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A DECISION-MAKING APPROACH TO ASSESS AND PRIORITISE INTERVENTION SOLUTIONS IN WATER DISTRIBUTION SYSTEMS

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Abstract

The present paper aims at proposing and demonstrating the application of a decision-making approach for the identification, assessment, comparison and prioritisation of different intervention solutions. Infrastructural, financial, performance and economic perspectives are considered in the study. The proposed approach is composed of three main modules: 1) Analysis planning and database construction; 2) Infrastructure, asset or component diagnosis and prioritisation; and 3) Study of intervention solutions for priority assets or components. Three assessment levels – macro, meso and micro – are proposed, and the decision-making approach is adapted to each level. A water distribution system located in Portugal is used to demonstrate the proposed approach. This case study comprises five water subsystems, including different assets, such as water storage tanks, pumping and booster stations and water distribution pipes. Five intervention solutions are defined by identifying the main problems associated with the priority subsystem and the respective causes. The intervention solutions are compared considering the financial metrics and performance indicators, such as standardised energy consumption, energy in excess per unit of the authorised consumption, infrastructure value index and non-revenue water. New metrics regarding the assets' physical condition are also incorporated in the assessment system. Results have shown the influence of considering different assessment criteria and performance indicators in the solutions' prioritisation, highlighting that the solution with the lowest capital cost does not always correspond to the solution with the highest overall performance.

Keywords
Decision-making approach, Intervention solutions, Prioritisation process, Water distribution systems.

1 INTRODUCTION

Decisions on the rehabilitation of urban water systems are traditionally made considering only economic indicators or subjective analysis perspectives. Nowadays, it is well recognised that the decision-making process based on a single perspective is limited and inappropriate, as other essential aspects, such as the technical performance, the physical condition, water quality issues and the risk of failure, are not taken into account [1].

Decision-making approaches aim to identify and prioritise all potential solutions with consideration of different perspectives (e.g., performance, condition, risk assessment, financial analysis) and to establish trade-offs [2]. In these approaches, intervention solutions are identified and compared with the *status quo* situation, corresponding to maintaining the current O&M practices and not making any investment.

Solutions can be classified as infrastructural, O&M or non-infrastructural [3]. Infrastructural solutions include investment interventions, such as rehabilitation works, as well as any expansion interventions. O&M solutions are considered due to deficiencies or potential improvements of

O&M or new operating and maintenance needs associated with the implementation of infrastructural solutions. O&M interventions can be divided into localised (e.g., flow-meters installation), permanent (e.g., changes in the operating mode of pump group) or systemic (e.g., inspection and repair of storage tanks). Examples of non-infrastructural solutions are pressure management or the implementation of efficient water-use measures.

Different techniques can be used to improve the decision-making process and the respective outcomes, such as multicriteria analysis (e.g., [1], [4], [5] and [6]), cost-benefit analysis (e.g., [7], [8] and [9]) and life-cycle cost analysis (e.g., [10], [11], [12] and [13]). Although there are several decision-making approaches, most are too complex to be used by water utilities hindering their use and the interpretation of results. Therefore, the use of simplified approaches, considering only one point of view, or of too many unjustified assumptions can make the purpose of implementing these approaches unfeasible. Many decisions are not sufficiently explored and can cause a premature end of asset life concerning their physical condition [14]. Besides, the selection of solutions is inherent to the rehabilitation or maintenance strategy of the water utility. Attention is now moving away from reactive strategies, which involve none or minor long-term planning, towards pro-active approaches based on predictive analyses to provide a sustainable service in the long-term [15].

The present paper aims at proposing and demonstrating the application of a decision-making methodology that allows the identification, assessment, comparison and prioritisation of different intervention solutions considering infrastructural, financial, performance and economic perspectives. Firstly, a description of the proposed decision-making approach is presented in Section 2. The case study is presented in Section 3 and the application of the proposed approach to this case study is presented in Section 4. Finally, conclusions are drawn and further research is presented in section 6.

2 DECISION-MAKING APPROACH

2.1 General approach

The proposed decision-making approach is composed of three main modules (Figure 1): 1) Analysis planning and database construction; 2) Infrastructure, asset or component diagnosis and prioritisation; and 3) Study of intervention solutions for priority assets or components. The aim of this approach is to identify, assess, compare and prioritise intervention solutions in urban water infrastructures considering infrastructural, financial, performance and economic perspectives. This approach is aligned with the infrastructure asset management approaches proposed by the ISO 5000x standards and the ISO 24512 [16].

The main innovative contributions from this approach compared to existing approaches are the proposal of three assessment levels – macro, meso and micro – and the adaptation of the decision-making approach to each level. Depending on the chosen assessment level, necessary data may vary in terms of detail, models in terms of complexity and results in terms of applicability. This approach can be applied by utilities with different levels of maturity and of infrastructural and operational knowledge and for different scopes and purposes of the analysis. A detailed explanation of each module will be presented, highlighting the differences between the three assessment levels.

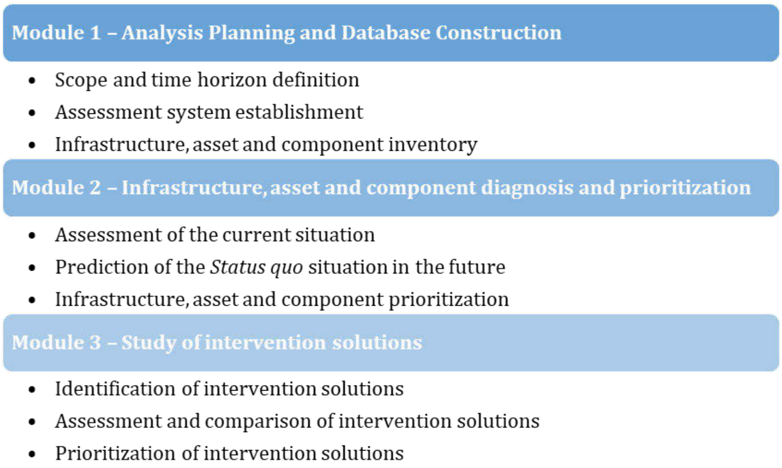

Figure 1. Decision-making approach to study intervention solutions in urban water infrastructures.

2.2 Analysis planning and database construction

Module 1 aims at defining the scope and time horizon of the analysis, to establish the assessment system and to construct a database per infrastructure, asset or component. The scope of the analysis is related to the assessment level. The macro assessment level aims at planning investment and maintenance tactics through the analysis of different scenarios and establishing policies and future directions at the infrastructure level. The meso assessment level corresponds to an intermediate analysis at the subsystem or asset level. The micro assessment level aims at planning and comparing intervention solutions at the asset and component level. These three assessment levels are carried out at the tactical planning level for a time horizon of 3-5 years; however, the period of analysis, in which the impacts of each solution are evaluated, should be larger than time horizon (e.g., 20-30 years). The period of analysis can significantly influence the results, thus, it should be defined taking into consideration different factors, such as the assets' service lives, the utility concession period and the assessment level.

The definition of the assessment system includes the establishment of objectives, criteria, performance indicators and reference values. The ISO 24512 [16] establishes a set of main objectives for drinking water utilities and all objectives must be measurable to ensure their monitoring over time by defining assessment criteria, performance indicators and reference values. For each assessment criteria, different performance indicators (PI) are defined according to the utility objectives and viewpoints. Some PI can be more disaggregated and applied to the entire system and subsystems to prioritise areas of analysis. Reference values allow to classify the obtained PI as good (represented by the green colour), average (represented by the yellow colour) or unsatisfactory (represented by the red colour).

The database construction includes the collection and processing of asset data for each urban water infrastructure. Three data categories are defined: technical, operational and economic. Technical data are associated with the physical characteristics of each asset, operational data with the asset operating mode and condition and economic data with CAPEX (capital expenditures) and OPEX (operating expenditures). The information detail may vary depending on the chosen assessment level. The macro assessment level requires basic information to study different investment and maintenance solutions, while the micro assessment level needs basic and complementary information to assess and select intervention solutions. Meso assessment level corresponds to an intermediate level of data needed. At the macro and meso levels, some basic information can be qualitative, such as the asset condition (i.e., the condition can be defined using a qualitative scale: excellent, good, reasonable, poor and unsatisfactory condition). However, at the micro assessment level, the information should be more robust and accurate and, therefore, it is preferable to be quantitative.

2.3 Infrastructure, asset or component diagnosis and prioritisation

Module 2 aims at assessing the current situation and predicting the time evolution of the *status quo* situation (i.e., not considering rehabilitation interventions and maintaining the current O&M practices) and prioritising infrastructures, assets or components in terms of intervention needs. The assessment of the current situation is carried out by calculating the defined PI in the previous module and is used to identify the main operational and physical problems. The diagnosis and the prioritisation processes can be carried out in the infrastructure, asset or component depending on the chosen assessment level, respectively for macro, meso or micro.

Condition assessment is one of the most important steps in the assessment of the current situation however, the complexity of the process and the robustness of the results can vary with the assessment level. At the macro assessment level, the condition assessment is carried out using a value-based approach, corresponding to the calculation of the Infrastructure Value Index (IVI) not requiring inspection. This is one of the most appropriate approaches for the macro assessment level since it is easy and straightforward to calculate and less resource-consuming. At the meso assessment level, the condition assessment is carried out by using a direct rating-based approach, consisting of visually inspecting each component, evaluating it against the rating criteria and selecting the appropriate rating as: excellent, good, reasonable, poor and unsatisfactory condition. At the micro assessment level, the condition assessment is carried out using a distress-based approach to assess the physical condition of urban water assets through visual inspection for the identification and classification of anomalies. The direct rating-based approach and the distress-based approach were proposed by Cabral et al. [17]. A prediction of the *status quo* situation in the future is also developed to verify the evolution of the current situation and to predict future problems not yet identified considering future changes in terms of consumption demand, new regulatory requirements and asset deterioration.

After the assessment of the current and future situations, infrastructures, assets or components are prioritised for intervention, considering the assessment results of PI and their criticality. The asset criticality is associated with the failure consequences, that is assets with high failure consequences are considered critical. Five prioritisation levels can be defined: extreme low, low, moderate, high and critical. If more than one PI is used in the prioritisation process (for example, condition assessment and supplied energy index), weighting factors for each PI may be used to obtain an overall assessment.

2.4 Study of intervention solutions

Module 3 aims at identifying, assessing, comparing and prioritising intervention solutions considering infrastructural, financial, performance and economic perspectives to solve the problems identified in the previous module.

At the macro assessment level, a set of long-term rehabilitation solutions at the system or subsystem level is identified considering the future uncertainties. Examples of these solutions are: the asset replacement at the end of service life; the assets' replacement for maintaining a constant IVI at 0.50; and the assets' rehabilitation at a 5% rate (in terms of costs). At the micro assessment level, solutions can be divided into infrastructural, O&M or non-infrastructural. Infrastructural solutions can be replacing equipment or replacing/renewing civil work components. The modern engineering equivalent replacement asset (MEERA) approach should be used to assess the intervention solutions, in which technologically similar assets are selected. This approach should be applied whenever the assets are no longer available in the market (e.g., asbestos cement pipes have fallen into disuse) or the assets have significant changes in technology (e.g., pump groups with higher efficiency). Besides, different technologies of replacement and renewal should be considered since it may have different costs and benefits. At the meso assessment level, it is possible to develop a detailed assessment of long-term rehabilitation solutions or a simplified assessment of intervention solutions.

The assessment of each solution presupposes an analysis of costs and benefits during a time horizon. Infrastructural, economic, performance and financial perspectives are considered to assess the benefits of each solution using different PI and metrics. Regarding financial metrics, the following metrics are calculated for each analysed solution: net present value (NPV), internal rate of return (IRR), payback period (PBP) and the profitability index.

The comparison of solutions is carried out by comparing each one with the *status quo* situation in terms of the different PI. The comparison of solutions allows their prioritisation for each PI or studied metric. If more than one PI is used, an overall prioritisation process is carried out to select the solution that maximises the investment recovery. This prioritisation process is based on the methodology proposed by Alegre and Coelho [18], in which a weighting of each PI to express its relative importance in the assessment system is assigned. Besides, a normalisation process is necessary since each PI is expressed in different units. A continuous scale varying from 0 to 3 is used and divided into three levels:

- [2; 3]: good assessment, represented by the green colour;
- [1; 2[: average assessment, represented by the yellow colour;
- [0; 1[: unsatisfactory assessment, represented by the red colour.

A ranking of solutions based on the overall assessment is carried out allowing to select the solution with the best performance assessment considering the utility budget.

3 CASE-STUDY

The decision-making approach is applied to a water distribution system located in a touristic area in the Algarve region of Portugal at the micro assessment level, corresponding to the most detailed and complex assessment level. This water distribution system is characterised by a high seasonal water consumption variation, with significantly higher consumption during the summer period than in the winter period (i.e., four times higher). The water distribution system is divided into five water subsystems (1 – 5), including different assets, such as water storage tanks, pumping and booster stations and water distribution pipes. The general characteristics of the subsystems are presented in Table 1. The characteristics of water distribution pipes of Subsystem 1 were not provided by the utility, thus, these will not be considered in the subsequent analysis.

Table 1. General characteristics of the five subsystems of water distribution case study.

Subsystem	Asset inventory
1	1 water storage tank: Capacity = 2 250 m^3 1 booster station: Total hydraulic power = 4.4 kW Characteristics of the network pipes: unknown
2	2 water storage tanks: Capacity = 800 m^3 and 125 m^3 3 booster station: Total hydraulic power = 0.3 kW, 1.8 kW and 0.3 kW 49 203 km of pipes in AC, PVC, DI; HDPE: DN = [60; 350] mm
3	1 booster station: Total hydraulic power = 1.3 kW 2 476 km of pipes in AC and PVC: DN = [80; 110] mm
4	1 booster station: Total hydraulic power = 1.6 kW 3 891 km of pipes in AC and PVC: DN = [60; 110] mm
5	2 water storage tanks: Capacity = 10 200 m^3 and 500 m^3 1 pumping station: Total hydraulic power = 11.6 kW 1 booster station: Total hydraulic power = 1.2 kW 38 169 km of pipes in AC, PVC, DI; HDPE: DN = [60; 500] mm

Notes: AC – Asbestos Cement; PVC – Polyvinyl Chloride; DI – Ductile Iron.

4 RESULTS

4.1 Analysis planning and database construction

The application of the decision-making approach aims at analysing and comparing different intervention solutions at the asset and component level considering a time horizon of 20 years. The asset diagnosis and prioritisation process and the study of solutions are developed by calculating different PI associated with the occurrence of failures, the economic and infrastructure sustainability and integrity and the energy use efficiency (Table 2).

Table 2. Assessment system, including criteria, performance metrics and respective reference values.

Criteria	Performance indicators (units)	Reference values
Occurrence of supply failures	Failures of service connections (no./(1000 service connections.year)) [19]	🟢 [0.0; 1.0] 🟡]1.0; 2.5] 🔴]2.5; +∞[
Economic and financial sustainability of the utility	Non-revenue water (%) [19]	🟢 [0; 20] 🟡]20; 30] 🔴]30; 100]
Infrastructure sustainability and integrity	Infrastructure value index* (IVI) (-) [20]	Long-term planning: 🟡]0.60; 1.0] 🟢 [0.40; 0.6] 🔴 [0.0; 0.40[Condition assessment: 🟢]0.60; 1.0] 🟡 [0.40; 0.6] 🔴 [0.0; 0.40[
	Residual life ratio* (RLR) (-) [20 [21]]	🟢]0.60; 1.0] 🟡 [0.40; 0.6] 🔴 [0.0; 0.40[
	Asset condition rating** (-) [17]	🟢 {5}, {4} 🟡 {3} 🔴 {2}, {1}
	Infrastructure average and maximum deterioration index*** (IDI) (-) [17]	🟢 [0; 40] 🟡]40; 60] 🔴]60; 100]
	Asset average and maximum deterioration index*** (ADI) (-) [17]	🟢 [0; 40] 🟡]40; 60] 🔴]60; 100]
	Component average and maximum deterioration index*** (CDI) (-) [17]	🟢 [0; 40] 🟡]40; 60] 🔴]60; 100]
Energy use efficiency	Standardised energy consumption (kWh/(m^3.100m)) [19]	🟢 [0.27; 0.40] (average efficient between 68 and 100%) 🟡]0.40; 0.54] (average efficient between 50 and 68%) 🔴]0.54; 5] (average efficient lower than 50%)
	Energy in excess per unit of the authorised consumption (kWh/m^3) [21]	🟢] 0; 0.15] 🟡]0.15; 0.30] 🔴]0.30; +∞[

Notes: *Calculated at the macro assessment level; **Calculated at the meso assessment level; ***Calculated at the micro assessment level.

The Component Deterioration Index (CDI), Asset Deterioration Index (ADI) and Infrastructure Deterioration Index (IDI) are new metrics of the assessment system that were proposed by Cabral et al. [17]. These metrics allow to obtain a more robust condition value of components, assets and infrastructures than the existing metrics that presuppose the use of reference service lives (e.g., IVI and RLR).

4.2 Infrastrcuture, asset and component diagnosis and prioritisation

The assessment system results for the current situation (reference year of 2018) are presented in Table 3. All subsystems have an opportunity to improve pump groups in terms of energy efficiency, since the standardised energy consumption presents an average (Subsystems 1, 4 and 5) or unsatisfactory performance (Subsystems 2 and 3). The PI of energy in excess per unit of the authorised consumption corroborates a potential improvement, especially in Subsystem 3, with unsatisfactory performance, and in Subsystems 4 and 5, where the indicator shows an average performance.

Table 3. Subsystem diagnosis using performance indicators defined in Table 2 (reference year of 2018).

Criteria	Performance indicator	Subsystem				
		1	2	3	4	5
Occurrence of supply failures	Failures [no./(1000 service connections.year)]	🔴 5.35	🟢 0.00	🟢 0.00	🟢 0.00	🟢 0.00
Economic and financial sustainability of the utility	Non-revenue water (%)	🟢 2.4	🟢 15.0	🟢 15.0	🟢 15.0	🟢 15.8
Infrastructure sustainability and integrity	IVI (-)	🟢 0.65	🔴 0.39	🔴 0.28	🔴 0.14	🔴 0.26
	Average IDI (-)	🟢 13	🟢 15	🟢 21	🟢 28	🟢 27
	Maximum IDI (-)	🟢 21	🟡 49	🟢 33	🟢 32	🟡 49
Energy use efficiency	Standardised energy consumption [kWh/(m^3.100m)]	🟡 0.49	🔴 0.85	🔴 1.35	🟡 0.53	🟡 0.42
	Energy in excess per unit of the authorised consumption (kWh/m^3)	🟢 0.15	🟢 0.11	🔴 0.41	🟡 0.21	🟡 0.16
Normalised global assessment (0-3; 0 corresponds to the lowest performance)		🟡 **1.93**	🟡 **1.84**	🟡 **1.67**	🟡 **1.70**	🟡 **1.83**
Ranking (1-5; 1 corresponds to the highest priority)		**5**	**4**	**1**	**2**	**3**

Subsystem prioritisation is carried out considering an equal weight (default value of 1) for each indicator, representing the relative importance of the assessment system's metric. Subsystem 3 is considered the highest priority with an overall evaluation of 1.67, representing the lowest value of the five studied subsystems. This subsystem is composed of one booster station and 2 476 km of pipes in Asbestos Cement (AC) and Polyvinyl Chloride (PVC) with nominal diameters varying from 80 and 110 mm. The booster station includes four pump groups installed in parallel and a variable speed driver with a rated flow rate of 16 m^3/h, rated head of 58.4 m and a total hydraulic power of 7.63 kW.

The diagnosis for each pump group of the booster station is presented in Table 4. The pump groups present an unsatisfactory efficiency (24%) and lower than expected (provided by the manufacturer), which indicates a performance degradation. This efficiency was estimated by the ratio between the energy supplied and the billed electric energy. Thus, it represents the global efficiency of the pumping station, not being possible to distinguish the efficiency of each group. Moreover, according to the average pumped flow rate and rated flow rate ratio (Q/Q_R), pump groups are also operating, on average, away from their rated conditions (i.e., point of maximum efficiency). Values of RLR (i.e., ratio between the residual life and the service life) for each pump group show that groups have reached the end of their expected service lives, considering a service life of 20 years. However, the calculated average CDI (component deterioration index obtained through the identification and classification of anomalies during the assets' visual inspection) presents the same value of 21 for all pump groups. This means that the four pump groups are in good condition, according to the visual inspections, despite having a low power efficiency and also reached the end of their service life.

Table 4. Pump groups diagnosis (reference year of 2018).

Pump ID	**Flow rate (l/s)**	**Head (m)**	**RLR (-)**	**CDI (-)**	**Pump efficiency* (%)**	**Q/Q_R** (%)**
1	2.67	27	● 0	● 21	● 24	● 118
2	1.64	33	● 0	● 21		
3	1.25	33.4	● 0	● 21		
4	1.28	33.3	● 0	● 21		

Notes: *Pump efficiency: Good assessment [68%, 100%], Average assessment [50%, 68%], Unsatisfactory assessment [0%, 50%]. **Q/Q_R: Good assessment [90%, 105%], Average assessment [70%, 90%] and [105%, 120%], Unsatisfactory assessment [0%, 70%] and [120%, 150%].

The diagnosis for each distribution pipe of Subsystem 3 is presented in Table 5. Physical characteristics, including the material, nominal diameter and length of each pipe are presented, as well as the RLR, considering a service life of 40 years for the two pipe materials. The studied distribution pipes are reaching the end of their service life, representing a high investment in the short-term. The unit head losses for the winter and summer periods were obtained by simulation of the hydraulic models using EPANET. The first two water distribution pipes (with ID 1 and 2) present high unit head losses in the summer period due to their poor design (i.e., small diameter for summer operation). Note that only some distribution pipes are presented in the table to illustrate the diagnostic process

Table 5. Water distribution pipes diagnosis (reference year of 2018).

Pipe ID	**Material**	**Nominal diameter (mm)**	**Length (m)**	**RLR (-)**	**Unit head losses (-)**	
					Summer period	**Winter period**
1	PVC	110	107.40	● 0.13	6.44	0.24
2	AC	100	787.93	● 0.13	6.15	0.23
3	AC	80	116.40	● 0.13	1.76	0.14
4	PVC	80	168.77	● 0.13	0.09	0.00
…	…	…	…	…	…	…
19	AC	80	47.33	● 0.05	0.04	0.00
20	AC	80	33.51	● 0.05	0.00	0.00

Notes: AC – Asbestos Cement; PVC – Polyvinyl Chloride. RLR – Residual Life Ratio.

The prioritisation process aims at identifying the assets (i.e., water pipes) and components (i.e., pump groups) for intervention. Figure 2 depicts the prioritisation matrix, according to the assets and components criticality and the RLR. The component critically was defined considering the importance of each asset and component in the studied subsystem. A scale that varies between 1 (less important functional components) and 6 (very important functional components) was considered to assign the criticality of each asset and component. The four pump groups and the water pipes with the ID 1 and 2 were classified with a criticality 6, being essential components to the functioning of the subsystem. The remaining water pipes were classified with a criticality of 5.

The five points represent the set of assets/components with the same criticality and RLR. The four pump groups are represented by one point with a RLR of zero and a criticality of 6. The two water pipes with ID 1 and 2 are represented by one point with a RLR of 0.13 and a criticality of 6. Thus, these assets/components are considered critical priorities for intervention. The remaining water pipes are considered high priorities for intervention, due to the low values of residual life. Most pipes have their assessment overlapped in the figure.

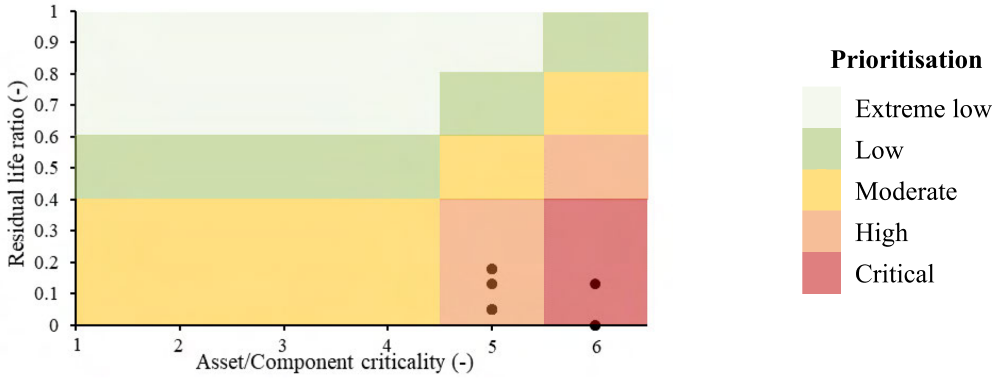

Figure 2 – Asset (water pipes) and component (pump groups) prioritisation for intervention (reference year of 2018).

4.3 Study of intervention solutions

The identification of intervention solutions is carried out through the identification of the main problems associated with the subsystem and the respective causes. The main problems were identified through the subsystem and component diagnosis and can be divided into three categories: pump group inefficiencies and water and head losses. Five intervention solutions are defined to attain the main problems identified:

- Solution 0 (S0): *Status quo*, not considering interventions and maintaining the current O&M practices. This solution is used only to compare with the other options to exemplify the benefit of each solution with the situation of non-intervention.
- Solution 1 (S1): Replacement of the four pump groups with the same rated characteristics (like-for-like replacement). An efficiency of 50% for the new pump groups is considered including the pump, the motor and the variable speed driver.
- Solution 2 (S2): Replacement of the four pump groups properly designed, considering the opportunity to improve the operating points of the pump groups. Hydraulic models provided by the water utility with consumption patterns are used to compare the average pressure in winter and summer periods with the minimum required pressure. A reduction of the operating head of the pump groups is considered, representing an average reduction of 13 m.

- Solution 3 (S3): Replacement of 895.33 m of water pipes (corresponding to water pipes ID 1 and 2) properly designed. Both water pipes are replaced by PVC pipes since it corresponds to the most predominant material in this subsystem and the nominal diameter considered for both replaced pipes is 125 mm.
- Solution 4 (S4): a combination of Solutions 1 and 3, including the replacement of pump groups with the same rated characteristics and the replacement of water pipes with high head losses.
- Solution 5 (S5): a combination of Solutions 2 and 3, including the replacement of the four pump groups and the replacement of water pipes with high head losses with an adequate design. This solution does not represent a complete combination of Solutions 2 and 3, since the reduction of the head losses in the water pipes allows to reduce even more the operating head of the pump groups.

A set of assumptions were established to assess the defined intervention solutions related to water and energy price, service lives, maintenance costs, water losses and efficiency degradation. The intervention solutions are compared considering the following PI: standardised energy consumption, energy in excess per unit of the authorised consumption, infrastructure value index and non-revenue water.

The standardised energy consumption allows to assess and to compare the pumping energy efficiency for a single pump group or the whole pumping or booster station (Figure 3a). Solutions 0 and 3 present the same evolution during the time horizon of the analysis since in these solutions no pump groups are replaced and the pump groups' efficiency continues to degrade until reach the minimum limit of 10 % (in the year 2032). After that year, the efficiency of the pump groups remains constant, causing the same behaviour in the shaft input energy. Solutions 1 and 4 also present the same results for this PI, since the rated conditions of the replaced pump groups are the same in the two solutions. An outstanding improvement of the standardised energy consumption in these two solutions is caused by the new pump groups' efficiency contributing to the decreases of the shaft input energy. However, results still indicate an unsatisfactory assessment. Finally, Solutions 2 and 5 present the best results for this PI (representing an average assessment), although their operating points are slightly different.

The comparison of intervention solutions by the energy in excess per unit of the authorised consumption is presented in Figure3(b). The increase of the pump groups' efficiency from Solution 0 to 1 and to 2 contributes to the improvement of this PI in these solutions, changing from an unsatisfactory assessment (S0) to an average assessment (S1) and, finally, to a good assessment (S2). A slight difference between Solutions 0 and 3, 1 and 4 and 2 and 5 is verified, mainly, due to the replacement of the two pipes (in Solutions 3, 4 and 5), which allows to reduce the water losses and, consequently, the pumped volume. Thus, the shaft input energy is lower in these solutions. Furthermore, the solutions that include the replacement of the water pipes consider lower total annual water losses. Therefore, the energy in excess in these solutions does not show such a pronounced increase.

The comparison of intervention solutions by the infrastructure value index (IVI) is presented in Figure3(c). Solution 0 presents the lowest IVI since no assets are replaced in this solution, achieving a null IVI in 2026 and compromising the correct functioning of the subsystem. This solution represents the IVI of the water pipes since the pump groups have already reached the end of service life in 2018. Solutions 1 and 2 present similar IVI since both solutions include the replacement of the four pump groups with the same service life and the replacement costs are very similar (being slightly lower for Solution 2). However, these two solutions still present an unsatisfactory IVI, due to the ageing water pipes that reach the end of service in 2026. Better results are achieved for the remaining solutions, with the replacement of two water pipes (S3) and the replacement of two water pipes and pump groups (S4 and S5). The greater the number of assets replaced is, the higher the obtained IVI becomes. In the three solutions, a null IVI is not reached during the time horizon of the analysis. Solutions 4 and 5 achieve the same IVI as well as Solution 3 in the last year of the analysis, due to the end of service life of replaced pump groups in the former solutions.

In the case of non-revenue water, the solutions are divided into two different results, depending on whether the solutions include the replacement of the two water pipes (Figure 3d). The non-revenue water is equivalent to the water losses, assuming that all consumption is billed. Results obtained for this PI are not as significant as in the previous ones, since water losses are not a problem in this subsystem.

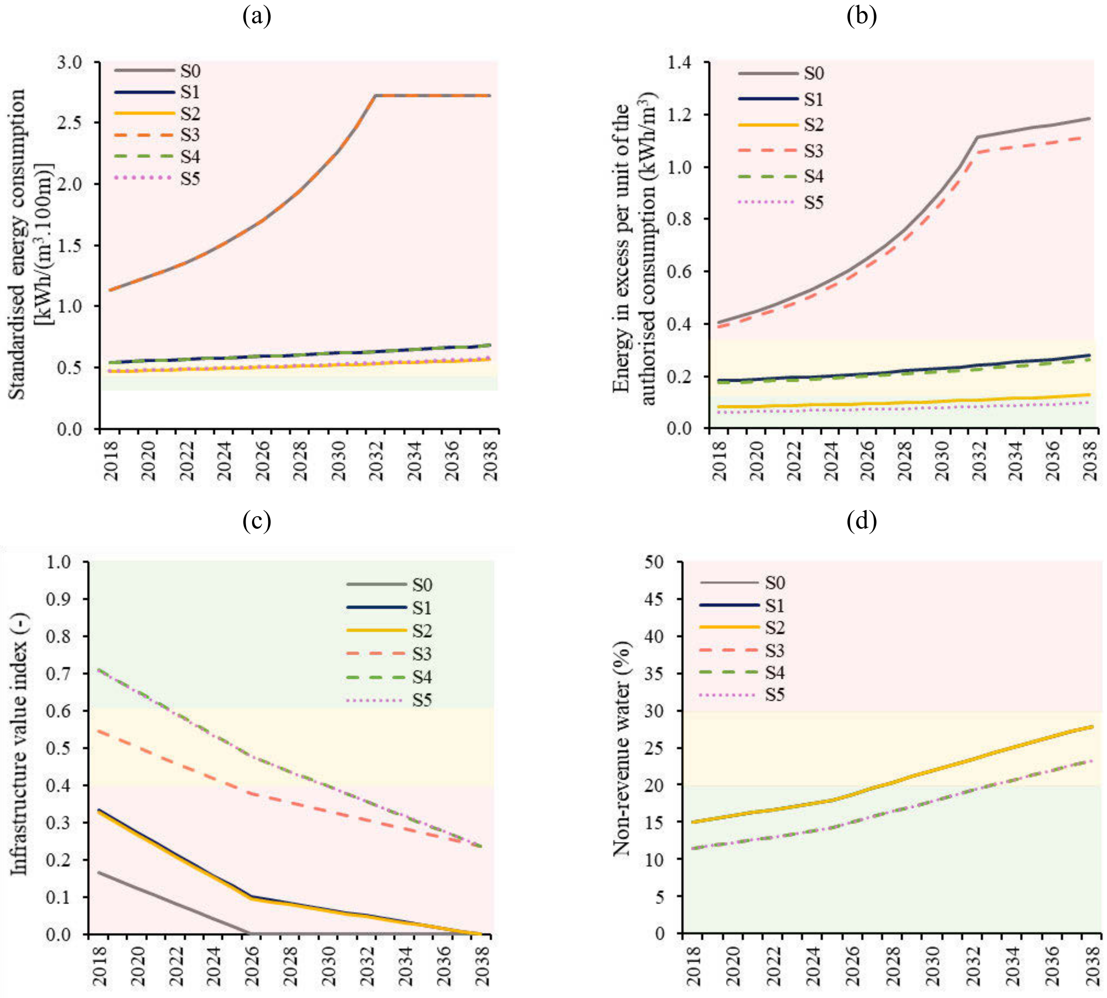

Figure 3 – Impact of intervention solutions on performance indicators between 2018 and 2038: (a) standardised energy consumption; (b) energy in excess per unit of the authorised consumption; (c) infrastructure value index; and (d) non-revenue water.

The comparison of intervention solutions by the infrastructure value index (IVI) is presented in Figure3(c). Solution 0 presents the lowest IVI since no assets are replaced in this solution, achieving a null IVI in 2026 and compromising the correct functioning of the subsystem. This solution represents the IVI of the water pipes since the pump groups have already reached the end of service life in 2018. Solutions 1 and 2 present similar IVI since both solutions include the replacement of the four pump groups with the same service life and the replacement costs are very similar (being slightly lower for Solution 2). However, these two solutions still present an unsatisfactory IVI, due to the ageing water pipes that reach the end of service in 2026. Better results are achieved for the remaining solutions, with the replacement of two water pipes (S3) and the replacement of two water pipes and pump groups (S4 and S5). The greater the number of assets replaced is, the higher the obtained IVI becomes. In the three solutions, a null IVI is not reached during the time horizon of the analysis. Solutions 4 and 5 achieve the same IVI as well as Solution 3 in the last year of the analysis, due to the end of service life of replaced pump groups in the former solutions.

In the case of non-revenue water, the solutions are divided into two different results, depending on whether the solutions include the replacement of the two water pipes (Figure 3d). The non-revenue water is equivalent to the water losses, assuming that all consumption is billed. Results obtained for this PI are not as significant as in the previous ones, since water losses are not a problem in this subsystem.

A comparison of the intervention solutions considering the cumulative cash flows is carried out and presented in Figure 4. All the studied solutions present significant cumulative cash flows, representing good potential solutions to implement. Solution 3 presents the highest payback period and the lowest cumulative cash flow, since the replacement of water pipes reduces water losses (and non-revenue water). However, this subsystem already has a good assessment for this PI.

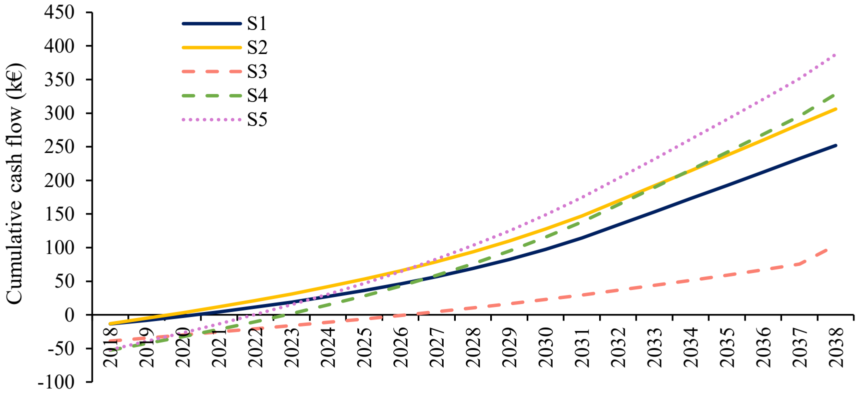

Figure 4 – Cumulative annual cash flow: comparison of intervention solutions between 2018 and 2038

The prioritisation of the intervention solutions is carried out, including different metrics. Regarding financial metrics, Table 6 presents the results obtained for the net present value (NPV), the payback period (PBP), the internal rate of return (IRR) and the profitability index for each analysed solution. Three discount rates are used (i.e., 5%, 7% and 10 %) since this rate represents one of the most uncertain variables of the analysis. All the studied solutions show positive NPV for the three discount rates, representing potential solutions to implement. Solution S5 presents the highest NPV, although it also corresponds to one of the highest investments. All solutions present extremely low values regarding the payback period, varying between 2 (S2) and 9 years (S3).

The IRR corresponds to the discount rate that gives a zero NPV. Solution 3 presents the lowest IRR (13%). If a discount rate of 13% or higher is considered, Solution 3 will present a null or negative NPV, respectively, and is no longer viable. The profitability index is the ratio between the NPV and the initial investment, allowing to quantify the amount of value created per unit of investment and, therefore, rank intervention solutions. Solution 2 presents the highest profitability index for the three discount rates, the lowest PBP and the highest IRR, being considered the best solution using these metrics.

Table 6 – Prioritisation of intervention solution using financial metrics.

Solution	Investment (€)	NPV (€)			PBP (years)	IRR (%)	Profitability index (-)		
		5%	7%	10%			5%	7%	10%
S1	13 700	133 437	105 659	75 911	3	49	10	8	6
S2	12 896	166 443	133 487	98 050	2	67	13	10	8
S3	38 835	40 732	25 918	10 562	9	13	1	0.7	0.3
S4	52 535	161 580	122 386	80 282	5	24	3	2	2
S5	51 731	197 715	152 869	104 548	4	29	4	3	2

The prioritisation of intervention solutions is also carried out using the PI used to compare the solutions (Table 7). Thus, the same normalisation process applied in the subsystem diagnosis is considered, using a continuous scale varying from 0 to 3 and divided into three levels: [2; 3] – good performance (🟢), [1; 2[– average performance (🟡); and [0; 1[– unsatisfactory performance (🔴). Moreover, a weight to each PI is necessary to assign its importance in the assessment system to calculate the overall assessment of each intervention solution, in this study equal weights for the PI are considered (default value of 1).

Regarding the PI associated with the energy use efficiency (standardised energy consumption and energy in excess), an improvement in the solutions with the replacement of the pump groups is verified, especially if properly designed (Solutions 2 and 5). The majority of solutions still present an unsatisfactory performance for IVI, since the assets of Subsystem 3 are reaching the end of their service lives, corresponding to an overall IVI of Subsystem 3 during the time horizon of the analysis of 0.12 (Solution 0). Solutions 4 and 5 include the replacement of more assets (pump groups and water pipes), allowing to obtain an average performance. The non-revenue water has not been identified as a problem in this subsystem and all solutions present good results, although Solutions 0, 1 and 2 show an average performance (even though very close to good performance). All studied solutions present an average performance for the overall assessment; however, Solution 5 has the highest overall assessment and a value close to 2, representing good performance.

Table 7– Prioritisation of intervention solutions using normalised performance indicators.

Normalised performance indicators	Solutions					
	S0	S1	S2	S3	S4	S5
Standardised energy (-)	🔴 0.71	🟡 1.03	🟡 1.28	🔴 0.71	🟡 1.03	🟡 1.25
Energy in excess (-)	🟡 1.48	🟢 2.56	🟢 2.88	🟡 1.52	🟢 2.60	🟢 2.95
IVI (-)	🔴 0.12	🔴 0.42	🔴 0.40	🔴 0.99	🟡 1.28	🟡 1.28
Non-revenue water (-)	🟡 1.95	🟡 1.95	🟡 1.95	🟢 2.25	🟢 2.25	🟢 2.25
Overall assessment (-)	🟡 **1.06**	🟡 **1.49**	🟡 **1.63**	🟡 **1.36**	🟡 **1.79**	🟡 **1.93**
Ranking (1-5; 1 corresponds to the best solution)	**-**	**4**	**3**	**5**	**2**	**1**

Notes: [2; 3] – Good performance (🟢); [1; 2[– Average performance (🟡); [0; 1[– Unsatisfactory performance (🔴).

The comprehensive evaluation of the intervention solutions and the corresponding investment is presented in Figure 5. Properly designed asset replacement solutions (S5 and S2) are preferable to asset replacement like-for-like solutions (S4 and S1). In addition, Solutions 5 and 2 show a higher overall performance assessment and slightly lower investment costs than Solutions 4 and 1, respectively. Furthermore, Solution 3 presents the lowest overall assessment; however, the investment cost is higher than for Solutions 1 and 2. For that reason, this solution should not be considered for implementation. The choice of the solution to implement will always depend on the available water utility budget, in which the chosen solution presents the best overall performance assessment and investment values lower or equal to the defined budget.

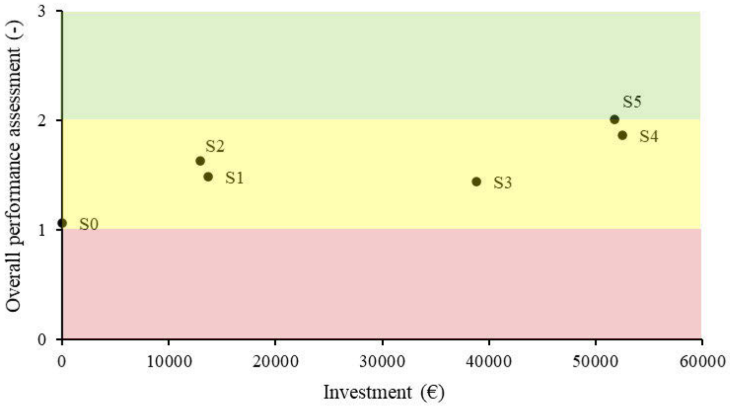

Figure 5 – Overall performance assessment of the intervention solutions in Subsystem 3 considering equal weights for the performance indicators.

5 CONCLUSIONS

The present paper aimed at proposing and demonstrating a decision-making approach to identify, assess, compare, and prioritise different intervention solutions. A three-module decision-making approach was applied to a water distribution system in Portugal. Five intervention solutions were defined and compared considering the financial metrics and performance indicators, such as standardised energy consumption, energy in excess per unit of the authorised consumption, infrastructure value index and non-revenue water.

The application of the proposed approach has demonstrated the influence of considering different assessment criteria and PIs in the solutions' prioritisation, highlighting that not always the solution with the lowest associated capital cost corresponds to the solution with the highest overall performance (i.e., the most technically and operationally recommendable). The study of less-conventional interventions (e.g., the replacement of pump groups by other adequately designed and operated) was carried out. These solutions were compared with conventional interventions (e.g., the like-for-like pump replacement, replacing pumps by others technologically equivalent and with the same operation conditions). Results have shown that less-conventional interventions may result in a higher overall performance, especially in the long-term, and may even lead to a lower capital cost.

This proposed approach was a step forward in the implementation of IAM approaches in urban water infrastructures since it allows to integrate different perspectives, which is important for the establishment of policies and future rehabilitation solutions at the infrastructure or asset level and for the improvement of intervention solutions prioritisation necessary for the development of sounder tactical level plans. The definition of three assessment levels – macro, meso and micro – and the incorporation of new metrics associated with the assets' physical condition were the main novel contributions of this research.

Further research should include the study of different intervention solutions, such as system zoning, leak detection and changes in the system layout. Addicionally, a sensitivity analysis to help in the prioritisation process and to study the variables of analysis with the highest uncertainty should be carried out, such as the discount rate, the O&M costs and the time horizon.

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