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A decision support framework for integrated multi-infrastructure intervention

Un cadre d'aide à la décision pour une gestion intégrée d'interventions sur infrastructures interdépendantes

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RÉSUMÉ

Les infrastructures vieillissantes et défailtantes entraînent pour les municipalités un problème important de perte d'efficacité et de surcoûts. De plus, les activités d'intervention en zone urbaine ont un impact négatif sur la communauté de diverses manières, notamment sociales, environnementales et économiques. Par conséquent, une coordination de l'entretien des infrastructures municipales basée une gestion intégrée d'infrastructures interdépendantes devient de plus en plus importante pour réduire les interruptions de service, les coûts de réparation et les temps d'interruption. Cette étude a visé à développer un cadre permettant de maintenir un niveau acceptable de service tout en maximisant l'efficacité des dépenses financières entre les différentes infrastructures interdépendantes lors des planifications budgétaires. Trois piliers principaux composent ce cadre : I. Modèles de risque associé aux infrastructures individuelles, II. Modèles coûts-bénéfices, et III. Modèles d'aide à la décision. Les résultats préliminaires démontrent l'applicabilité de ce cadre. Comparativement à l'approche d'intervention conventionnelle, le cadre proposé est plus efficace en termes de dépenses municipales sur un même périmètre.

ABSTRACT

A major problem for municipalities is the inefficiency and financial burden that comes from aging infrastructure that does not perform well. Additionally, intervention activities occurring in cities negatively impact the community in a variety of ways, including social, environmental, and economic. As a result, coordinating municipal infrastructure maintenance through integrated multi-infrastructure asset management has become increasingly important to reduce service disruptions, repair costs, and interruption times. The current study seeks to develop a framework that helps maintain an acceptable level of service while maximizing the efficiency of expense utilization among interdependent assets during planning horizons. Three core pillars make up the framework: I. Risk model of individual assets, II. Cost-benefit model, and III. Decision support model. The preliminary results show the applicability of the framework. As compared to the conventional intervention approach, the proposed framework is more efficient from the standpoint of municipal expenditures on the same corridor.

KEYWORDS

asset management, deterioration, joint interventions, risk assessment, urban networks

1 INTRODUCTION

Several challenges confront asset managers when it comes to inspecting, maintaining, repairing, and replacing existing infrastructure assets in a cost-effective manner: ranging from ageing assets, lack of maintenance budget, rising facility usage and high expectation of the society for better service quality. Many infrastructure systems and their constituent components can be thought of as interdependent, complex, adaptive systems, where "what happens to one infrastructure can have an effect on others". In practice, however, infrastructure systems and their components are generally managed separately, and the data is stored and managed in separate and often incompatible dashboards (Marzouk & Osama, 2017). In this regard and to reduce service disruptions, repair cost, and time, an integrated multi-infrastructure asset management system can be adopted; Moreover, this approach facilitates the flow of information across different disciplines and activities, improving reliability, consistency, and efficiency of decisions.

A study by Carey and Lueke (2013) examined three infrastructure networks (roads, sewers, and water distribution), by emphasizing on the economic benefit and monetary savings. In addition, random network conditions are used instead of real existing ones. Marzouk and Osama (2015) investigated how to optimize the replacement timing of different infrastructure networks (roads, sewers, water, gas, and electric cables) in a hypothetical numerical case study without geographical components. In order to facilitate the decision-making process for corridor rehabilitation projects, Shahata and Zayed (2016) developed an integrated risk-assessment framework for municipal infrastructure. In this study, risk was used to prioritize the corridors' rehabilitation, using mixed-Delphi and AHP paired with unsupervised K-means clustering, and they proposed cost-efficient risk mitigation strategies. Moreover, some scholars investigated multi-objective optimization to model the suitable intervention timing for two or more networks. However, due to some limitations (e.g., dataset size, computational cost) few numbers of corridors were compared (Abu-Samra et al., 2020). Recently, Daulat et al. (2022) highlighted seven main challenges that can hinder the application and acceptance of an integrated approach.

Our study mainly addresses the challenge VI: problems of scale and VII: problems of interplay presented in Daulat et al. (2022). It aims to develop a framework based on the efficient expense utilization among the interdependent assets throughout the planning horizon while maintaining an acceptable level of service.

2 METHODOLOGY

The methodology is based on the combination of three modules: I. Risk model of individual assets, II. Cost-benefit model, and III. Decision support model (Figure 1). The risk model determines which asset(s) need intervention. It combines the failure (or survival) probability of an asset (which can be obtained via deterioration modeling) with the asset importance (the relative importance of assets to each other). For low important pipes, relatively higher risk of failure is tolerated compared to medium and high important pipes. The same goes with medium compared to high important pipes. The different tolerances for risk can be translated into intervention thresholds as described in Daulat et al. (2022).

The cost-benefit model compares the cost savings of integrated multi-infrastructure intervention (which can be obtained by calculating the shared work between the utilities i.e., the shared trench volume) with the costs of premature replacement (i.e., the remaining value of an asset at the time of replacement).

From the comparison, the model calculates the net benefit for an integrated intervention. The benefit varies depending on joining of the other co-located assets and their degree of co-location. The decision support model then suggests if joint intervention to be carried out based on a decision rule. There is only one decision rule: integrated intervention to be carried out only if the net benefit is positive.

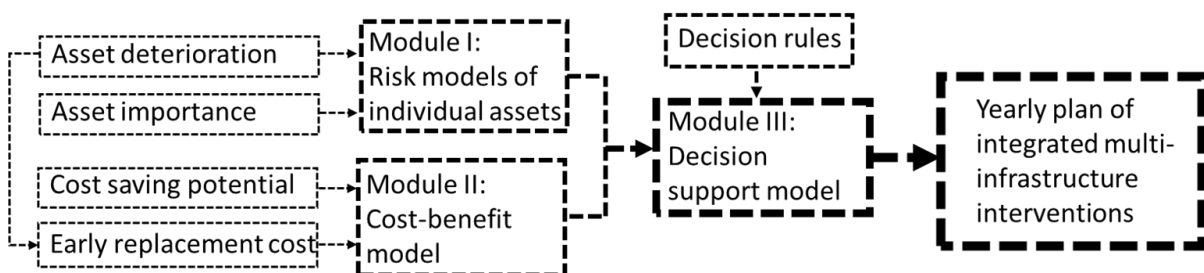


Figure 1. Flow chart for decision support framework of integrated multi-infrastructure interventions

3 CASE STUDY

The presented method has been applied to a portion of a city in Norway. Deterioration models for water and sewer pipe was trained using random survival forest, a machine learning approach which provides probability of changing from an initial state to a posterior state versus time for individual assets. In the case of water pipes, the probability of next failure versus time, and in the case of sewer pipes, the probability of changing to a bad condition (either condition 4 or 5) from a good condition (either condition 1, 2 or 3) versus time was achieved. For roads, data was not available to model their deterioration. Instead, the road authorities provided their own model results in which the model considers not only deterioration but also the importance of different roads. The results show the time of a road construction and the time that it needs reconstruction. For simplicity, this study assumed a linear deterioration from the time of construction to the time of reconstruction.

The importance (criticality) of the water and sewer pipes were assumed to be directly correlated with pipe diameter and hence, the importance of pipes was divided into three categories based on diameter.

Table 1. Importance categorization of pipes based on diameter

	Low importance	Medium importance	High importance
Water pipes diameter [mm]	≤ 150	150 – 500	≥ 500
Sewer pipes diameter [mm]	≤ 200	200 – 500	≥ 500

The intervention thresholds are subjectively selected for different pipe categories as illustrated in the figure below.

The intervention thresholds are subject to change based on available budgets and level of service of the utilities. For roads, the intervention times are predicted by the road authority and the data is provided.

Cost saving potential is obtained by calculating the amount of common work among the utilities. The amount of common work is defined by the shared trench volume among the co-located assets. The trench volume for an asset is the volume that is needed to be excavated to replace the asset. The shared trench volume among the assets is calculated using python libraries, and Buffer and Intersect functions in ArcGIS Pro (ESRI, 2021) (Figure 3). The share of cost by a utility is then determined by dividing the shared volume by the number of assets sharing this volume.

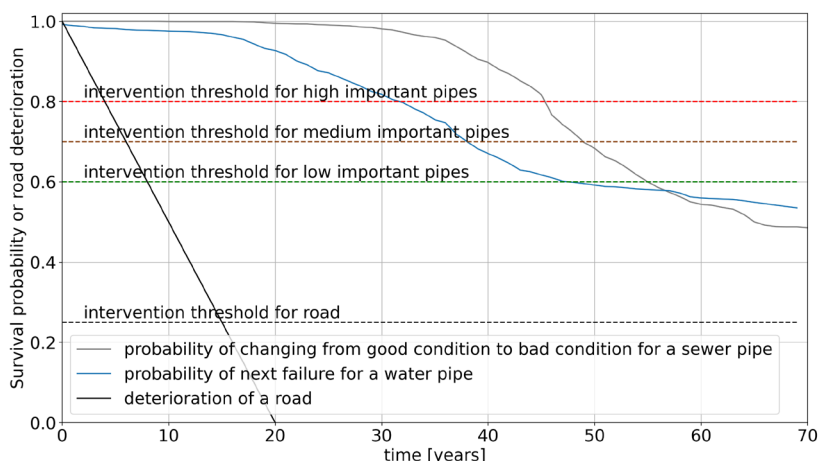


Figure 3. Intervention thresholds for a sample of water and sewer pipes based on the relative importance of pipes

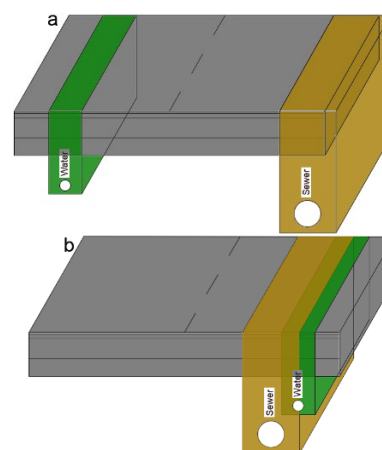


Figure 2. Shared trench volumes (a) between road and water/sewer (b) between road, sewer, and water

Cost of early replacement is obtained by assuming a linear decrease between the initial state of an asset (time=0, value=100%) and at the time when the pipe needs intervention (time=intervention time, value=0%). For pipes, however, the remaining value include not only the remaining value of a pipe but also the remaining value of the trench that needs to be excavated, because every time we renew a pipe prematurely, we also discard a trench that could have been used until the end of the pipe life. Think of it like the trench is deteriorating exactly as the pipe (although it is not correct). To compare the remaining value with the cost saving potential of pipes, the pipe value needs to be presented in terms of percentage of trench cost. Pipe value is considered to be roughly 10% of the total cost of trench, after an online search. Finally, the cost-benefit model subtracts the cost of early replacement from the cost saving potential. As an example, one project is selected for the intervention plan in 2025 to showcase the results (Figure 4 and Table 2).

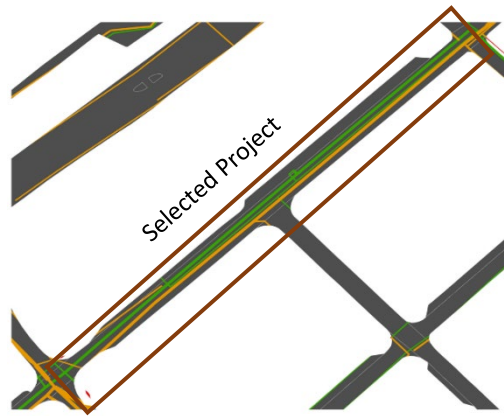






Figure 4. A selected project

Table 2. A selected project in the yearly plan 2025 to examine the possibility of joint intervention

	IT^*	Age [y ^{**}]	Remaining use [y]	Remaining value	Shared trench volume	Cost sharing potential	% of saving (Joins intervention?)
 Road	-	12	3	20%	18% (with water 1) 19% (with sewer)	18%/2 = 9% 19%/2 = 10%	9%+10%-20% = -1% (no)
 Water1	0.7	58	0	0%	38% (with road)	38%/2 = 19%	19% (Triggers action)
 Water2	0.6	31	16	34%*(0.1+1) = 37%***	38% (with road)	38%/2 = 19%	19%-37% = -18% (no)
 Sewer	0.8	31	1	3%*(0.1+1) = 3%	25% (with road)	25%/2 = 13%	13%-3% = 10% (yes, if road joins)

* Intervention threshold, ** years, *** 34% of pipe and trench value is remaining (a pipe value is 10% of a trench value)

The selected project is interesting. Road will not join the intervention because it does not benefit with the current decision rule. However, if water pipe 1 accepts to incur a bit more than half of the shared trench cost (e.g., 70% by water pipe 1 and 30% by road) for the road to gain benefit, the road will join the intervention. As a secondary effect, sewer will also join the intervention. However, water pipe 2 is far from gaining benefit, thus it does not join the intervention.

4 CONCLUSIONS

An integrated multi-infrastructure intervention framework for road, water, and wastewater networks was presented in this research. The proposed structure stands on 3 pillars: I. Risk model of individual assets, II. Cost-benefit model, and III. Decision support model. A project in a city of Norway was used as an example of how the suggested integrated multi-infrastructure intervention framework could be used. Results for one selected project show that the framework is applicable and can be expanded for all the projects in a city, and eventually an yearly action plan can be obtained and shared among the utilities.

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