REHABILITATION INTERVENTIONS IN URBAN WATER SUPPLY ASSETS USING THE MULTICRITERIA DECISION TOOL ELECTRE III

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Abstract

The current paper briefly presents the infrastructure asset management (IAM) methodology developed in the framework of the AWARE-P project for the comparison of alternative rehabilitation solutions and applies it to a Portuguese water supply system taking into consideration different criteria. These criteria incorporate three assessment dimensions – performance, cost and risk – expressed by several assessment measures (e.g., investment cost, risks of pipe leakage, risk of pipe burst and infrastructure index value). Criteria are aggregated by a Multiple Criteria Decision-Aid (MCDA) technique – the ELECTRE III method. Alternative rehabilitation solutions were established and assessed using this approach. Results are presented and discussed.

Keywords
Multiple Criteria Decision Aiding, Cost, Performance, Risk, Rehabilitation, Urban water systems.

1. INTRODUCTION

Most of water distribution systems (WDS) in Europe were designed and built several decades ago and, currently, water utilities are facing the challenge of keeping their systems operational, efficient and reliable to provide water in enough quantity and good quality. Deterioration of urban water infrastructures and equipment is a normal and inevitable process. Components reach the end of their useful life, and consequently problems such as increase in leakage levels, breakdowns and supply interruptions become more frequent and maintenance costs rise. As a consequence, water utilities face the need to choose between different alternatives for rehabilitation.

A study carried out in Portugal involving 200 municipalities has shown that the total extent of water distribution assets were 42,743 km long and the wastewater drainage assets were 40,313 km long [2]. If an average unit replacement cost of 100 €/m is considered, the total replacement cost of these assets is 8,306 billion of euros, representing around 3.5% of the Portuguese gross domestic product (GDP). This study only included 64% of the Portuguese municipalities and did not include any private or public water company; stormwater drainage assets were also not considered. If a replacement rate of 2%/year is considered, all assets will be replaced in 50 years and, in every year, about 166 million euros are spent for the rehabilitation of water assets in these municipalities. Due to the current economic situation, this represents a significant amount of money and, therefore, proactive rehabilitation approaches are required.

Rehabilitation of water assets is considered by the Portuguese Water and Waste Services Regulator (ERSAR) as a key issue to increase efficiency of water utilities. A recently published Portuguese law imposes to water utilities, providing a service to populations above 30,000 inhabitants to develop Infrastructure Asset Management (IAM) plans.

Infrastructure Asset Management is defined as the corporate strategy and the corresponding planning, systematic and coordinated activities and practices through which an organization optimally manages its assets and their associated performance, risks and costs over their lifecycle [1]. Regardless the complexity and maturity level of the water utilities, IAM involves three planning levels: strategic, tactical and operational. At each planning level, performance, risk and cost should be taken into account [2; 3]. At the strategic level, the direction of the corporation in terms of IAM for the long-term (10-20 yrs.) is defined. At the tactical level the way in the medium-term (3-5 yrs.) is defined, establishing intervention priorities and selecting solutions. Finally, at the operational level the solutions selected at the tactical level are implemented considering short-term periods (1-2 yrs.), defining the programme of actions to be carried out [4].

AWARE-P Project, involving R&D and technological partners, the Portuguese water regulator and several end-users, aims at the development and implementation a structured procedure for IAM in water utilities [1]. Based on previous and new R&D results, an open-source, professional-grade computer application, together with manuals of best practice [2;3] and e-learning materials are being developed and made public available. These materials aim to assist water utilities in defining objectives, performing diagnoses, setting up priorities, comparing alternatives and selecting intervention solutions. The methodology developed in the AWARE-P project is based on plan-do-check-act principles and is organized in levels of planning (strategic, tactical and operational), where each level is composed of different stages and tasks: (i) definition of objectives and targets; (ii) elaboration of diagnosis; (iii) elaboration of the plan; (iv) implementation; and (v) monitoring and revision. The proposed methodology for water supply and for wastewater infrastructure asset management includes the three levels of planning. The three different dimensions - cost, risk and performance are incorporated in each level of planning to better support decision-making, particularly at the tactical level. The aggregation of criteria from these three dimensions for decision making is a Multiple Criteria Decision-Aid (MCDA) problem.

In the AWARE-P methodology one of the steps is to define rehabilitation alternatives and prioritize these interventions or choose the best alternative. In any case the decision needs to consider multiple criteria and the AWARE-P framework allows balancing the three assessments. A method to aggregate the three assessments and select the best alternative is presented in this paper applying it to a case study and discussing the results.

2. REHABILITATION: A MULTICRITERIA DECISION PROBLEM

In IAM, after the study of possible alternatives (i.e., user defined actions), the selection of the best alternative should be based on the balance between three assessments – performance, cost and risk – for the whole period of analysis. This means that the assessments should include the time dimension; the assessments may be applied to one moment in time (a time frame) or a period of time (i.e., several time frames, e.g. at 0, 5, 10 and 15 years). The evaluation can typically be made by comparing each alternative with the *status quo* situation (*i.e.*, the alternative corresponding to maintaining the current O&M practice).

Scenarios (*i.e*., user defined events that affect decision) can be used to project time evolution (*e.g*., demand evolution). The alternatives should be assessed for performance, risk and cost for one or more scenarios, and the different alternatives are compared by checking how they respond to the different scenarios.

Generally, the maximization of performance and minimization of risk and cost are conflicting objectives. The aggregation of criteria from these three dimensions for decision making can be formulated as a MCDA problem. There are two approaches to formulate this multicriteria problem: (i), the first one is to aggregate the selected criteria from the three dimensions simultaneously (see Figure 1a), and (ii) the second is to aggregate the selected criteria from each dimension into a single measure and then aggregate them (see Figure 1b). In this paper the approach used to aggregate the selected criteria is the former, as presented in Figure 1(a). It is not clear yet which of these two approaches leads to better results, being a current research issue of the authors.

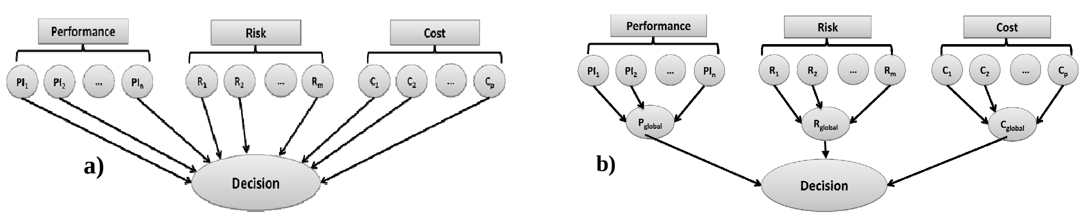

Figure 1. Multicriteria problem formulation: a) aggregation of the three dimensions simultaneously; b) aggregation from each dimensions into a single global criteria

3. MULTICRITERIA TOOLS AND THE ELECTRE III

The main purpose of MCDA is to provide decision aiding tools that help finding solutions for real-world problems, most often, problems having conflicting points of view [4]. Decision aiding means the activity of the person who, through the use of explicit but not necessarily completely formalized models, helps obtaining responses to the questions posed by a stakeholder of a decision process [5]. The multicriteria problem is related to the methods and procedures by which the different criteria can be formally involved in the decision process.

Generally, these problems fall into multi-attribute (discrete problems) or multi-objective problems (continuous problems). The main difference between these two types of problems is the number of possible alternatives.

ELECTRE (ELimination et Choix Traduisant la RÉalité) methods are a family of MCDA techniques developed in France. Since their development, which started in the 1960s, ELECTRE methods have been widely used in many real-world decision problems (*e.g,.* energy, transportation, environmental and water management) and proved to be suitable for situations where at least five decision criteria are involved [6]. The main advantage of these methods is the possibility of evaluating actions (or alternatives) using ordinal scales (similar or different) for assessing different criteria and not having to normalise results. ELECTRE family includes several methods distinguished by the type of problems involved, such as choice, ranking or sorting.

ELECTRE methods involve two phases: the construction of one or several outranking relation(s) followed by an exploitation procedure [6-8]. The concept of outranking relations was created due to the difficulties encountered with several real problems and is the basis of the so-called French or European school of MCDA [9;10]. The outranking relation is built through the following steps [8;11]: (i) computation of the partial concordance indices $c_j(a,b)$ and $c_j(b,a)$; (ii) computation of the overall concordance indices $c(a,b)$; (iii) computation of the partial discordance indices $d_j(a,b)$ and $d_j(b,a)$; (iv) computation of the fuzzy outranking relation grounded on the credibility indices $\sigma(a,b)$; (v) determination of a λ-cut of the fuzzy relation in order to obtain a crisp outranking relation [8].

Water asset interventions for rehabilitation can be treated either as a *ranking* or a *sorting* problem. In this paper, the comparison of different rehabilitation alternatives is treated as a *ranking* problem and the ELECTRE III method is used for the aggregation of criteria.

4. CASE STUDY

The case study presented in here to illustrate the proposed methodology is a water transmission pipe that supplies water to an important industrial park in Portugal. The system comprises a water treatment plant (WTP) at an elevation of 70 m, a pipe approximately 10 km long with circular cross section dimension between 1.5 m and 1.0 m. Water flows by gravity and the pipe supplies a distribution storage tank with 50,000 m^3 capacity at 53 m elevation. The pipe material is reinforced concrete, except when traversing the valve chambers (four in total) where the pipes are of steel with reduced diameters. Local site inspections have showed that most structural condition problems are located in these valve chambers.

The maximum flowrate that the pipe can convey by gravity is 1.3 m^3/s; however, it is currently operated at 0.3 m^3/s. Two demand scenarios were considered in this study. Scenario 1 corresponds to a continuous increase of demand in the period of analysis (2011-2035); Scenario 2 presents an initial increase in demand followed by a reduction in the middle of the period of analysis. The time variation of demand for the two scenarios is presented in Table 1.

Table 1. Time variation of demand for the two scenarios considered in this study

Scenario	2011	2013	2015	2017	2020	2025	2030	2035
S1	25	30	30	30	60	60	60	60
S2	25	30	30	30	20	20	20	20

As mentioned in Section 2, alternatives consist of different approaches to resolve the problem(s) in study. In this particular case, the main problems of the water distribution system are related with the lack of redundancy of the system, its unsatisfactory structural condition (evaluation based in known age and life cycle of reinforced concrete pipe), costumer sensitivity to interruptions of supply and possible lack of hydraulic capacity for future demands. In order to address these problems, four alternatives were considered:

– Alternative A0: the *status quo* (i.e., keeping the current O&M practice) (no cost);
– Alternative A1: the implementation of a set of systematic repairs in the existing pipe (2.5 M€);
– Alternative A2: the construction of a new pipe for 25 hm^3/year + rehabilitation of the existing one (15.1 M€);
– Alternative A3: the construction of a new pipe for 60 hm^3/year abandoning the existing pipe (11.7 M€).

In order to evaluate each alternative, seven criteria were considered, each expressed by means of one measure. Three criteria are related with risk: risk of lack of hydraulic capacity of pipes (R1), risk of pipe leakage (R2) and risk of pipe burst (R3). Three criteria are related with performance: real water losses (P1), exceeding pipe capacity (P2) and the Infrastructure Value Index, IVI (P3) [12]. One cost criteria is considered: total investment costs (C1).

5. RESULTS AND DISCUSSION

The time variation of four criteria (R2, R3, P2 and P3) for all alternatives (A0, A1, A2 and A3) and for the two considered scenarios (S1 and S2) is presented in Figure 2. IVI does not depend on the scenarios.

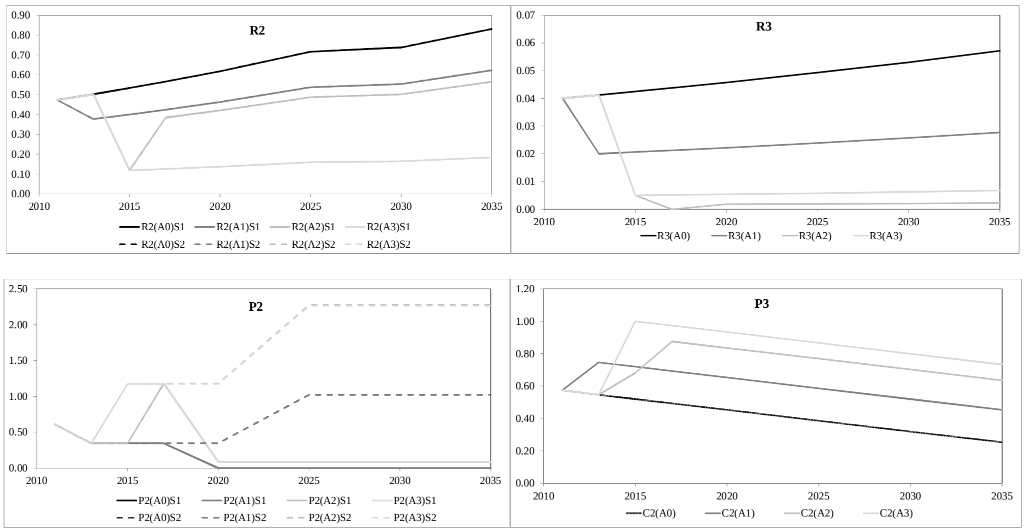

Figure 2. Time variation of four assessment criteria: risk of pipe leakage (R2); risk of pipe burst (R3); exceeding pipe capacity (P2); Infrastructure Value Index (P3).

Results have shown that only the criteria R1 and P2 present different results for each scenario. Criteria R1 is null in scenario 2 for all alternatives because pipes always have enough hydraulic capacity and, therefore, the consequence is always null; in the case of scenario 1, for alternatives A0 and A1, the risk R1 increases with time, beginning from null to moderate risk level at the end of the period of analysis. A moderate risk level corresponds in a coloured risk matrix of three levels to yellow, while the green colour corresponds to an acceptable risk level, and the red colour to the intolerable risk level. The criteria P2 is demand-dependent (i.e., the greater the demand, the lower this indicator, and vice-versa).

One question that arises is how to aggregate the results of the risk and performance criteria of the different time instants into a single value. The cost criteria can be easily aggregated in time because the net present values can be summed up. The solution used herein was the average of the values obtained for each criterion at each time instant for the period of analysis. Figure 3 presents the results for each alternative and criterion, for both scenarios. Note that the values were normalized only for the purpose of graphical presentation.

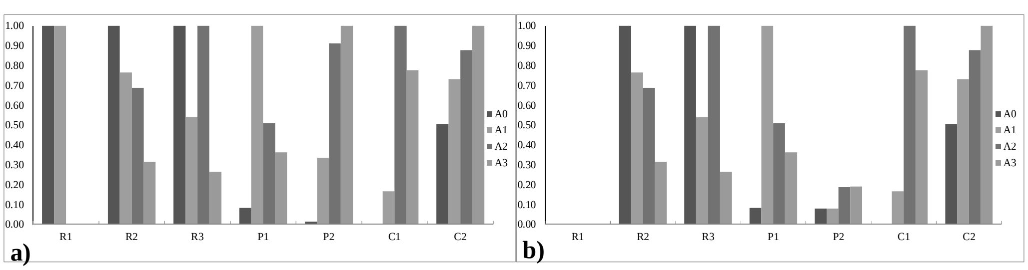

Figure 3. Results of each alternative per assessment for: a) Scenario 1; b) Scenario 2

To evaluate the four alternatives with the selected criteria ELECTRE III/IV software was used. In this software the criteria, alternatives, performances and thresholds should be defined. Note that performances in MCDA are the metrics of the criteria in each alternative. Thresholds are preference parameters of the method such as the indifference, preference and veto thresholds. These parameters were considered to be null meaning since a traditional model of preference is used. In a traditional model a difference between two alternatives implies a strict preference by one of them. In some situation the decision-maker is not sure if his preference is strict and can hesitate. In this case other type of preference model using the thresholds should be used.

Table 2 presents the results obtained in the performance matrix of the ELECTRE III software considering the different criteria, for the scenario 1. For scenario 2 similar results were obtained. In the case of the risk criteria three methods to obtain the final value were calculated, namely, the sum, the average and the maximum value.

Table 2. Performance matrix for ELECTRE III

	R1			R2			R3			P1	P2	C1	P3
	Sum	Average	Max	Sum	Average	Max	Sum	Average	Max				
A0	0.69	0.03	0.06	16.62	0.66	0.83	1.00	0.04	0.04	26	0.12	0	0.41
A1	0.69	0.03	0.06	12.71	0.51	0.62	0.54	0.02	0.04	13	0.12	2.5	0.60
A2	0	0	0	11.44	0.46	0.56	0.20	0.01	0.04	7	0.31	15.1	0.72
A3	0	0	0	5.23	0.21	0.52	0.27	0.01	0.04	5	0.34	11.73	0.82

The units for P1, P2, and C1 are m^3/(km.day), %, and Million € respectively. P3 is unitless.

If no weights are used the results obtained with ELECTRE III software allowed to conclude that is indifferent to use a sum, average or the maximum value to aggregate risk in the period of analysis. In this case the order rank is as follows (from the best to worst): A3, A2, A1 and A0. If the decision-maker argues that the different criteria should not have the same relative importance, weights can be used. In Table 3 the weights defined by the decision-maker are given, resulting in attributing higher importance to the risk of pipe burst (R3) and to the total investment cost (C1).

Table 3. Weights attributed to each criterion

	R1	R2	R3	P1	P2	C1	P3
Weight	8	2	10	1	1	10	2

Using weights to evaluate the four alternatives, results in significant differences from those obtained previously where no weights were used (Table 4).

Table 4. Rank order for the four alternatives, aggregating risk: a) by a sum or an average; b) by using the maximum value.

a)

Rank	Alternative
1	A2 A3
2	A0 A1

b)

Rank	Alternative
1	A3
2	A0 A1
3	A2

Table 4 shows that the best alternative is A2 in *ex aequo* with A3 when considering the sum or the average of risk over time, and is A3 when using the maximum value. Nevertheless, this does not reflect the feeling of the decision-maker that the risk of pipe burst is high, that it is important to have redundancy and thus, alternative A2 is the best choice. This result can be obtained only when the cost criteria has a lower weight in the analysis.

6. CONCLUSIONS

The present paper presents the application of the decision making process part of the AWARE-P project framework to real life case study. The aggregation of each dimension into a global single criterion is a matter for further research. ELECTRE III is an easily implementable method to aggregate different criteria allowing obtaining an overall measure to rank rehabilitation alternatives. The results obtained in this study showed that the best alternative is A3 except when the cost criteria have lower weight in the analysis. In this case the best alternative is A2. Further research is also being carried out to evaluate the sensitivity of the length of period of analysis and of the weights used and to deal with the uncertainty associated with several scenarios.

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