Performance-Based Budget Allocation Model for Water Networks

By

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ABSTRACT: Budget distribution over water network segments is one of the challenges that face municipalities worldwide. Most water distribution networks (WDNs) are deteriorating, and thus, they require urgent rehabilitation, which costs billions of dollars. Therefore, there is a need to develop a prioritization tool for allocating the budget to the inspected components and selecting the most suitable rehabilitation actions. The present research aims to develop a Water Network Performance-Based Budget Allocation (WNPBA) model to allocate budgets based on the performance assessment optimally. The WNPBA model utilizes Weibull distribution to predict the performance for the components, as well as both genetic algorithm (GA) and Greedy Heuristics (GH), to allocate the available funds optimally. The data required for this research is collected from experts in Montreal's water services as the developed model is applied to a sub-network from Montreal. The model's recommended actions matched the city water services' actions, utilizing the AQUAMODEX tool by almost 94%. The developed WNPBA has proven to be a promising tool in allocating budget to water networks. Data from a water sub-network in Montreal is used to demonstrate the proposed model. Therefore, the model is useful for the decision-making process through any water municipality to facilitate the budget allocation process.

Keywords: Water Networks, Budget Allocation, Rehabilitation, GA, GH, Weibull.

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INTRODUCTION

WDNs are of the most crucial infrastructure assets worldwide. However, aging causes them to deteriorate significantly, reflecting in lower water quality and an increase in the number of breaks and leaks. With time, the increase in society's needs for service is simultaneous to the deterioration in WDNs, which lowers the quality of the provided service and requires infrastructure managers to plan and execute interventions (Kerwin and Adey, 2020). Those interventions are carried out as periodic maintenance for infrastructure assets to maintain the service level and extend the asset's life if possible. This maintenance or rehabilitation can be broken down into three categories; minor repair, major rehabilitation, and replacement (World Economic Forum, 2009). If the pipeline's structural condition meets the standard, then only minor repair is considered to either clean the pipe or treat any leakage. Methods used in cleaning the pipes include Flushing (Hydro-jetting) and air scouring, while leakages are stopped using sleeves. On the other hand, major rehabilitation is considered if the pipeline does not meet the structural standards. The pipe is rehabilitated through coating or lining techniques such as; slip lining, spray-on polymer lining, close fit pipe, and cured in place pipe. Finally, replacing is considered as a last resort. Examples of replacement techniques include open trench replacement and trenchless technologies such as pipe bursting and directional drilling. (Wu, 2020).

Since most WDN rehabilitation projects require billions of dollars, tight budgets are the main obstacle to implement any rehabilitation and maintenance actions. According to the Canadian Infrastructure Report Card (2019), 25% of Canada's water mains are in fair or bad condition. On the other hand, the American Society of Civil Engineers Report Card (2017) graded the drinking water networks in the United States with a "*D*" grade for being of "poor condition" and an estimate of USD 150 billion of investments were required for rehabilitation. Since the funds available were estimated to be USD 45 billion in 2016, there was an investment gap of USD 105 billion. According to the United States Environmental Protection Agency's 6th Drinking Water Infrastructure Needs Survey and Assessment (2018), about USD 472.6 billion is necessary to maintain and expand the service to cover the demand over the next two decades. The figures mentioned above reflect how conducting thorough research on the water infrastructure assets management is significant in achieving a better improvement with a limited budget. Therefore, besides properly managing the funding, it is crucial to sufficiently understand the inspected structure. For instance, accurate budget allocation is much more difficult for complex infrastructure assets. Most of the interventions are planned for the network components (e.g., pipes, pumps, etc.); however, the level of service provided to users and the performance are measured at the network level (Alegre and Coelho, 2012). Therefore, the incremental improvement of network performance achieved by executing specific interventions on specific network components should be measured.

Many models have deployed different methods to allocate budgets for infrastructure in an optimal manner. The development of such models should consider both the suitability of various repair methods to different pipe characteristics and the surrounding conditions. As such, this paper presents a performance-based budget allocation model and rehabilitation plans for WDNs. The developed model suggests a full rehabilitation and maintenance plan for failed segments based on their performance indices (PIs).

BACKGROUND

In recent years, decision-makers have been facing the significant challenge of selecting the suitable rehabilitation technique for water mains. Thus, several studies proposed condition-based asset management tools for WDNs. The main objective of most of these studies was to enhance the condition of the asset. However, fewer researchers studied performance-based budget allocation and rehabilitation of water networks. For example, Saegrov (2005) and Le Gauffre et al. (2007) proposed a Multi-criteria decision analysis (MCDA) based tool to prioritize pipes for replacement. Dandy and Engelhardt (2006) developed a multi-objective GA framework to schedule pipe replacement to maximize reliability while minimizing cost. Nafi et al. (2006) presented a multi-objective optimization model for water mains rehabilitation to minimize cost and pressure. The model used GA and hydraulic simulation. Giustolisi and Berardi (2009) scheduled pipes for replacement using GA with various objectives of minimizing replacement cost and breaks cost while maximizing reliability. Nafi and Kleiner (2010) presented a renewal scheduling method for water pipes with the primary objective of minimizing repair and replacement costs. The model covered road interventions and economy of scale. A budget allocation model was proposed by Tantawy (2012) for assets using GA. The problem was formulated in either of two ways: a) maximizing the average condition under a constrained repair budget, and b) minimizing the cost of repair to achieve the desired condition index. Xu et al. (2013) optimized the pipe replacement timing for part of the Beijing network using GA. In a different effort for budget allocation of water mains, Zayed and Mohamed (2013) utilized an integrated Analytical Hierarchy Process (AHP), Multi-Attribute Utility Theory (MAUT), and simulation methodology. This methodology aims to guide decision-makers to allocate budgets effectively through a fund allocation priority index. A condition-based repair prioritization and fund allocation model for water pipelines were developed by El-Masoudi (2016). The optimization objective was to minimize the life cycle cost of all pipelines' repair, while the constraints covered the planning horizon, the yearly budget, and the pipe condition. Salehi et al. (2017) proposed a comprehensive criteria-based multi-attribute decision-making model for the rehabilitation of WDN. The model covered around 42 factors related to the mechanical and hydraulic characteristics of the WDN.

Kerwin and Adey (2020) presented a bottom-up approach for renewing the aging infrastructure. They developed an optimization model of two phases; one to allocate intervention strategy to each object and another to define which year to apply these interventions on each specific object. Their objective was to maximize the benefit (risk reduction) of any intervention under budget constraints. Zagenehmadar et al. (2020) utilized GA to optimize the planning of repair works for pipelines in WDNs by maximizing the use of the annually allocated budget by the municipality.

Other researchers, such as Tscheikner-Gratl et al. (2016), developed an integrated infrastructure rehabilitation prioritization model based on overall priority factor. They considered roads, water, and sewer networks for their analysis. While Kielhauser et al. (2017a) and Kielhauser and Adey (2019) proposed an integrated infrastructure rehabilitation optimization model for roads and all buried pipes (water, sewer, gas, electricity) to improve risk reduction. They used Voronoi polygons to determine the neighborhood. In addition to these studies, others across different infrastructure assets have studied the optimization of the rehabilitation process such as pavement (Saad et al. 2017), road (Lethanh et al. 2018), and rail (Burkhalter et al. 2018).

It is observed that most of the previous models have analyzed the restoration of WDNs through hydraulic simulation. However, this may not be the best option because of its extended computational time due to the increasing size and complexity of the network. Also, models that investigated intervention in WDNs overlooked several vital issues such as (1) depending only on one factor such as; breakage rate or leakage rate to allocate the budget while for the model to be able to assess preventive and corrective actions, a lot of physical, operational and quality of services factors should be included; (2) covering multiple rehabilitation and repair techniques and their impacts on the objective to be optimized; (3) taking into account the inflation rate of the rehabilitation techniques cost over the planning horizon; (4) only a few models considered the deterioration effect of the segments through the planning horizon of the budget allocation model; and (5) linking between PIs of the water network components and the suggested rehabilitation strategies; (6) integrating the performance/condition indices of pipelines, segments, networks within the budget allocation process. As such, the main objective of this paper is to develop a performance-based optimization model for prioritizing budget allocation over WDN. The model efficiently distributes the available budget over the segments by maximizing the performance of the WDN while respecting the annually allocated budget by the municipality and considering the segments' deterioration and costs inflation effects.

RESEARCH METHODOLOGY

Water networks are one of the most complicated systems that deteriorate over time. As highlighted in the literature review, enhancing the performance of these systems require huge investments. Therefore, it is necessary to develop a functional tool that prioritizes budget allocation over the network components to reach the highest PI.

This paper presents a newly developed optimization framework named "performance-based budget allocation model," which takes three inputs to achieve its objective. Those inputs are the outputs of three models: performance assessment model, deterioration model, and rehabilitation and maintenance model, as presented in Figure 1. The performance assessment model integrates performance indicators weights and attributes values to reach the performance index. The deterioration model forecasts each pipe segment's deterioration or, in other words, its performance index in the future. The rehabilitation and maintenance model defines a set of feasible rehabilitation methods for the pipe segment and the unit cost of each. The time value of money is integrated into the optimization framework by considering the inflation in the rehabilitation methods' unit cost. The details of the developed methodology are described subsequently.

MODEL DEVELOPMENT

Performance Assessment Model

This research proposes a methodology that addresses water networks at different levels: pipes and accessories, segments, sub-networks, and the entire network. The performance assessment model utilizes the functional indicators to assigns a performance index to the pipelines. The indicators are grouped into a hierarchy of four functions (i.e., physical, operational, quality of services, and environmental). The model adopted Fuzzy Analytical Network Process (FANP) to evaluate the sub-criteria and functional weights. The MCDA method (PROMETHEE) is utilized to perform the model's mathematical decision analysis and calculate each component's performance index. Afterward, two fictitious limits (lower and upper bounds) and a simple straight-line relation were introduced to overcome the PROMETHEE major limitation by transforming the ordinal scale-based rank into a cardinal scale-based index. The PI is evaluated for each function separately by aggregating the pseudo criteria reaching the functional performance index (FPI). Finally, each pipeline's global performance index (GPI) is obtained by applying MAUT between the four FPIs. After that, the weights of importance of the components within the segments are calculated using the probability theory to reach Segments PIs. Afterward, the sub-network (a group of segments sharing the same land-use) PI is calculated using topological clustering on segment PIs. Finally, the entire network PI is obtained by combining the sub-networks' weighted PIs based on its length and land use.

Deterioration Model

After calculating the PIs of the network components, a model that can forecast the performance of the components (deterioration model) should be developed. Elhakeem (2005) proposed a classification for deterioration techniques: (1) deterministic, (2) stochastic, and (3) artificial intelligence models. The deterministic models were either straight-line extrapolation, curve fitting models, or regression analysis models. The stochastic models were Markovian models or reliability-based models. Additionally, the artificial neural network was considered as a form of artificial intelligence models. In the water field, various researchers analyzed the deterioration of pipelines such as; Wang et al. (2009). They used multiple-regression analysis to predict the condition of water mains. The Weibull analysis was widely utilized in predicting the condition of bridge decks and other steel and concrete elements. Agrawal et al. (2010) used both; Weibull distribution model and Markov chain model to predict the deterioration of different bridge elements in New York State.

Jardine and Tsang (2006) discussed one of the world's most popular methods to analyze and predict failures and malfunctions of different infrastructures known as the Weibull analysis. The Weibull analysis provides realistic deterioration curves and performs better probabilistically in terms of the observed condition. That is due to the incorporation of time dependency and physical characteristics in the condition indices calculations. Also, the shape parameter of Weibull distribution facilitates modeling different elements performance with high flexibility. It takes an exponential shape when β equals 1, representing elements with an increasing failure rate at $\beta > 1$ and representing elements with a decreasing failure rate at $\beta < 1$ (Agrawal et al., 2010).

The newly developed deterioration model uses Weibull cumulative function to expect the deterioration for each component based on three points: PI when constructed, PI at the inspection time utilizing the performance assessment, and the anticipated PI at the end of the service life. Weibull reliability function starts at the maximum reliability and decreases slowly at the beginning, then rapidly in the middle, and eventually at a slower rate at the end of the service life, similar to the performance index in this study. In both cases, the slope decreases, and the function goes through an inflection point. Also, water networks' inspection reports are few. Thus, Weibull distribution is used for its simplicity and because it does not need a lot of historical data. It can also easily model any component deterioration up to network deterioration. It also incorporates the knowledge of the user in identifying its parameters.

Weibull curve represents the transition from one state to another. This study assumes that the network elements deteriorate in the same manner as Weibull distribution works (Newly installed state, current state, and end of service life state). Thus, the deterioration curve has the same shape as the Weibull reliability curve, so based on the Weibull reliability function, the performance prediction function can be presented as:

$$P(t) = \alpha * e^{-(\frac{t}{\tau})^{\delta}} \qquad [1]$$

Where: P (t) = Performance index at (t) and, τ = service life.

The deterioration curve for the pipelines and accessories should agree with the following conditions:

1) The newly installed components at t=0 have a PI=10, which can be expressed as 1 on a scale from 0 to 1:

$$1 = \alpha * e^{-(\frac{0}{\tau})^{\delta}} \qquad [2]$$

$$1 = \alpha$$

1) PI=0 at the end of the component's lifetime span, and PI=3 (critical performance index), which is presented as 0.3 on a scale from 0 to 1 and it represents the end of the useful service life (t):

$$0.3 = 1 * e^{-(\frac{100}{\tau})^{\delta}}$$, then

$$\ln(0.3) = \ln(1) - (\frac{100}{\tau})^{\delta}$$, and finally:

$$\tau = \frac{100}{(-\ln(0.3))^{1/\delta}} \qquad [3]$$

2) $\delta = 3$ as it makes the shape of the curve fit more elements.

Hence, by substituting equations [2], & [3] into equation [1] the updated deterioration (performance) curve can be defined as follows:

$$P(t) = 1 * e^{\ln(P_i)(\frac{t}{\tau})^3} \qquad [4]$$

Weibull analysis and the PIs are used to build the components' ideal deterioration curves, both with and without considering maintenance. Ideal deterioration curves represent the perfect components, working for the whole service life.

Rehabilitation and maintenance plan

This research introduced a rehabilitation and maintenance plan for water network components based on their PIs, as shown in Figure 2. This plan helps decision-makers to select the most suitable rehabilitation action for each segment based on its PI. The PI is calculated based on a set of physical, operational, environmental, and quality of services characteristics for each segment. Consequently, this set of criteria for each segment is integrated into the choice of suitable rehabilitation action through PIs. The city of Montreal supported this research with inspection reports and historical data for the analyzed sub-network. It was found that most of the pipes rehabilitated in the past suffered from significant failing signs, e.g., corrosion, wall thickness, and breakage rate. By analyzing these signs, their levels, and the actions taken in the past, four categories were defined, and the fifth one is added afterward to count for the newly installed pipes that require no intervention. Thus, the PI index is divided into five categories. Each category has its description and recommended action out of the five actions that were considered by the city of

Montreal; (0) No Action, or Cleaning (1) Epoxy Lining, or Internal joint sealing, (2) Cathodic Protection, (3) Slip lining, or CIPP, and (4) Open Cut Replacement.

For example, consider a scenario where the PI is critical when it is below (3), the description is stated as "severe corrosion," coatings are almost damaged, remaining wall thickness is 30% of the original, and BR>3, or the cathodic protection is poor. Hence, the recommended action is replacement or major rehabilitation (CIPP or slip lining). It is assumed that all the actions redeem the PI to (9), except for the replacement action, which leads to (10). Finally, this model's output is a rehabilitation and maintenance plan covering multiple repair methods, their cost, and their performance improvement on any failed pipe segment.

Budget Allocation Model

The number of possible solutions to this problem is relatively high, as it is directly related to the number of segments to be rehabilitated and possible rehabilitation methods. Therefore, the search space is significant as there are five possible rehabilitation methods, and the number of investigated segments is 63, then the search space will be ($\mathbf{63! \times 5^{63}}$). Through this research, two optimization algorithms are applied, and the results are compared to identify the best performing algorithm and for more certainty in the suggested budget allocation plan. These optimization algorithms are GA and GH.

Optimization Framework

The model's objective is to maximize the PI of the entire network by improving the PIs of its components, segments, and sub-networks through rehabilitation actions, as presented in Equation [5]. The model is subjected to budget constraints to keep the cost below the allowable annual budget for the municipality, as shown in Equation [6]. Thus, the decision variables are either (1), which represents “doing the recommended action at this point of time,” or (0), which represents “do nothing.” The model should be applied over a specific time horizon for one year as an example.

Therefore, the objective function is:

$$Max\ f(x) = \sum_{i=1}^{i=n} W_i * PI_i \quad [5]$$

Subject to the following constraints:

$$\sum_{i=1}^{i=n} \sum_{j=1}^{j=k} C_{ij} \leq C_{max} \quad [6]$$

Where;

$W_i = Weight\ of\ importance\ of\ each\ sub-network\ to\ the\ total\ network$

PI_i = Each sub-network performance index.

$C_{ij} = \text{Cost of rehabilitation strategies j applied to sub} - \text{network i components}$

$C_{max} = \text{max. allowable} \frac{\text{budget}}{\text{year}}, \qquad i = \text{sub} - \text{networks} = 1,2,3, \ldots . \text{n}$

The model inputs are:

1) The unit cost of each rehabilitation action for different pipe sizes (Diameter) and accessories replacement costs;
2) Deterioration function (curve) of each component;
3) Diameter and length of each pipe;
4) And PIs calculations.

The main outputs of this problem are; (1) a budget allocation plan close to the optimal solution, which is accepted due to the complexity of the problem, numerous levels within the network, and various actions for each component; (2) Proposed rehabilitation actions across the components; and (3) Improved water network PI at the end of the plan.

Genetic algorithm

GA was first introduced by John Holland (Holland, 1975). It is known to be one of the most powerful optimization techniques. It can deal with a broad set of data and reach a very close solution to the optimum (Ismaeel, 2016). The algorithm starts with population initialization (generating a random solution). The sub-networks are here accounted for as chromosomes. During the encoding process, each sub-network is represented by several genes representing the number of its components to be rehabilitated. The rehabilitation and maintenance actions represent the encoding for the genes, as shown in Figure 3. Then, a fitness value, which is the same as the objective function, is calculated for each chromosome (maximization of the performance index). Only chromosomes with higher PI are considered for the next generation formation through crossover and mutation genetic operators.

Crossover is exchanging genes between two random chromosomes in a random cross-site within the length of the chromosome (assumed 0.5 in this study). In contrast, the Mutation operator controls the diversity of the chromosomes' genes by changing the genes continuously using a low random probability (assumed 0.01 in this study), which aids in keeping the algorithm working to reach better solutions and avoids premature convergence.

The GA model keeps working in the same manner until reaching a population size (solution) that satisfies the objective function (stopping criteria) or reaching a maximum number of defined iterations. The budget is allocated over the whole network, based on each component's performance calculations.

Greedy Heuristics

GH was selected due to its simplicity and the fact that it is almost a ranking algorithm that requires minimum and simple calculations only. The objective function cost calculations and the rehabilitation action selection process are the same for both GA and GH, while the prioritization is different. The budget in the GA model is allocated based on the PIs obtained from the performance assessment model. Through the GH process, the multiplication of different weights of importance, as clarified in Equation [7], is considered the benefit of rehabilitation of any component to the entire network. The GH prioritization is based mainly on these benefits. Therefore, GH-Model is working based on the following steps:

1) Benefits calculation for each component = $W_1 * W_2 * W_3$ [7]

Where;

W_1 : the weight of importance of the component within the segment.

W_2: the weight of importance of the segment within the sub − network.

W_3: the weight of importance of the sub − network within the entire network.

2) Calculating the cost for each component.

3) Calculating the benefit/cost ratio (B/C).

4) Ranking the components for rehabilitation according to the B/C ratio.

Finally, after applying the GA and GH models, the two budget allocation plans are compared based on the final amount of spent budget, the number of segments rehabilitated, and the final Network-PI reached. Hence, the best option is selected.

DATA COLLECTION

Various sources of data were utilized to develop this model. The first source was a Database of an actual WDN in Montreal, Quebec, Canada, collected from Montreal water services. The database covered 850 pipe segments from Montreal's water network. A sub-network of 64 pipe segments had been selected for the implementation of this research. These segments' characteristics were extracted from the database, such as the date of installation, material, diameter, and length. The database also covered the location of the segments (street names). Each segment's performance was assessed based on these data sets by utilizing FANP and PROMETHEE, as explained previously. In addition to the database, an inspection report of the same WDN was collected. It comprised the failure history of different segments, the rehabilitation history in the last ten years, the coordinates of each pipe, the final cost of the implemented action, and the PIs. This report was generated by AQUAMODEX, which is the software utilized by the city of Montreal. It was used to develop both the deterioration and rehabilitation & maintenance plans.

MODEL IMPLEMENTATION

The model is implemented on a subnetwork composed of 63 pipe segments (13 km) in the southwest of the city of Montreal in Quebec, Canada, as shown in Figure 4. This subnetwork is part of an extensive water network covering 850 pipe segments and was selected due to the diversity of the land use and serviced facilities within its area. The pipes diameter within the subnetwork has a range of 150 to 300 mm with only one pipe of 100 mm. The material is Cast Iron for 90% of the pipes. The oldest pipe of the subnetwork was installed in 1870 and the latest in 2011. The subnetwork was rehabilitated in 2016; thus, the model is implemented on the subnetwork condition just before rehabilitation. Table 1 shows a sample of the database gathered from the city of Montreal.

The PIs for all pipe segments and the subnetwork were calculated following the methodology explained earlier. Detailing the steps of the implementation of the performance assessment model is beyond the scope of this study. Readers can refer to Ismaeel and Zayed (2018) for more about the calculation process of PIs. As mentioned earlier, this study introduced a performance-based rehabilitation and maintenance plan for water networks. Thus, Table 2 presents the pipelines' selection process and accessories rehabilitation actions based on their PIs. The calculation of any action's total cost is based on the action's unit cost for a specific pipe diameter multiplied by the pipe length. The accessories are either replaced or remained. Shahata et al. (2006) developed a questionnaire to gather the unit costs of different rehabilitation and replacement actions of water mains. This questionnaire was distributed among experts and engineers of the industry, and the results were proven to be of acceptable accuracy compared to the market prices utilized by municipalities. Thus, the unit costs for a 400 mm diameter pipe were derived and utilized herein, considering the inflation from 2006 to 2020. While other diameters unit costs were calculated using means of cross multiplication. The unit cost for cathodic protection was assumed as it wasn't covered in their questionnaire.

After calculating the current PIs for WDN elements, Weibull analysis is utilized to draw the deterioration curves. Three points are utilized for each element to illustrate the deterioration Curve: the assessment point obtained from the performance assessment model, the installation point (PI=10), and the end of service life point (PI=0). Thus, the deterioration curve for pipe #2 in the city of Montreal sub-Network is as shown in Figure 5. Finally, these deterioration curves should be updated after implementing any rehabilitation action, as presented in Figure 6 for pipe #1.

Next, the budget is allocated, utilizing GA and GH algorithms as per Eq [5]. An inflation rate of 1.6% is included in the budget allocation plan to cover the unit costs' inflation. It is calculated using the bank of Canada inflation rate calculator. The plan is assumed to be a short-term plan (3-Years). Thus, the average annual inflation over the last three years (2017-2020) was found to be 1.63%, and it is assumed to be the same for the upcoming three years. An integrated Excel-Evolver tool software is built to solve the GA-Model on an 8-GB RAM, 3.60-GHz i7 core CPU, and Windows 7 with a 64-bit operating system. The range of the computational time of the model is between 6 and 8 mins. The output is a rehabilitation plan composed of rehabilitation method choice, priority, and cost, as shown in Table 3. On the other hand, the GH model is implemented following various steps, as mentioned earlier. The allocation process is the same as the GA-model, except that it is based on the B/C ratio order.

The annual allowable budget for the 3-year plan is either predefined by the municipality or assumed by the model user. Thus, to have confidence about this allocation, an annual budget of CAD 500,000 that can be increased by increments of CAD 250,000 is assumed. The maximum annual budget is CAD 750,000, and the annual allocated budget at any year cannot increase before reaching the maximum budget of the previous year. Accordingly, four scenarios are generated as follows; [(0.5, 0.5, 0.5), (0.75, 0.5, 0.5), (0.75, 0.75, 0.5), & (0.75, 0.75, 0.75)] $*10^6$ CAD. Those solutions were performed for the three years, and (0.75, 0.5, 0.5) $*10^6$ (CAD) was found to be the best solution, as it achieves the highest PI enhancement for each year of the 3-years plan. The sub-network PI improved rapidly by increasing the allowable budget of the first year to CAD 750,000, and it did not change by increasing the budget of the second year. The sub-network PI didn't change in the second year due to either unnecessary rehabilitation that doesn't impact the sub-network PI or an extensive rehabilitation that requires more than the CAD 250,000 increase. Therefore, it is pushed to the 3rd year. The best budget distribution scenario using GA and GH models is shown in Figure 7. The amount of money spent using GA & GH equals CAD 1,722,108, & CAD 1,741,873 respectively. The percentages of rehabilitation done vs. parts to be rehabilitated are presented in Figure 8. Meanwhile, the sub-network PI is improved by almost 85%, from 4.8 to 8.9. Finally, it is concluded that the two algorithms provide similar solutions in terms of rehabilitation cost and performance improvement.

The developed model is evaluated by comparing its outputs to Montreal's city software (AQUAMODEX), which provides an intervention plan based on the pipes' historical data. This plan encompasses intervention method recommendation, performance improvement, and cost of the selected action. The result of this comparison is presented in Table 4. It was found that the developed model enhanced the PI of the network by almost 8% more than the value obtained from the city's approach. Also, compared to the city's approach, the developed model has cost savings of CAD 77,042 & CAD 57,277 utilizing GA and GH, respectively. The two approaches match in almost 94% of the recommended actions of interventions despite having different sequences. It was found that according to AQUAMODEX, three segments need to be replaced, while according to the WNPBA model, the same segments have slip lining as a recommended action. After several meetings with municipal engineers and managers, it was found that most of these segments can be lined. However, due to different factors such as preventive actions, construction site issues, and integrated infrastructure management issues, the recommended action was replaced instead.

Additionally, the developed model recommended replacing only one segment, which was rehabilitated following the city's approach. This segment is believed to be a highly critical segment within the sub-network, considering its connectivity. Thus, it was selected for replacement, resulting in a higher PI than the city's approach. Finally, the difference of 6% between the two approaches' recommended actions is believed to be due to the reasons mentioned above. Therefore, the model is recommended to be used by municipalities.

SENSITIVITY ANALYSIS

Several sensitivity analyses were conducted to assess the impact of the decision variables (rehabilitation strategies) of various segments on the rehabilitation cost and network PI, as shown in Figures 9 & 10, respectively. It was found that the rehabilitation of pipe segments 18, 41, 31 &

42 affects the rehabilitation cost the most. Which is justified since pipe segment 18 is one of the largest in this network with a diameter of 300mm, pipe segment 41 is the longest in the network, pipe segment 31 recommended action is major rehabilitation, and pipe segment 42 recommended action is a replacement. On the other hand, it was found that Network PI is highly sensitive to the rehabilitation of pipe segments 9, 29, 35, & 42 because of their connectivity, location within the network, and deterioration curve. The main output of this kind of analysis is identifying the most critical pipe segments within the network to monitor them carefully and intervene accordingly.

CONCLUSION

This paper presents a performance-based budget allocation model to optimize the total performance improvement under budget constraints. The rehabilitation actions for the segments are considered as the decision variables of the optimization. The budget is allocated based on PIs and using GA and GH means. The performance prediction model is developed using Weibull distribution, and it is considered one of the inputs to the budget allocation model. Other inputs, such as a performance-based rehabilitation and maintenance strategy, actions unit costs, components PI, and inflation rate, are also considered.

The model is implemented on an actual WDN in Montreal, Quebec, Canada, and the results are compared to the city's suggested plan developed by the software (AQUAMODEX). It is found that the developed model resulted in 5% cost savings and 6% performance improvement. Several sensitivity analyses are then conducted to assess the impact of various segments' rehabilitation strategies on the rehabilitation cost and the entire Network PI, and the most critical pipe segments were identified. The model is proven to have the flexibility of dealing with the rehabilitation of network components (pipes & accessories), segments, and sub-networks. That is done by linking the performance assessment model to the budget allocation model through defining the objective function as maximizing the performance index of a specific sub-network. Thus, the developed WNPBA-Model can optimally rehabilitate WDNs to maximize their performance while respecting managerial constraints, such as the allowable budget.

However, the developed model has some limitations that need to be addressed in future studies. The model does not consider the rehabilitation time, which covers the scheduling criticality and its effect on the budget (cost of service interruptions). This work assesses the performance of pipe segments and accessories; however, the accessories are considered one element with many assumptions. Therefore, the model can be extended to analyze the accessories and other elements separately, such as pumps, hydrants, and water tanks. Finally, this methodology can be applied to other infrastructure networks, such as sewer and road networks. These networks' indices can be integrated with the water indices to develop an integrated infrastructure management tool. Finally, it is required to develop an automated tool with a graphic user interface (GUI) that can easily deploy user inputs, draw the network layout considering all its components and connections, and perform all the model calculations in a user-friendly format.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code generated or used during the study are available at (https://spectrum.library.concordia.ca/981481/1/Ismaeel_MASc_F2016.pdf) following funder data retention policies. Data that are not covered in the mentioned document are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENT

Writers would like to express their thanks and appreciation to "Montreal Water Services, Department of strategic management" for the valuable data they provided for experimenting with this model and for their feedback and comments.

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Table 1 Sample of Montreal Water Network Database

ID	Street Name (From)	Street Name (at)	Street Name (To)	DATE INSTALL	A	M	D	L	INTERVENTION-TYPE_AQUAMODEX	INTERVENTION-DATE	JURISDICTION	Owner	STATUS	SEWER EXISTANT
43018	Saint-Paul	Nazareth	Notre-Dame	1891	125	Cast Iron	250	250.99			Loc Ctre-ville	Sud-Ouest	Existant	
43019	Inspecteur	William	Notre-Dame	1892	124	Cast Iron	250	179.73	Replacement	01-Jan-11	Loc Ctre-ville	Sud-Ouest	Existant	
43020	Peel	William	Notre-Dame	1934	82	Cast Iron	150	298.48			Loc Ctre-ville	Sud-Ouest	Existant	
43021	Murray	William	Notre-Dame	1892	124	Cast Iron	200	149.41			Loc Ctre-ville	Sud-Ouest	Existant	
43022	Eleanor	William	Notre-Dame	2011	5	Ductile Iron	200	148.90			Loc Ctre-ville	Sud-Ouest	Existant	
43023	Montagne	William	Notre-Dame	1890	126	Cast Iron	300	155.44	Replacement	01-Jan-11	Loc Ctre-ville	Sud-Ouest	Existant	Yes

Table 2 Performance-based Rehabilitation plan for water pipelines and accessories

(a) Water pipelines						
Min (PI)	**Max (PI)**	**Joint**	**D**	**Action ID#**	**Unit Cost (CAD/m')**	**Inflation rate (%)**
0	3	100-4	100	4	158	1.60%
		150-4	150	4	236	
		200-4	200	4	315	
		250-4	250	4	394	
		300-4	300	4	473	
		400-4	400	4	630	
		450-4	450	4	709	
3	4	100-3	100	3	141	
		150-3	150	3	211	
		200-3	200	3	281	
		250-3	250	3	351	
		300-3	300	3	422	
		400-3	400	3	562	
		450-3	450	3	632	
4	6	100-2	100	2	150	
		150-2	150	2	200	
		200-2	200	2	250	
		250-2	250	2	300	
		300-2	300	2	350	
		400-2	400	2	450	
		450-2	450	2	500	
6	8	100-1	100	1	88	
		150-1	150	1	131	
		200-1	200	1	175	
		250-1	250	1	219	
		300-1	300	1	263	
		400-1	400	1	350	
		450-1	450	1	394	
8	10	100-0	100	0	0	
		150-0	150	0	0	
		200-0	200	0	0	
		250-0	250	0	0	
		300-0	300	0	0	
		400-0	400	0	0	
		450-0	450	0	0	
(b) Water accessories						
0	4	N/A	N/A	1	10000	1.60%
4	10	N/A	N/A	0	0	

Table 3 Sample of GA 3-Years budget allocation plan for Montreal sub-network

	Age_1	Age_2	Age_3	D	PI_1	PI_2	PI_3	$R.A_1$	$R.A_2$	$R.A_3$	$D.V_1$	$D.V_2$	$D.V_3$	C_1	C_2	C_3	PI'_1	PI'_2	PI'_3
P.1	125	126	127	200.00	3.61	3.52	8.98	3	3	0	0	1	0	0.00	52572	0.00	3.61	9.00	8.98
P.2	49	50	51	300.00	8.95	8.89	8.83	0	0	0	1	0	0	0.00	0.00	0.00	8.95	8.89	8.83
P.3	125	126	127	250.00	8.64	8.61	8.58	0	0	0	1	0	0	0.00	0.00	0.00	8.64	8.61	8.58
P.4	5	6	7	250.00	3.56	8.34	7.49	3	0	1	1	0	0	68299	0.00	0.00	9.00	8.34	7.49
P.5	82	83	84	150.00	9.16	9.13	9.10	0	0	0	1	0	0	0.00	0.00	0.00	9.16	9.13	9.10
P.6	124	125	126	200.00	8.69	8.66	8.63	0	0	0	1	0	0	0.00	0.00	0.00	8.69	8.66	8.63
Acc. 1	125	126	127	NA	3.38	3.29	3.21	1	1	1	0	0	1	0.00	0.00	10323	3.38	3.29	9.90
Acc. 2	125	126	127	NA	3.38	3.29	3.21	1	1	1	0	0	1	0.00	0.00	10323	3.38	3.29	9.90
Acc. 3	49	50	51	NA	8.59	8.51	8.42	0	0	0	0	0	0	0.00	0.00	0.00	8.59	8.51	8.42
Acc. 4	102	103	104	NA	3.45	9.90	9.89	1	0	0	1	0	0	10000	0.00	0.00	9.90	9.90	9.89
Acc. 5	102	103	104	NA	3.45	9.90	9.89	1	0	0	1	0	0	10000	0.00	0.00	9.90	9.90	9.89
Acc. 6	102	103	104	NA	8.52	8.48	8.44	0	0	0	0	0	0	0.00	0.00	0.00	8.52	8.48	8.44

"P.1 - P.6 & Acc.1 - Acc.6" represent the pipes and accessories of the studied sub-network, respectively. "D" is the pipe diameter. While "PI, R.A, D.V, C, and PI'" represent the performance indices before rehabilitation, the recommended rehabilitation action, the decision variable of the optimization problem (0 or 1), the cost of rehabilitation, and the performance indices after rehabilitation respectively. The numbers 1-3 reflect the 3-years plan.

Table 4 Comparison between the developed model and the city's software

Criterion	WNPBA-Model (GA)	WNPBA-Model (GH)	AQUAMODEX (City's software)	Enhancement (%)
PI	8.9	8.9	8.5	8
Cost ($x10^6$CAD)	1.722	1.742	1,799	3.3 (GH) – 4.5 (GA)

List of Figures:

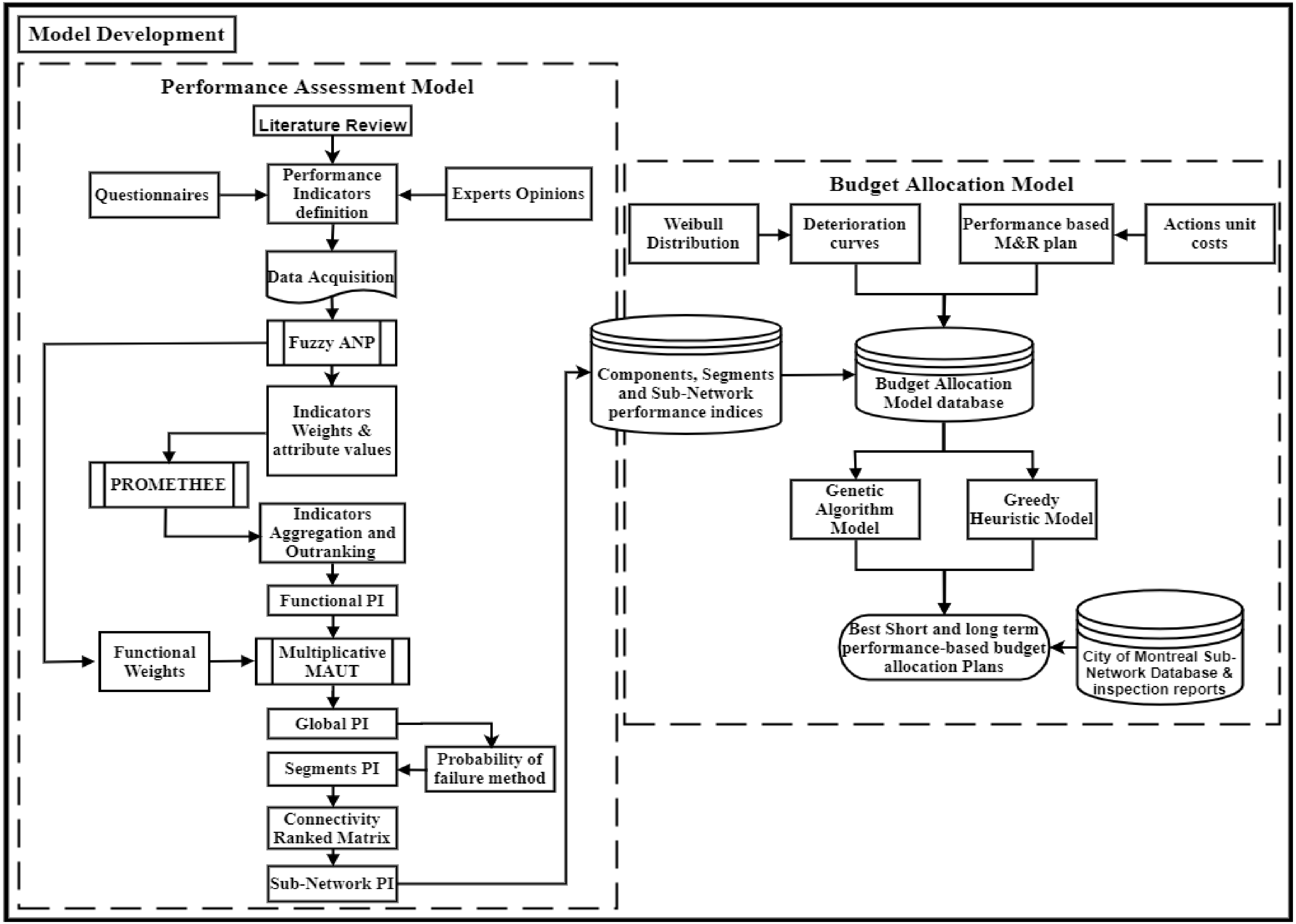

Fig. 1. WNPBA model outline

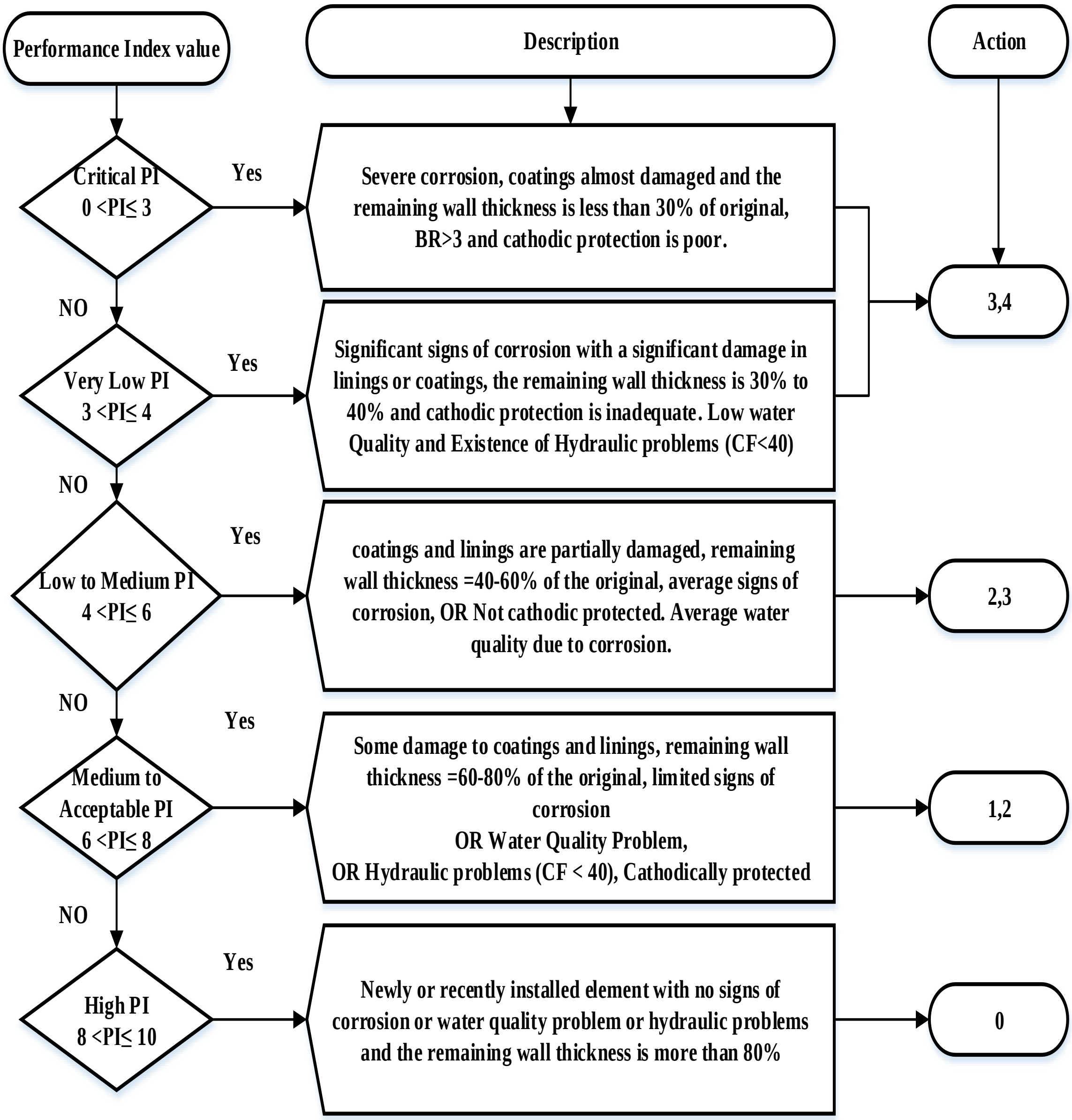

Fig. 2. Performance-based rehabilitation and maintenance plan

Where;

(0) No Action.
(1) Epoxy Lining, or Cement Lining, or Internal joint sealing.
(2) Cathodic Protection.
(3) Slip lining, CIPP.
(4) And Replacement.

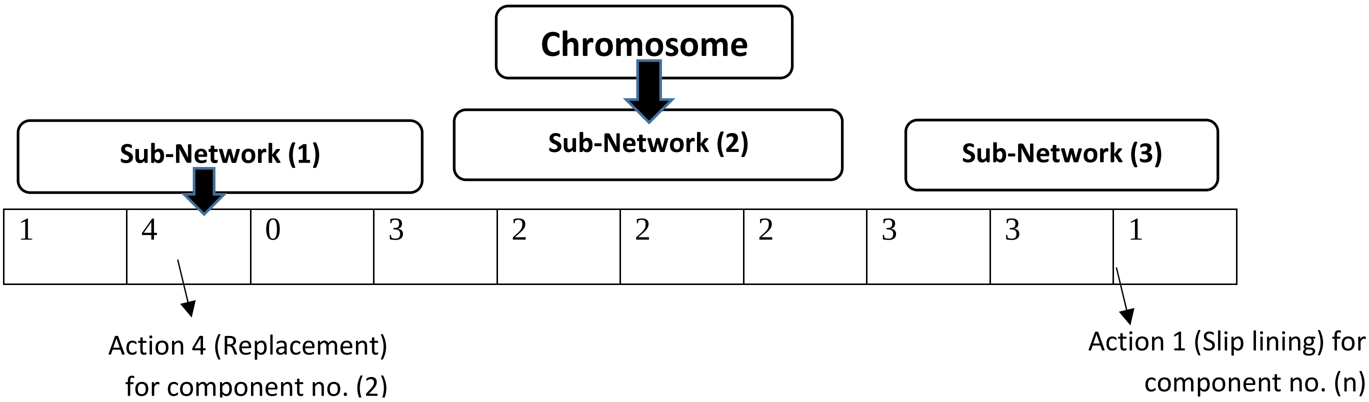

Fig. 3. GA Chromosome encoding

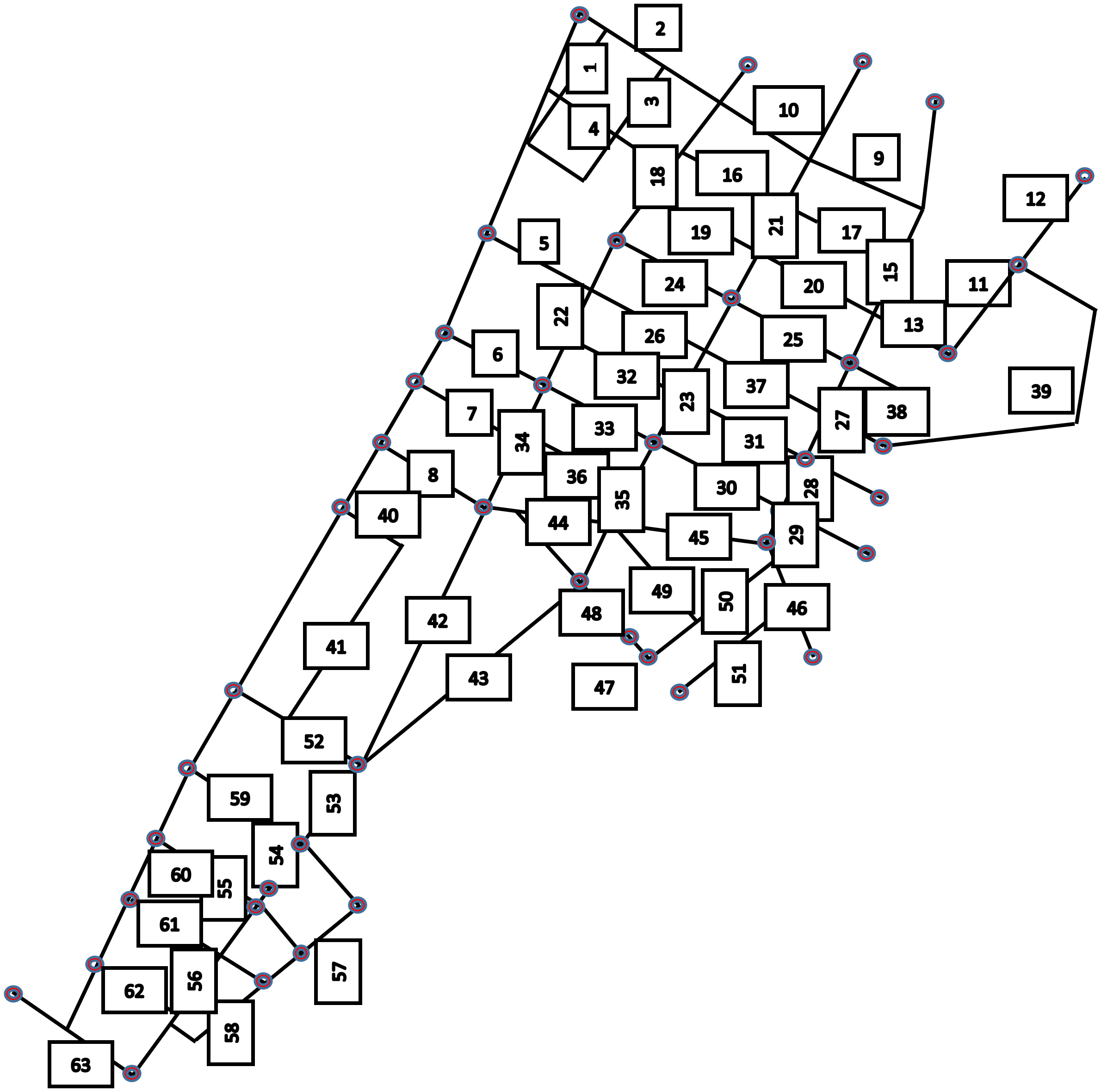

Fig. 4. City of Montreal sub-network layout

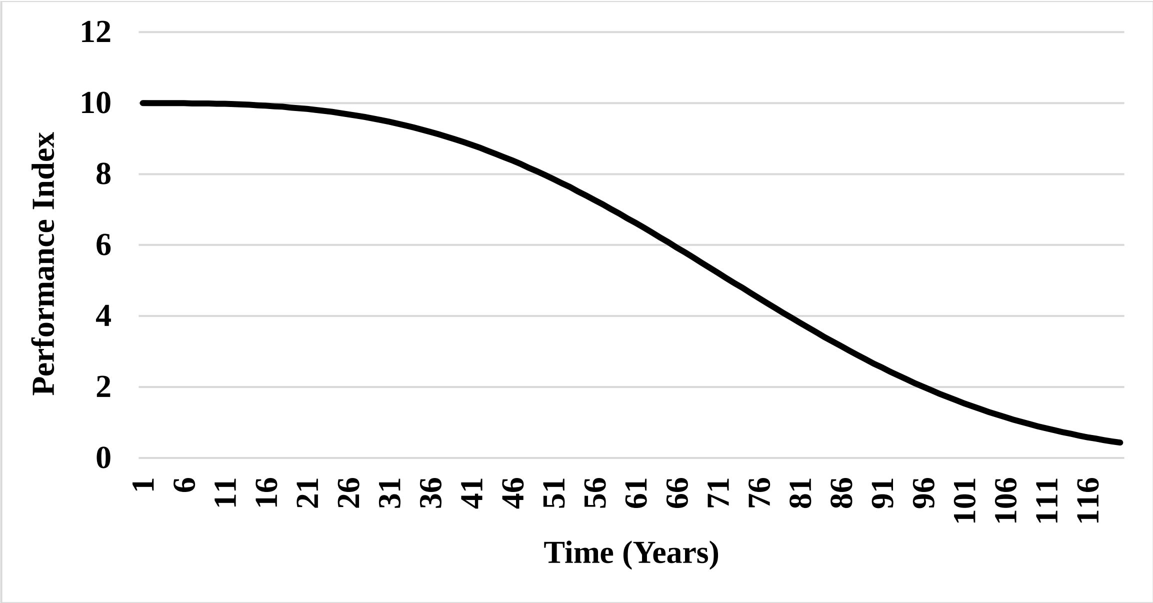

Fig. 5. Deterioration curve of pipe #2 without rehabilitation

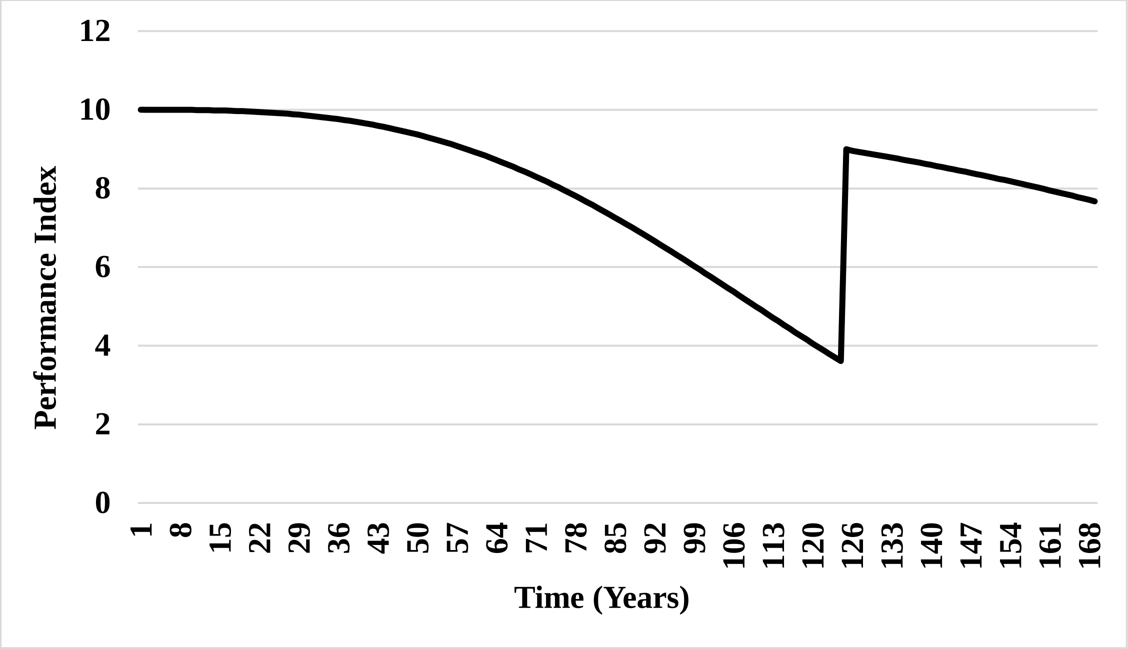

Fig. 6. Deterioration curve of pipe #1 including rehabilitation

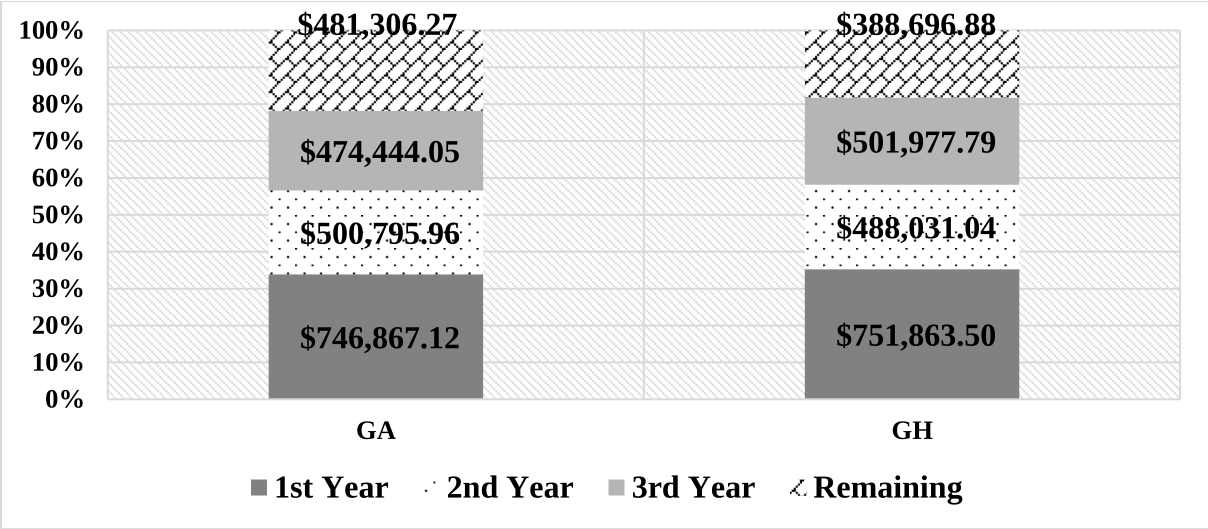

Fig. 7. Three-Years Budget allocation plan best scenario [CAD (0.75, 0.5, 0.5)*10^6]

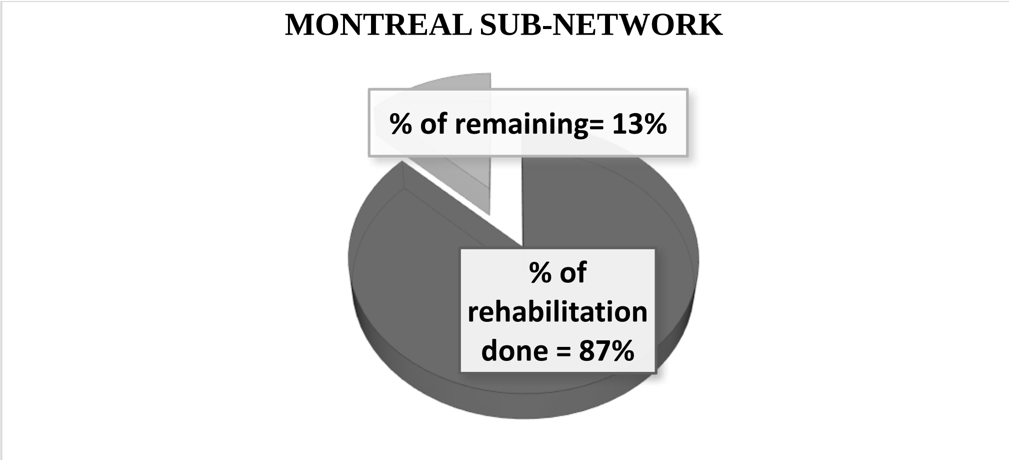

Fig. 8. Percentage of the rehabilitation done vs. the remaining part.

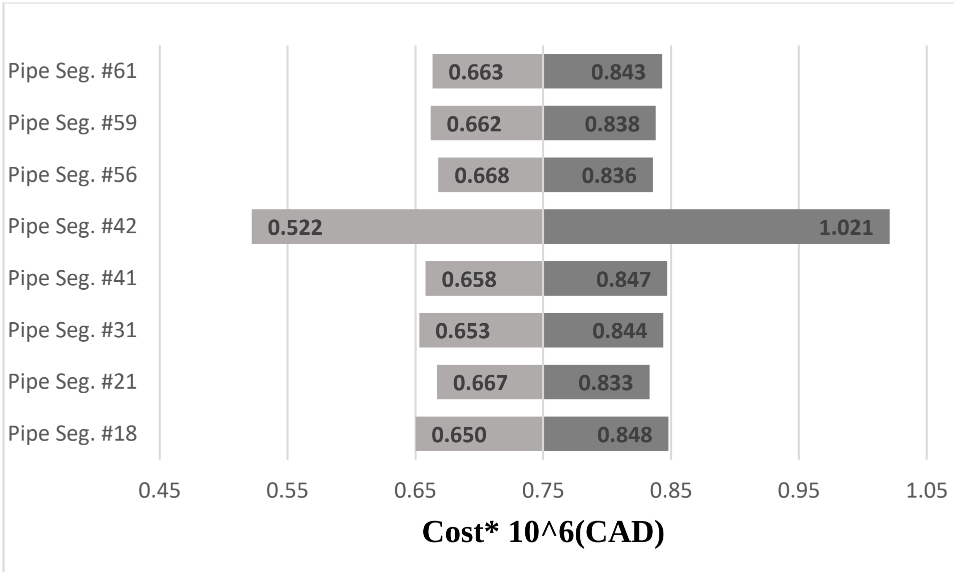

Fig. 9. Sensitivity analysis of the rehabilitation cost to pipe segments rehabilitation

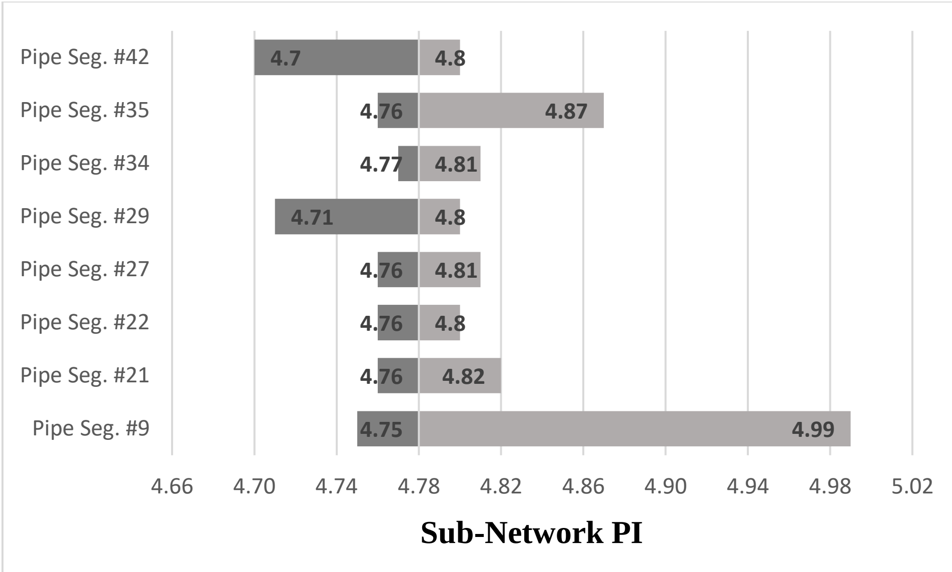

Fig. 10. Sensitivity analysis of the sub-network PI to pipe segments rehabilitation