation project); N/A, not available.
The minor and major scale of rehabilitation costs are thousands (K) and millions (M).

(about 25% saving). Planning for multiple short-term phases and investing more in minor rehabilitation actions is not a good approach at least for the current case study. In other words, larger, fewer, and more timely targeted investments are better than more frequent and smaller investments, particularly in the case of road rehabilitation. It is worth mentioning that the original study also used optimization, which means that more than 25% can be achieved in ordinary master planning where optimization may not have been used. Another benefit of a decrease in the number of interventions (35 against 12 for the scenarios of $n_p = 25$ and $n_p = 4$, respectively, about 65% fewer interventions) are savings in the public nuisance (including traffic, water, and sewer services interruptions), which translates to indirect costs not evaluated in this study.

As seen in Figure 7, longer phases achieve a better balance between investments in major and minor actions compared with the ones obtained from shorter phases. This indicates, at least for this case study, that longer phases force the plan to make large early investments that will be beneficial in the long run because an element must undergo rehabilitation action if its structural condition in a planning horizon year is under the threshold values.

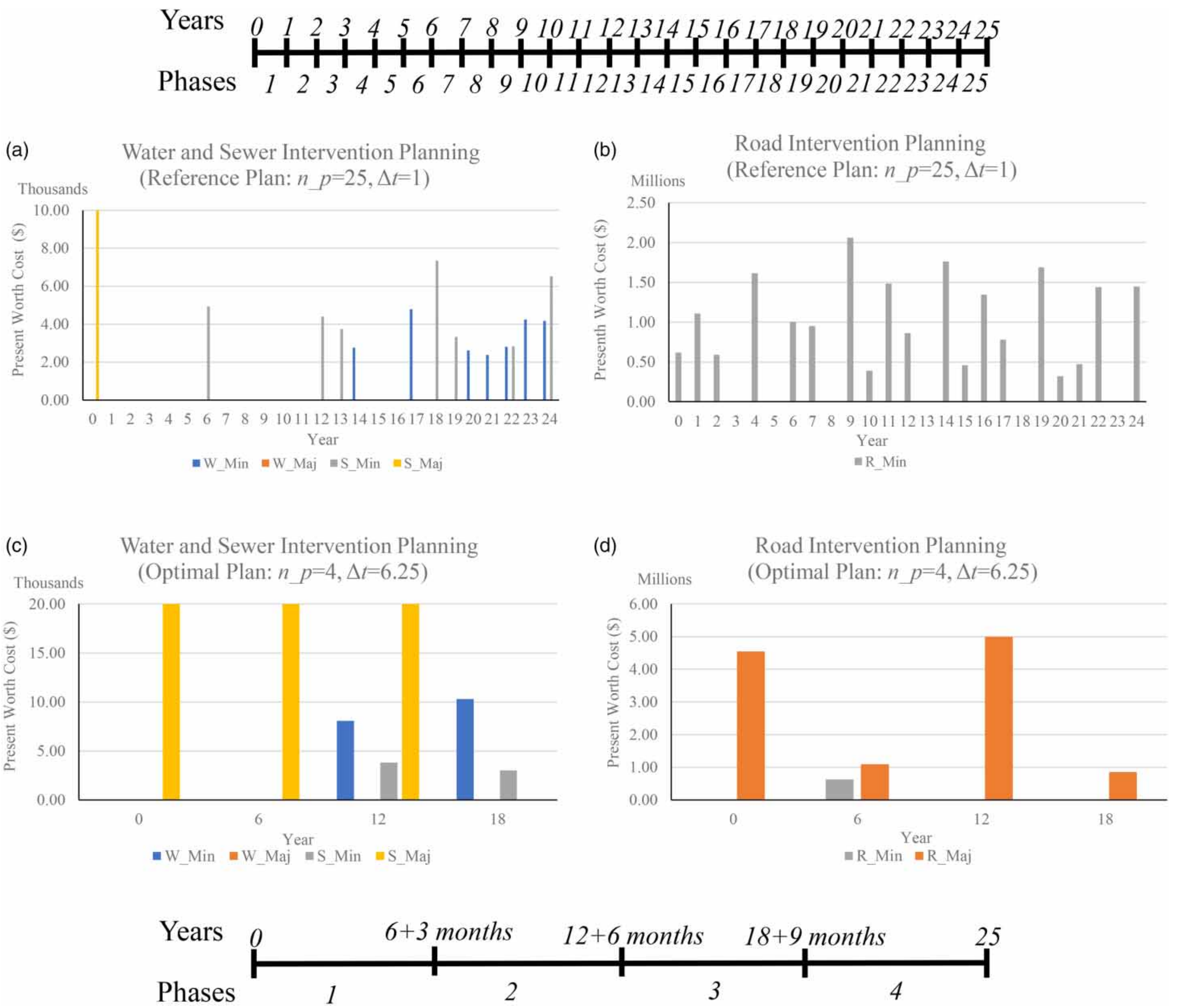


Figure 7 | Comparing phased design period and intervention scheduling between optimal the reference work's (Abu-Samra *et al.* 2020) planning: W_Min, water minor action; W_Maj, water major action; S_Min, sewer minor action; S_Maj, sewer major action; R_Min, road minor action; R_Maj, road major action; n_p, number of phases.

Considering the results, the costs related to road activities exceed those related to water and sewer activities (millions vs thousands of dollars), showing the important role of optimal road intervention planning in minimizing the total integrated rehabilitation cost. This could help asset managers prioritize asset management activities.

Comparing Figure 7(a) and 7(c), in both reference and optimal plans, similarly larger investments are required for the sewer system than the water system indicating the more critical condition of the sewer system than the water system (the major rehabilitation cost is truncated in Figure 7(a) and 7(c) for the clear comparability demonstration with minor rehabilitation cost). This is due to the critical condition of sewer pipes in the year 0 in some corridors (as seen in Table 4, some sewer pipes have more than 100 years and urgent action is needed for their reclamation). This shows that the initial condition of systems is an important factor in optimal decision-making for the integrated rehabilitation of systems where the impacts of phase durations and other variables are minor. For example, in both reference and optimal plans, due to the fact the age of the water system is lower than the sewer system, multiple minor rehabilitation actions have been scheduled in the water system through some phases (without any major rehabilitation actions). The total present value costs are \$23.75 K and \$18.40 K (CAD) in the reference and optimal plan, respectively, achieving around 22% cost savings. The case study is done on a small part (only 9 km) of the city of Montreal network, which makes $23.75 K and $18.40 K very small investments compared with what the city is spending on repairing leaks in the water networks.

In the reference plan, the sewer system has undergone a major rehabilitation action with around $7.70 M in the first phase. Its health condition is then maintained above the threshold by minor rehabilitation activities over several phases with the total present value costs of $33.10 K. The corresponding costs for the optimal plan are $8.88 M and $6.85 K, respectively, meaning around 15% excessive cost on the total rehabilitation investment on the sewer system.

Figure 7(b) and 7(d) compares the road rehabilitation scheduling over phases in the optimal and reference plan. In the optimal plan, major and minor rehabilitation actions have been planned with a total net present value cost of $11.50 M and $631.77 K, respectively. In the reference plan, frequent minor rehabilitation interventions have been designed through many short phases. That makes the total cost around $20.40 M, meaning 41% saving the rehabilitation cost on the road system.

Considering the proposed methodology and the results of the current study, the question may arise of whether fixed intervals bring about an overall optimal solution. For example, while 4 years and 3 months is an optimal duration in phase 1, another duration could be optimal for the second phase. This issue together with the fixed number of phases have been two important challenges and limitations of the phased design and construction approach within the application of the evolutionary optimization for solving many types of engineering problems. This study proposed an approach to overcome the challenge of a fixed number of phases while the challenge of fixed intervals remains an important question and will be investigated in future research work.

5. CONCLUSIONS

In the literature, interval optimization within the dynamic intervention planning of urban infrastructure systems has been missing to date. This study introduced phased design and construction to the rehabilitation of three spatially interdependent urban infrastructure systems: water, sewer, and road. In this approach, the design period is divided into a different number of equally long phases where each scenario includes a particular phase duration. The integrated system is then optimized to find the least cost design for intervention planning while keeping the health condition of the systems above the associated thresholds. Not only the interventions were among the decision variables, but also the duration of phases was determined in the process of optimal decision-making. This has been overlooked in previous studies in the context of multi-phase design and construction approaches to the rehabilitation of infrastructure systems. The case study shows that the timing of the rehabilitation can play a major role in finding the minimum investment cost. In this case, four phases, each lasting about 6 years led to around 25% cost savings for the rehabilitation of Montreal's urban infrastructures compared with the reference work's plan (Abu-Samra *et al.* 2020) where there were 25 phases, each one year long. In the current case study, the longer duration and larger investment interventions (as opposed to the shorter duration and smaller investments) contribute to an optimal integrated rehabilitation plan. Hence, decision-makers can use this important finding for better planning of their projects to achieve even more cost savings than demonstrated in the current study due to it being applied to a small part of a large interdependent system.

Another interesting finding of the current study is related to the impacts of the number of phases (and their duration) on making synchronized rehabilitation planning among different systems. Shorter phases could be a barrier to achieving a coordinated intervention plan for different systems. This depends significantly on the deterioration rates of different elements in considered systems (pipes and pavements), which were tackled through a deterministic approach. Future work will include an exploration of the impact of variable phase durations, the effects of applying uncertainty evaluation to the deterioration models, and the addition of operating, social and environmental costs to the cost model.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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