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Investment Strategies to Maintain the State of Water Networks

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Abstract:

Purpose: This article focuses on the problem of deciding the annual investment that a water company should allocate to the rehabilitation of its distribution and sanitation networks. The objective is to find the investment amount necessary to maintain an adequate quality and sustainability of the infrastructure. It is not a simple decision, as there are different criteria that may be of interest to the different agents involved. In this paper, we consider four criteria related to the reliability of individual pipes and the complete network. These indicators are the infrastructure value index, the average age of network pipes, the risk index and the probability of failure.

Design/methodology/approach: A methodology is proposed to estimate the best annual investment by analysing the evolution of these indicators. Concretely, two strategies are tested. The first one is a minimax-based approach that seeks a balanced solution for all the indicators. The second one is named as minimal deviation strategy and seeks to minimise the deviation of all the indicators in the last year of the time horizon compared to the initial year.

Findings: In order to obtain a realistic sample of the performance of both strategies, 201 scenarios, i.e. 201 different annual investments have been simulated. According to the first strategy, an annual investment of 55.5 M€ is the best option, while the minimal deviation strategy presents an annual investment of 39.5 M€ as the best decision. The study reveals that different evaluation functions lead to completely different annual investment. Concretely, the minimax evaluation function is more conservative than the minimal deviation strategy.

Originality/value: This study proposes an original approach to address the decision problem of investments in asset management. To the best of the authors' knowledge, it is the first attempt to treat that problem using this kind of evaluation functions. However, it is still a relatively straightforward proposal and there are many possible options to continue this line of research.

Keywords: water supply networks, sewer networks, infrastructure asset management, investment, rehabilitation

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1. Introduction

Water supply and sewer networks are vital infrastructures for the proper development and growth of cities. However, most of these systems were built decades ago and show signs of deterioration. The management of water networks can be carried out by public, private or semi-public companies; regardless of who manages them, the investment allocated to renewing network assets is often not sufficient to maintain their proper condition (Aparicio-Ruiz, Onieva, Muñuzuri & Ramos-Salgado, 2022). Like any other industrial infrastructure, it is crucial to keep them in good condition. Nowadays, there is a current trend to implement predictive instead of corrective maintenance, as it has proven to be more sustainable and cost-effective. Numerous recent studies explore the use of novel techniques, such as machine learning, to enhance water network management (Barton, Hallett & Jude, 2022; Godbole & Sarawagi, 2004; Robles-Velasco, Cortés, Muñuzuri & De-Baets, 2023; Robles-Velasco, Muñuzuri, Onieva & Cortés, 2021). All these studies aim to predict vulnerable pipes or network segments to prioritise their replacement. In the article developed by (Forero-Ortiz, Martinez-Gomariz, Sanchez-Juny, Cardus-Gonzalez, Cucchietti, Baque-Viader et al., 2023), papers published in the last 15 years on models predicting water pipe failure in water supply and distribution networks are reviewed. Furthermore, the authors analyse the most common explanatory variables. One example is the work developed by (Yan, Wang, Zhou, Huang, Tian, Zha et al., 2013), where the rehabilitation system is divided the into four modules: data processing, pattern display, model training and risk prediction. Within predictive modelling, they compare several approaches using real network data: survival models, neural networks, logistic regression and Chaid trees.

In order to apply these novel techniques, it is essential for companies to have historical data on the characteristics of its networks and other operational aspects such as pipe failure history. (Rokstad, Ugarelli & Sægrov, 2015) analyse the cost-benefit of collecting and using data in infrastructure asset management. Data collection is a long-term investment. While certain data may be of little use today because of the tools available, it is very likely that in the future, following the development of new tools, they will produce many benefits. It is therefore important that companies implement good practices in the collection and processing of their data.

Another trend in the field is the use of fuzzy logic to build multi-criteria decision-making systems. In the study developed by (Salehi, Fontana, Tscheikner-Gratl, Herrera, Sadiq & Mian, 2024), they calculate a rehabilitation index of individual pipes applying the fuzzy TOPSIS method to a battery of surveys answered by 20 experts of different nationalities. This work is an advanced version of their earlier study (Salehi, Jalili-Ghazizadeh & Tabesh, 2018), where it can be found an interesting classification of models on water distribution system rehabilitation developed within 1996-2016.

Elimination and Choice Expressing Reality (ELECTRE) is an alternative method to select performance indicators for water networks. In the study developed by (Pereira, Morais & Figueira, 2020), the authors apply the aforementioned technique to select alternatives among different maintenance and rehabilitation orders. The methodology is tested in a real case study from a city located at the northeast of Brazil, whose water distribution network is divided into 11 different areas. (Caetano, Carriço & Covas, 2022) also apply ELECTRE TRI-C and FlowSort (an extension of the PROMETHEE method) to assign each network pipe to a predefined priority category (high, intermediate or low priority). The authors point out that these approaches treat pipes individually, however, actual rehabilitation projects plan works that include many pipes taking into account their geographic location. Therefore, the authors propose the use of clustering to group individual pipes into coherent rehabilitation units considering cost criteria.

Once the replacement tasks have been decided, it is also important to measure how the condition of the water networks evolves after these decisions. In order to evaluate the condition of water networks, it is necessary to have indicators that adequately represent different aspects of the infrastructure. In the work developed by (Alegre, Coelho, Covas, Do-Céu-Almeida & Cardoso, 2013), they analyse the evolution of several metrics, such as the percentage of asbestos cement pipes or a risk index indicator, in a network with 12.5 km of supply pipes that serves 10,000 people. Their work establishes the optimal range for each metric based on expert opinion. Another study developed by (Shin, Joo & Koo, 2016) proposes a model to find the optimal annual investment, taking into account the costs of different actions (no action, renovation and replacement), and measuring the pipe failure rate of a network composed of 16 km of drinking pipes. A more recent study (Caetano, Carriço, Figueira & Covas,

2023) proposes a methodology divided into two phases. First, graph theory is used to cluster the pipes that compose the water network. Then, a scheduling of interventions is proposed in the medium and long term according to two relevant criteria: the Average Residual Life (ARL) and the Infrastructure Value Index (IVI), indicator that the authors take from the previously mentioned study (Alegre, Vitorino & Coelho, 2014). The methodology is evaluated on a real network of 113 km located in the south of Portugal.

This paper presents two strategies to measure the evolution of water networks' conditions over the years according to different annual investments. For this purpose, the use of four indicators is proposed. In addition, the strategies are tested on the water network of Seville, a Spanish city whose network is managed by the public company EMASESA. The study aims to find the optimal annual investment necessary to maintain the infrastructure in adequate conditions over the years. The analysis of this case study is a continuation of a previous study developed by (Ramos-Salgado, Muñuzuri, Aparicio-Ruiz & Onieva, 2022) in which they determined the annual investment using one specific metric, the risk index. Our study intents to refine this criterion by analysing the evolution of all available metrics rather than just one. To the best of the authors' knowledge, it is the first attempt to treat that problem using this kind of evaluation functions, being the major contribution of the study.

The paper is organised in five sections. After this introduction, Section 2 presents the two proposed strategies. To this end, the indicators used to represent water networks' conditions are first defined in section 2.1. Then, the strategies are explained in sections 2.2 and 2.3. In order to evaluate the strategies' performance, they are implemented in a real case study, the water distribution and sanitation network of Seville, a city in southern Spain. The indicators are analysed for this case study of in Section 3. Section 4 presents and discusses the results. Finally, the conclusions of the study are developed in section 4.

2. Proposed Methodology

In this section, the proposed strategies to find the best annual investment that a water company should allocate to the rehabilitation of its networks are described. Firstly, the indicators selected to address networks' conditions are presented. Secondly, two strategies for determining the optimal annual investment are presented in subsection 2.2 and 2.3.

2.1. Definition of Indicators

Four indicators are used to represent the state of the water network. The selection of the indicators is due to their availability as well as their suitability for the purpose of their use.

2.1.1. Infrastructure Value Index (IVI_t)

This indicator was developed by (Alegre et al., 2014) and represents the weighted average of the remaining life of pipes based on their replacement cost. This indicator has been previously used by other authors to represent the evolution of water network condition according to replacement strategy employed by the management company (Caetano et al., 2023).

Equation (1) shows the calculation of the indicator, where $cs_{i,t}$ represents the cost of substituting pipe *i* in year *t*, $r\_life_{i,t}$ is the remaining pipe service life, and $s\_life_{i,t}$ is the total pipe service life. The *IVI* is an index whose value ranges from 0 to 1, representing the renewal rate of the network and allowing to characterise its overall situation.

$$IVI_t = \frac{\sum_{i=1}^{N}(cs_{i,t} \cdot \frac{r\_life_{i,t}}{s\_life_{i,t}})}{\sum_{i=1}^{N} cs_{i,t}} \quad (1)$$

An *IVI* below 0.5 would indicate an infra-maintained network and a consequent uncontrolled increment of operational problems, while as the indicator approaches 1, it would indicate a young or over-rehabilitated network. Therefore, the *IVI* should be around 0.5, which would imply an adequate renewal rate.

2.1.2. Age of Network Pipes (AGE_t)

This indicator represents the average age of all the pipes that compose the water distribution and sewer network. It is measured in years. The indicator is typically obtained from the installation year of all the pipes that compose the network. However, it is not so easy to calculate because many of the repairs or replacements only affect a part or section of the pipes and not the whole piece. It is therefore necessary to establish a procedure for calculating the indicator that accurately represents the real age of the network.

2.1.3. Probability of Failure (PF_t)

Although there are many different ways to estimate the probability of failure of water pipes, in this case, the indicator depends on five factors related to the individual pipes: network type, pipe material, age, diameter and location. More information on its calculation could be found in (Muñuzuri, Ramos, Vázquez & Onieva, 2020). In this study, the authors conclude that this indicator has a high influence on the estimation of individual pipes' condition.

2.1.4. Risk Index (RI_t)

This indicator was also presented in the study developed by (Muñuzuri et al., 2020), and it is calculated using the previously mentioned probability of failure of the pipe section, the demand of the supply pipes, the maximum evacuation flow rate of the sewerage pipes, the leakage flow rate of the control sector (only for supply pipes), and the relevance of the pipe, which is directly related to the nature of its consumers. For instance, a pipe is more relevant if it supplies to sensitive consumers such as hospitals.

The last three indicators, AGE, PF and RI, are calculated as the weighted average of their values according to the length of the pipes. In certain way, the first two indicators refer to the age of the infrastructure and the last two to its vulnerability.

The objective of this study is to find the annual investment that optimise all the indicators at the same time. For this purpose, we propose the following steps: (1) Normalise the indicators; (2) Establish an evaluation function; (3) Evaluate the evaluation function for a battery of the scenarios; and (4) Choose the annual investment (or scenario) that optimises the evaluation function. It needs to be considered that, in general, companies aim to maintain the good condition of the network using the lowest required budget.

2.2. Minimax-Based Strategy

The first strategy consists of minimising the worst value achieved by the four indicators over the set time horizon. All indicators are updated annually according to the company's investment in network maintenance. Consequently, the higher the annual investment, the better the values of the different indicators in the different years of the study horizon.

The evaluation function of this strategy is shown in Equation (2). Where the subscript i refers to the annual investment of the different scenarios, being i=1,...,Q; and the subscript t refers to the different years of the analysed time horizon, being t=1,...,T. Q is the set of annual investments tested and T is the time horizon analysed.

$$F1(IVI, AGE, RI, PF) = \min_i \left(\max_t(AGE_{t,i}) - \min_t(IVI_{t,i}) + \max_t(PF_{t,i}) + \max_t(RI_{t,i}) \right) \quad (1)$$

The evaluation function first obtains the maximum value of the AGE, IR and PF indicators for each annual investment i, as well as the minimum value of the IVI on the time horizon. These are the worst values of the indicators for the time horizon. Next, it seeks the annual investment whose sum of the four values previously found is the minimum. In other words, the objective is that in none of the years, an undesired value of any of the indicators is reached, seeking to reduce them globally.

As each indicator has its proper units, they are all normalised before calculating the evaluation functions.

2.3. Minimal Deviation Strategy

The second strategy consists of reducing the deviation of all indicators at the end of the time horizon with respect to the initial year. To achieve this objective, the absolute difference between the indicators' values in all years within the designated time horizon and their initial values is computed. This calculation is performed for each annual investment. To facilitate a comparative analysis of both strategies, an identical set of scenarios (i=1,...,Q) must be simulated over the same time horizon (t=1,...,T).

The evaluation function is shown in Equation (3).

$$F2(IVI, AGE, RI, PF) = \min_i\left(\left|AGE_{25,i} - AGE_{0,i}\right| + \left|IVI_{25,i} - IVI_{0,i}\right| + \left|PF_{25,i} - PF_{0,i}\right| + \left|RI_{25,i} - RI_{0,i}\right|\right) \quad (1)$$

This strategy aims to maintain the initial state of the water network over the years and not to have a large deviation for any of the indicators in any of the years.

3. Case Study: The Water Network of Seville

Seville is a Spanish city with more than 1 million inhabitants whose water network has almost 7000 km and it is managed by a public company named EMASESA. In this section, the evolution of the aforementioned indicators according to different annual investments is analysed. Specifically, annual investments from 0 to 100 million euros with increments of 0.5 have been simulated, a total of 201 simulations, i.e., i=1,…,201. Moreover, in all simulations, the time horizon has been established in 25 years, i.e., t=1,…,25, being the initial year 2023.

Figure 1 shows the expected value of the indicators in the last year of the horizon (in our case 2048) for the different simulated annual investments. In addition, the values of the indicators in the starting year have been marked with a horizontal red line, which helps to obtain the annual investment required to maintain these values over time (vertical red line). It can be seen how maintaining the current value of each indicator in the year 2048 requires a different annual investment. Particularly, 33.0 M€ per year are necessary to maintain an average overall network age of 35.09 years and an overall network PF of 1.35% (initial values). According to the risk index, 24.5 M€ per year are needed to maintain its initial value of 1.0. Finally, maintaining an IVI of 0.46 (initial value) requires an annual investment of 43.5 M€, the highest amount.

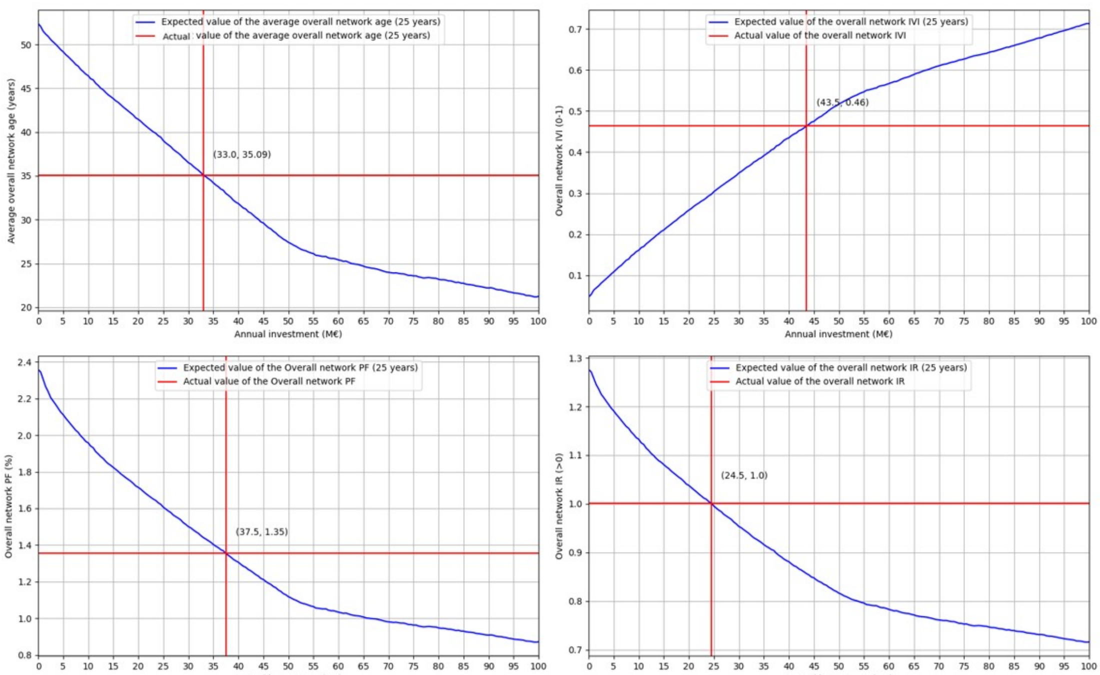

Figure 1. Expected value of the indicators in the last year of the horizon (2048) according to the different simulated annual investments

To gain a more comprehensive understanding of the study's scope, Figure 2 shows the evolution of one of the indicators, the IVI, over the time horizon for three different annual investments. Firstly, it is represented for the annual investment required to maintain the initial value of the indicator at the last year of the time horizon (43.5 M€), as well as when the annual investment is 10 M€ lower (33.5 M€) and 10 M€ higher (53.5 M€). It can be seen how the infrastructure value index varies over the years. Moreover, and in line with the previous Figure 1, this indicator grows as the annual investment increases, contrary to the other indicators.

The above figure is also illustrated separately for each type of water network, namely the water supply network (Figure 3) and the sewer network (Figure 4). The infrastructure value index, along with the other indicators, is computed as an average weighted according to the length of pipes in the supply and sewer networks. The water supply network constitutes approximately 57% of the total network length, while the sewer network represents 43%. It should be noted that part of the annual budget is allocated to the maintenance and replacement of the supply network, and another part is designated for the sewer network. The management company has its own policy for determining this distribution, a policy that has been maintained throughout the analysis.

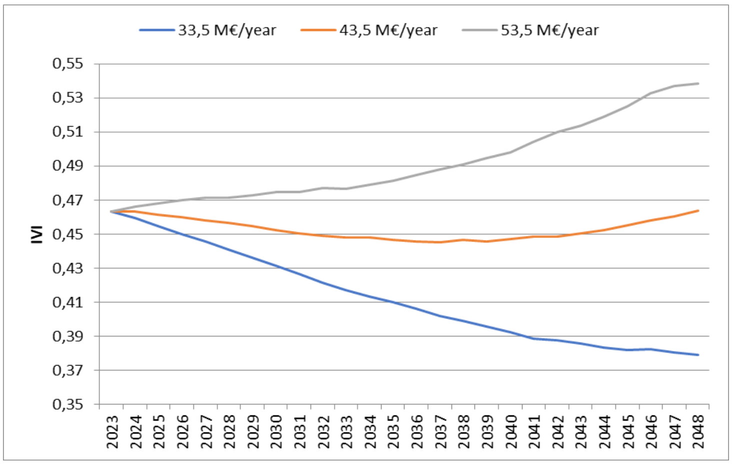

Figure 2. Evolution of IVI for three different annual investments for the whole network (supply and sewer)

In the following two figures, it can be seen that the conditions of the supply pipes are better than those of the sewer pipes according to the IVI. This is common in this type of infrastructure, as the supply networks require much greater control to comply with stricter legislation due to their direct impact on the quality of the water and the consequent health of the population. This behaviour is generally observed for all the indicators.

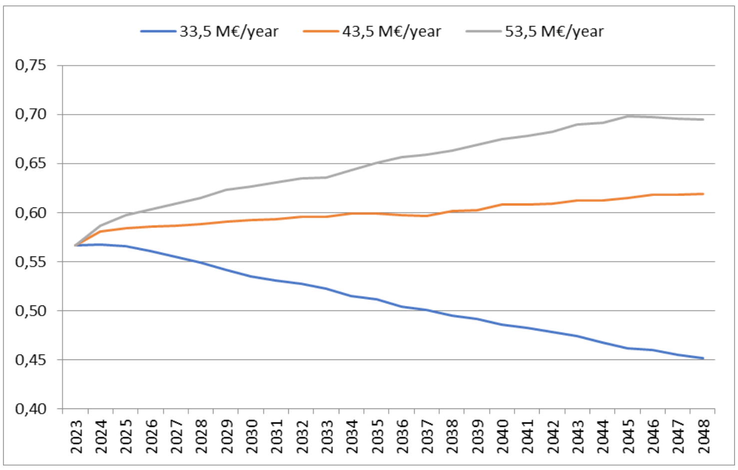

Figure 3. Evolution of IVI for three different annual investments for the water supply network

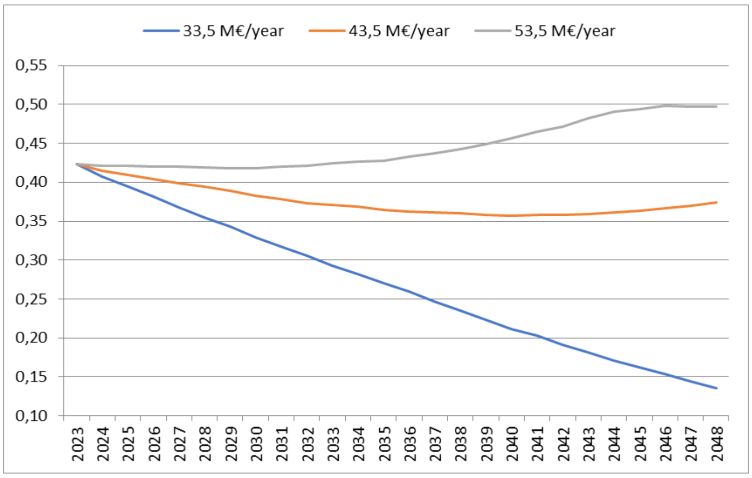

Figure 4. Evolution of IVI for three different annual investments for the water sewer network

4. Results

The results of the study have been obtained on the basis of a battery of 201 scenarios that contemplate annual investments ranging from 0.0 million euros (M€) per year to 100.0 M€ per year.

On one hand, Table 1 illustrates the results of applying the minimax-based strategy. The table contains the real value obtained for each indicator as well as the normalised value that is used to calculate the objective function. Due to space constraints, only some selected scenarios are presented, i.e., 6 different annual investments of 0.0, 25.0, 39.5, 50.0, 55.5 and 100.0 M€. According to this strategy, an annual investment of 55.5 M€ is deemed the optimal choice, yielding the minimum value for the evaluation function (F1=0.27-0.62+0.38+0.52=0.54, considering all decimal places and not solely the first two). For this investment quantity, the maximum average age that the infrastructure reaches over the simulated time horizon is 27.39 years, the worst value of the IVI will be 0.46, of the probability of failure 1.36%, and the risk index attains a value of 1.00. If we look at other investment values, for example an annual investment of 25.0 M€ would lead to the maximum average age of all the pipes being too much worse than in the optimal scenario, being 39.03 years and it would be reached in 2048, which corresponds to the last year of the horizon. On the other hand, the IVI without annual investment, i.e. 0 M€ per year attains an undesirable value of 0.05. From 55.5 M€ of annual investment, the network's condition demonstrates a gradual improvement over time, so that the worst values of the indicators (maximum AGE, PF and RI, and minimum IVI) appear in the initial year 0.

Annual investment$_i$	Indicator [Real value – Normalised value]								Evaluation function
	max($AGE_{t,i}$)		min($IVI_{t,i}$)		max($PF_{t,i}$)		max($RI_{t,i}$)		
0.0	52.39	1.00	0.05	0.00	2.36	1.00	1.28	1.00	3.00
25.0	39.03	0.61	0.30	0.39	1.61	0.53	1.00	0.52	1.28
39.5	32.10	0.41	0.43	0.57	1.36	0.38	1.00	0.52	0.74
50.0	28.39	0.30	0.46	0.62	1.36	0.38	1.00	0.52	0.57
55.5	27.39	0.27	0.46	0.62	1.36	0.38	1.00	0.52	0.54
100.0	27.39	0.27	0.46	0.62	1.36	0.38	1.00	0.52	0.54

Table 1. Annual investment (M€/year), (real and normalised) value of the indicators and evaluation function (F1) for the minimax-based strategy

On the other hand, following the minimal deviation strategy, an annual investment of 39.5 M€ is the best decision as shown in Table 2. For this investment, the evaluation function takes its minimal value (F2=0.13+0.05+0.03+0.20=0.41). For the comprehension of this table, it is important to mention that the value of the indicators in the starting year are an average age of 27.39 years, an IVI equals 0.46, a probability of failure of 1.36 and a RI of 1.00. Therefore, for an annual investment of 0.0 M€ (first line of the table), the age in the last year of the time horizon is 25 years older than in the initial year, i.e. the water network is on average 52.39 years old. Based on this assumption, the table shows that for an annual investment of 39.5 M€, the minimal deviation for the indicators are:

- A deviation of 4.61 for the average age of all the pipes that compose the water network. It corresponds to an average pipe age of 32 year achieved in 2047, the penultimate year of the time horizon.
- A deviation of 0.03 for the IVI, which corresponds to a value of 0.43 reached in the year 2034 and maintained in subsequent years.
- A deviation of 0.04 for the probability of failure. Contrary to the two previous indicators, this indicator improves, with a positive deviation, i.e. the probability of failure is better at the end of the horizon (1.32) than at the beginning (1.36).
- A deviation of 0.12 for the risk index. Like the probability of failure, the risk index shows a significant improvement if the company allocates €39.5M to pipe replacement, reaching a value of 0.88 in the last year of the time horizon.

It should be mentioned that this strategy seeks the minimum sum of the four deviations in absolute value, i.e., both positive and negative. Consequently, there may be other annual amounts that achieve the minimum deviation for a particular indicator, but not for the whole set.

Annual investment$_i$	Indicator [Real value – Normalised value]								Evaluation function
	$\lvert AGE_{25,i}-AGE_{0,i}\rvert$		$\lvert IVI_{25,i}-IVI_{0,i}\rvert$		$\lvert PF_{25,i}-PF_{0,i}\rvert$		$\lvert RI_{25,i}-RI_{0,i}\rvert$		
0.0	25.00	0.73	0.42	0.62	1.00	0.62	0.28	0.48	2.46
25.0	11.64	0.34	0.16	0.24	0.25	0.15	0.00	0.01	0.74
39.5	4.61	0.13	0.03	0.05	0.04	0.03	0.12	0.20	0.41
50.0	0.02	0.00	0.05	0.08	0.24	0.15	0.18	0.32	0.55
55.5	1.46	0.04	0.09	0.13	0.30	0.19	0.21	0.36	0.72
100.0	6.15	0.18	0.25	0.38	0.49	0.30	0.28	0.50	1.35

Table 2. Annual investment (M€/year), (real and normalised) value of the indicators and evaluation function (F2) for the minimal deviation strategy

4.1. Discussion

On the one hand, the analysis has shown the importance of the selection of indicators and their processing to stablish a rehabilitation planning in water networks. The first strategy implemented (minimax-based strategy) is clearly more conservative than the second one (minimal deviation strategy). In any case, these results provide estimated amounts that companies should analyse according to their possibilities. Nevertheless, the minimum value obtained, an investment of 39.5 M, should be the starting point that companies should assess.

On the other hand, if the indicators had not been normalised, the results would have been different in the case of the minimal deviation strategy. In this case, the optimal annual investment would be 50.0 M€. However, for the minimax-based strategy, the normalisation or not of the data would not influence the optimal solution, being in both cases 55.5 M€ per year.

5. Conclusions

The study presents two different strategies to decide the annual investment that a water management company should allocate to its replacement tasks by analysing the evolution of several indicators. Decision making about investments in network renewal and maintenance tasks by water management companies is an issue of great importance and has a direct impact on the (long-term) strategic plans of the company. It is therefore essential to choose indicators that reliably inform about the state of the network over the years.

As a conclusion, this study shows the importance of choosing the right indicators as well as the influence of developing a robust strategy to measure the state of water networks (evaluation function). The study reveals that different evaluation functions lead to completely different annual investments. Concretely, the first presented evaluation function is more conservative than the second one.

As the subject is indeed complex, it would be interesting to develop a more detailed analysis of the company's budget allocation policies and repair and replacement criteria. Furthermore, including these two aspects as variables in the study would help to reduce the investment needed to reach the same level of indicators.

As a future lines of research, it would be interesting to find the functions relating the annual investment to the indicators in order to develop a complete mathematical model. Additionally, it would be interesting to implement the proposed methodology to the different water types of networks (water supply network and sewer network) separately.

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References

Alegre, H., Coelho, S.T., Covas, D.I.C., Do-Céu-Almeida, M., & Cardoso, A. (2013). A utility-tailored methodology for integrated asset management of urban water infrastructure. *Water Science and Technology: Water Supply*, 13(6), 1444-1451. https://doi.org/10.2166/ws.2013.108

Alegre, H., Vitorino, D., & Coelho, S. (2014). Infrastructure Value Index: A Powerful Modelling Tool for Combined Long-term Planning of Linear and Vertical Assets. *Procedia Engineering*, 89, 1428-1436. https://doi.org/10.1016/J.PROENG.2014.11.469

Aparicio-Ruiz, P., Onieva, L., Muñuzuri, J., & Ramos-Salgado, C. (2022). Modelo de gestión de activos para empresas de infraestructuras hídricas. *Direccion y Organizacion*, 7(77), 22-30. https://doi.org/10.37610/dyo.v77i0.621

Barton, N.A., Hallett, S.H., & Jude, S.R. (2022). The challenges of predicting pipe failures in clean water networks: a view from current practice. *Water Supply*, 22(1), 527-541. https://doi.org/10.2166/ws.2021.255

Caetano, J., Carriço, N., & Covas, D. (2022). Lessons Learnt from the Application of MCDA Sorting Methods to Pipe Network Rehabilitation Prioritization. *Water (Switzerland)*, 14(5). https://doi.org/10.3390/w14050736

Caetano, J., Carriço, N., Figueira, J.R., & Covas, D. (2023). A novel methodology for pipe grouping and rehabilitation interventions scheduling in water distribution networks. *Urban Water Journal*, 20(7), 769-781. https://doi.org/10.1080/1573062X.2023.2209560

Forero-Ortiz, E., Martinez-Gomariz, E., Sanchez-Juny, M., Cardus-Gonzalez, J., Cucchietti, F., Baque-Viader, F. et al. (2023). *Models and explanatory variables in modelling failure for drinking water pipes to support asset management: a mixed literature review*. *Applied Water Science* (13). Springer International Publishing. https://doi.org/10.1007/s13201-023-02013-1

Godbole, S., & Sarawagi, S. (2004). Discriminative methods for multi-labeled classification. In Dai, H., Srikant, R., & Zhang, C. (Eds.), *Lecture Notes in Computer Science* (22-30). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-24775-3_5

Muñuzuri, J., Ramos, C., Vázquez, A., & Onieva, L. (2020). Use of discrete choice to calibrate a combined distribution and sewer pipe replacement model. *Urban Water Journal*, 17(2), 100-108. https://doi.org/10.1080/1573062X.2020.1748205

Pereira, L.S., Morais, D.C., & Figueira, J.R. (2020). Using criticality categories to evaluate water distribution networks and improve maintenance management. *Sustainable Cities and Society*, 61. https://doi.org/10.1016/j.scs.2020.102308

Ramos-Salgado, C., Muñuzuri, J., Aparicio-Ruiz, P., & Onieva, L. (2022). A comprehensive framework to efficiently plan short and long-term investments in water supply and sewer networks. *Reliability Engineering and System Safety*, 219. https://doi.org/10.1016/j.ress.2021.108248

Robles-Velasco, A., Cortés, P., Muñuzuri, J., & De-Baets, B. (2023). Prediction of pipe failures in water supply networks for longer time periods through multi-label classification. *Expert Systems with Applications*, 213. https://doi.org/10.1016/j.eswa.2022.119050

Robles-Velasco, A., Muñuzuri, J., Onieva, L., & Cortés, P. (2021). An evolutionary fuzzy system to support the replacement policy in water supply networks: The ranking of pipes according to their failure risk. *Applied Soft Computing*, 111, 107731. https://doi.org/10.1016/j.asoc.2021.107731

Rokstad, M.M., Ugarelli, R.M., & Sægrov, S. (2015). Improving data collection strategies and infrastructure asset management tool utilisation through cost benefit considerations. *Urban Water Journal*, 13(7), 710-726. https://doi.org/10.1080/1573062X.2015.1024692

Salehi, S., Fontana, M.E., Tscheikner-Gratl, F., Herrera, M., Sadiq, R., & Mian, H.R. (2024). A fuzzy group decision-making model for Water Distribution Network rehabilitation. *Urban Water Journal*, 21(3), 364-379. https://doi.org/10.1080/1573062X.2023.2295310

Salehi, S., Jalili-Ghazizadeh, M., & Tabesh, M. (2018). A comprehensive criteria-based multi-attribute decision-making model for rehabilitation of water distribution systems. *Structure and Infrastructure Engineering*, 14(6), 743-765. https://doi.org/10.1080/15732479.2017.1359633

Shin, H., Joo, C., & Koo, J. (2016). Optimal Rehabilitation Model for Water Pipeline Systems with Genetic Algorithm. *Procedia Engineering*, 154, 384-390. https://doi.org/10.1016/j.proeng.2016.07.497

Yan, J., Wang, Y., Zhou, K., Huang, J., Tian, C., Zha, H. et al. (2013). Towards effective prioritizing water pipe replacement and rehabilitation. *International Joint Conference on Artificial Intelligence (IJCAI)* (2931-2937).

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