Selection of the best rehabilitation solution using multicriteria decision analysis

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Abstract
This paper presents the application of a Multiple Criteria Decision Analysis (MCDA) framework to help selecting the best rehabilitation solution for a water service. MCDA is performed using different criteria from three dimension of analysis (performance, cost and risk) and is applied to a case study in Portugal. Two external scenarios, four rehabilitation alternatives and six evaluation criteria were considered to test the decision context. The ELECTRE III technique was used to rank the rehabilitation alternatives. The results obtained and the main conclusions are presented in this paper.

Keywords
AWARE; Infrastructure Asset Management; Multiple Criteria Decision Analysis

INTRODUCTION

Most of water and wastewater infrastructures in Europe were built several decades ago. Now these infrastructures are facing the natural and inevitable process of degradation. Therefore, infrastructure asset management (IAM) is of utmost importance for water utilities.

IAM 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 (Alegre *et al*., 2011a). 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 (Alegre and Covas, 2010; Almeida and Cardoso, 2010). At the strategic level, the direction of the corporation in terms of IAM for the long-term (10-20 years) is defined. At the tactical level the way in the medium-term (3-5 years) 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 years), defining and scheduling the set of actions to be carried out (Alegre *et al*., 2011b).

A novel integrated approach for water supply and wastewater IAM was developed under the framework of the Advanced Water Asset REhabilitation (AWARE) project. The procedure articulates the three decisional levels (strategic, tactical and operational) and the main knowledge competences involved (engineering, management and information), based on the capability to take informed decisions through continuous and standardized evaluation of the systems. Each level is composed of different stages (see Figure 1) and tasks. 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.

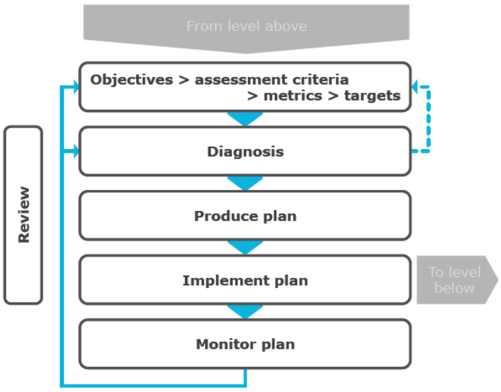

Figure 1 The AWARE IAM planning process

Generally, increasing performance and reducing risk and cost are conflicting objectives. Aggregation of criteria from different dimensions for decision making configures a Multiple Criteria Decision-Aid (MCDA) problem (Carriço *et al*. 2011).
The main objective of this work is the application of MCDA to select the best rehabilitation solution under the framework of the AWARE project. Multicriteria decision analysis is performed using six criteria from the three assessment dimensions and is applied to a case study in Portugal.

METHODOLOGY

Problem formulation

In IAM, after the establishment and design of different rehabilitation solutions, the selection of the best solution should be based on the balance between the referred three assessments – performance, cost and risk – for the whole period of analysis. This means that the assessments should include the time dimension. The evaluation can typically be made by comparing each solution 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). Solutions should be assessed for one or more scenarios.

The decision needs to consider multiple criteria and the AWARE framework allows balancing the three assessments. This brings MCDA into play. The main purpose of the MCDA methods is to help finding solutions for real-life problems, often problems with conflicting points of view (Vincke, 1992).

The current paper focuses on the selection of the best rehabilitation solution taking into account different criteria established for the assessment of performance, cost and risk. This selection can be treated either as a *choosing* or a *ranking* problem. In this paper, the comparison of the different rehabilitation solutions is treated as a *ranking* problem.

ELECTRE family methods

ELECTRE (ELimination et Choix Traduisant la RÉalité) methods are a family of MCDA techniques developed in France 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 (Figueira *et. al*., 2010). 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*.

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. The ELECTRE III method starts by a pairwise comparison of each alternative to the remaining one in order to accept, reject, or, more generally, assess the credibility of the assertion "alternative *a* is at least as good as alternative *b*" (Almeida-Dias *et al.*, 2006).

CASE STUDY

Description

The case study is an industrial water trunk main that comprises a water treatment plant at an elevation of 70 m, a gravity pipe around 10 km long with diameters varying from 1000 to 1500 mm and a storage tank with 50,000 m^3 of capacity at 53 m of elevation. The pipe material is reinforced concrete, except when in the valve chambers (four in total) where the pipes are made of steel with smaller diameters. Local site inspections have shown that most structural condition problems are located at these valve chambers.

The industrial park was built over 30 years ago with a high potential for future growth; the system is currently overdesigned. The decision process initiated with the possibility of a new large industrial consumer settling in the industrial park, which will increase the current demand by three times, and may compromise the whole system capacity. In addition, other concerns of the water utility are: the lack of redundancy of the system, the infrastructure bad structural condition (evaluation based on known age and useful life of reinforced concrete pipe), the customers sensitivity to water supply interruptions and the possible lack of hydraulic capacity for future demands.

In order to address these problems, two demand scenarios were considered. Scenario 1 corresponds to a continuous increase of demand in the period of analysis (2011-2035); Scenario 2 presents a reduction in the middle of the period of analysis which corresponds to end of the contract with the industry (see Figure 2).

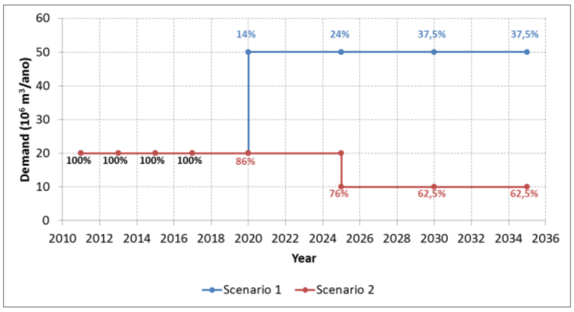

Figure 2 Scenarios of demand evolution

Four rehabilitation alternatives were considered:

- Alternative A_0 – the *status quo* (*i.e.*, keeping the current O&M practice) (no investment cost);
- Alternative A_1 – the implementation of a set of systematic repairs in the existing pipe (investment of 2.5 M€);
- Alternative A_2 – the construction of a new pipe for 25 hm^3/year + rehabilitation of the existing one (investment of 15.1 M€);
- Alternative A_3 – the construction of a new pipe for 60 hm^3/year abandoning the existing pipe (investment of 11.7 M€).

The decision-maker (a panel of specialists from the water utility) has chosen six criteria from the three assessment dimensions to evaluate each rehabilitation alternative: two risk assessment criteria – risk of pipe burst (R_1) and risk of lack of hydraulic capacity of pipes (R_2); three performance criteria – real water losses (P_1), exceeding pipe capacity (P_2) and the Infrastructure Value Index, IVI (P_3) and one cost criterion – total cost (C_1).

Risk

In engineering, risk is traditionally valued as the product of the likelihood of an event by the associated consequences. These consequences can be evaluated under different dimensions.

Risk of pipe burst (R_1). This criterion intends to estimate the risk of a burst event in the industrial water trunk main. The likelihood of a burst event can be estimated using the repair records history form the water utility assuming that all bursts in pipes are registered. If the water utility does not have historical records, the likelihood can be valued using expert-based estimates. In this case study, the likelihood was valued using the historical repair records from another utility which has similar pipes made of reinforce concrete and with diameters between 750 and 1200 mm. The repair data are a set of 29 records taken between 1998 and 2010. Pipes with no burst events were also included to evaluate the likelihood.

Commonly, the consequences considered relevant by the utility engineers result from a water supply disruption. These consequences are the impacts to the system operation and maintenance, disturbances to consumers for the service interruption and disturbances to third parties (e.g., floods and disturbances on traffic and on accessibilities). The dimension consequence considered herein was the water supply disruption to the industrial park expressed as the percentage of volume of water needed and not supplied when a burst occurs in the pipe. This criterion is given by Equation (1).

$$R_1(t) = C(t) \times P(t) \tag{1}$$

where $R_1(t)$: risk of pipe burst at time t (-); t: time (year); $C(t)$: consequence at time t (-); and $P(t)$: likelihood at time t (-).

Risk of lack of hydraulic capacity of pipes (R_2). In this risk criterion the likelihood is estimated using the likelihood associated to the occurrence of the annual water demand of each scenario (as Figure 1). These values were assigned by a panel of specialist from the water utility. The consequence considered to this risk criterion was the water supply disruption measured by the ratio between the water demand for a given time and the maximum hydraulic capacity of the pipes for the analysed alternative. The risk of lack of hydraulic capacity of the pipes is estimated according to Equation (2).

$$R_2(t) = P(t) \times \left(\frac{Q(t)}{N(t)} \right) \tag{2}$$

where $R_2(t)$: risk of lack of capacity of pipes at time t (-); t: time (year); $P(t)$: likelihood at time t (-); $Q(t)$: maximum hydraulic capacity of the pipes at time t (m^3/year) and $N(t)$: water demand at time t (m^3/year).

Performance

Real water losses (P_1). This performance indicator was estimated using the methodology presented in Laven and Lambert (2012). The methodology is based on statistical data collected over 15 years in 25 countries. This performance indicator can be assessed using Equation (3).

$$P_1 = 0{,}1029 \times a \tag{3}$$

where P_1: real water losses indicator ((m^3/year).km^{-1}); a: average age of the pipe that can be aggravated due pipe condition (years).

Exceeding pipe capacity (P_2). This indicator measures the ratio between potential water demand transported by a pipe in a given time and the maximum flow that can be transported by the pipe. Equation (4) shows the formula to obtain this indicator.

$$P_2(t) = \frac{N(t)}{Q(t)} \tag{4}$$

where P_2: exceeding pipe capacity at time t (-); $N(t)$: water demand at time t (m^3/year); t: time (year); $Q(t)$: maximum hydraulic capacity of the pipes at time t.

If $P_2<1$ than pipe is overdesigned in terms of hydraulic capacity, if $P_2=1$ than pipe hydraulic capacity is adequate to demand and if $P_2>1$ than pipe is under-designed.

Infrastructure value index – IVI (P_3). This is a performance index that represents the ratio between the current costs and the replacement costs of the infrastructure. IVI is assessed by Equation (5).

$$P_3(t) = \frac{\sum_{i=1}^{N}\left(rc_{i,t} \cdot \frac{r_{i,t}}{u_i}\right)}{\sum_{i=1}^{N} rc_{i,t}} \tag{5}$$

where P_3: IVI at time t (-); t: time (year); N: total of assets (-); $rc_{i,t}$: replacement cost of asset i at time t (€); $r_{i,t}$: residual life of the asset i at time t (years); u_i: useful life of the asset i (years). IVI should ideally be near 0.5 (Alegre and Covas, 2010).

Cost

Total cost (C_1). The total cost is the sum of the tangible costs associated to each alternative. The tangible costs considered were the investment cost, the annual operation and maintenance cost, the annual water acquisition cost from other utilities and the annual treatment cost. Equation (6) shows the total cost formula.

$$C_1 = IC + \sum_{i=1}^{m}\left(C_{O\&M} + C_A + C_T\right) \times \frac{1}{\left(1+t_a\right)^i} \tag{6}$$

where C_1: total cost (€); IC: investment cost (€); $C_{O\&M}$: operation and maintenance cost (€); C_A: water acquisition cost from other utilities (€); C_T: treatment cost (€); t_a: discount rate (-).

The investment cost includes the costs associated to the construction of tanks and pipes. In this paper the annual operation and maintenance cost is 1% of the investment cost. The utility needs to buy water from another utility whenever demand is greater than 25 hm^3/year. But the contract with that utility establishes that despite demand reaching the 25 hm^3/year or not they have to buy a minimum of 10 hm^3/year. The water acquisition cost includes the real water losses in the system. All amount of water that enters in the system is treated and, therefore, has additional costs that should be taken into account.

Criteria aggregation

The main question was how to aggregate different criteria considering multiple demand scenarios along the whole period of analysis. This question introduces complexity in the analysis since to use the ELECTRE III method to rank the alternatives only considers one value per criterion and per alternative.

The first step to solve the problem in this case study was the aggregation of each criterion along the time dimension. For the risk criteria, the maximum value along the period of analysis was assumed. For the performance criteria, except for IVI, it was considered the average value in the period of analysis. Finally, for the cost criteria, the global value assumed was the sum of all annual present costs.

The aggregation over time of the criteria leads to two global values per alternative and per criterion, one for each scenario. The second step is to deal with the scenarios. There are two ways to do it: the first is to use the ELECTRE III method for each scenario and to compare the results obtained, and the second is to aggregate the scenarios. In the case study presented in this paper the second way was used. The scenarios were aggregated using the value of a criterion and weighting it with the likelihood that the utility engineers gave for the demand in each scenario at different time steps (see Figure 2). Equation 7 shows the formula used to aggregate the scenarios.

$$g_j = \frac{1}{m}\sum_{i=1}^{m} g_i(t) \tag{7}$$

where $g_i(t)$: value of the criterion g in scenario i at time t; $p_i(t)$: likelihood of demand assigned to scenario i at time t; m: number of scenarios.

RESULTS AND DISCUSSION

Results obtained along the period of analysis for the six assessment criteria (R_1, R_2, P_1, P_2, P_3 and C_1), for the four alternatives and for the two scenarios considered are presented in Figure 3.

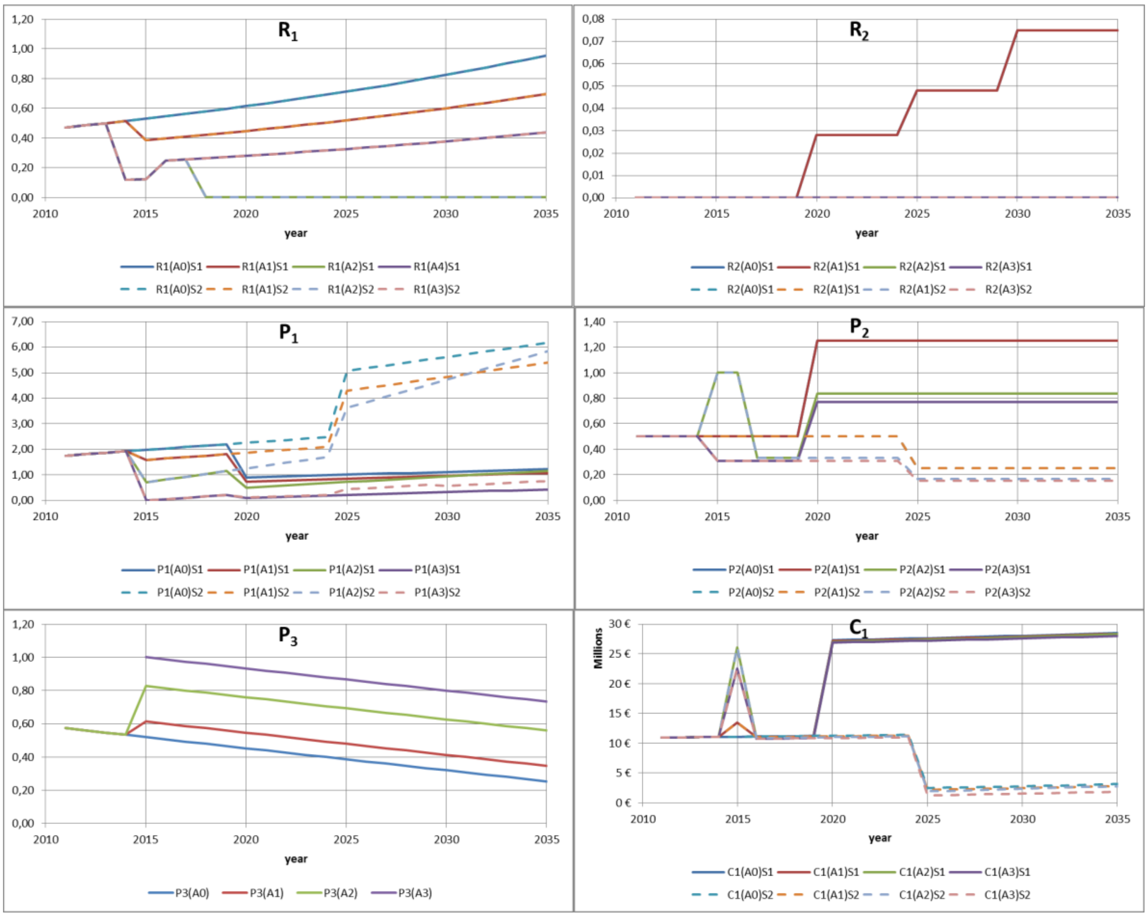

Figure 3 Time evolution for six assessment criteria: risk of pipe burst (R_1); risk of lack of hydraulic capacity of pipes (R_2); real water losses (P_1); exceeding pipe capacity (P_2) infrastructure index value, IVI (P_3) and total cost (C_1)

The results for time evolution for the risk criteria R_1 show that there is a decrease of pipe burst risk after the rehabilitation intervention. Afterwards, the risk will increase over time because of pipe ageing. For alternative A_2 risk will be null after 2017 since the new pipe is in service and is estimated that in this year the existing pipe will be placed into service after rehabilitation intervention. Results for each alternative for R_1 are similar for both demand scenarios.

R_2 is null in Scenario 2 for all rehabilitation alternatives because pipes always have enough hydraulic capacity and, therefore, the consequence is always null; in the case of Scenario 1, for rehabilitation alternatives A_0 and A_1, the risk R_2 increases with time, starting from null to moderate risk level at the end of the period of analysis.

The performance criteria P_1 and P_2 are demand-dependent. The performance indicator P_1 is higher, the lower the demand. The real water losses rate is the same in both scenarios but in percentage is more expressive for lower demands. This is the reason why P_1 is higher in Scenario 2 than in Scenario 1. P_2 is the ratio between water demand and pipe capacity and, therefore, it will be higher for Scenario 1 than Scenario 2.

The results obtained showed that only criterion P_3 does not differ per scenario. This is because IVI is independent of demand and decreases along time because of pipe ageing.

The total costs of alternatives are higher in Scenario 1 than Scenario 2 because the water acquisition cost from other utilities and the treatment cost are higher when demand is higher. Cost differences between alternatives are very small, less than 2% in Scenario 2 and 7% in Scenario 1.

To evaluate the four rehabilitation alternatives with the selected criteria, ELECTRE III method was used. In this method, criteria, alternatives and thresholds are defined. If the decision-maker argues that the different criteria should not have the same relative importance, weights can be used. The attributes, the weights and the preference direction of the criteria are shown in Table 1.

Table 1 Attributes, weights and preference direction of the criteria

	R_1 (-)	R_2 (-)	P_1 (%)	P_2 (-)	P_3 (-)	C_1 (M €)
A_0	0.91	0.01	1.85	0.36	0.42	192.54
A_1	0.48	0.01	1.61	0.36	0.50	192.76
A_2	0.25	0.00	1.39	0.32	0.68	203.76
A_3	0.12	0.00	0.62	0.26	0.87	195.98
Weight	10	8	1	1	2	10
Preference direction	↓	↓	↓	↓	↑	↓

According to ELECTRI III, the rank order is A_3, A_0 in *ex aequo* with A_1 and A_2 when considering all six criteria. However, when the total cost criterion is neglected in the analysis or a lower weight is assigned to this criterion, the rank is A_3, A_2, A_1 and A_0.

The results are consistent since the alternative A_3 has the best attributes for at least five criteria (R_1, R_2, P_1, P_2 and P_3). When the criterion C_1 is considered in the analysis, alternative A_2 is penalized. The reason for that is because this alternative is the most expensive and the criterion is considered as very important relatively to the others. Alternatives A_0 and A_1 are quite similar, but alternative A_1 shows a slight improvement in performance P_1 and P_3 and reduction of risk R_1 comparatively to A_0.

CONCLUSIONS

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. ELECTRE methods are a family of MCDA techniques distinguished by the type of problems involved, such as *choice*, *ranking* or *sorting*. The selection of the best rehabilitation solution taking into account different criteria established for the assessment of performance, cost and risk can be treated either as a *choosing* or a *ranking* problem. In this paper, the comparison of different rehabilitation solutions is treated as a *ranking* problem and for that the ELECTRE III method is used for the aggregation of criteria.

A possible way to aggregate each criterion along the time dimension is by using for the risk criteria the maximum attribute, for the performance criteria (except for IVI) the average attribute along the period of analysis and for the cost criteria the global attribute results from sum of all annual present costs. The scenarios can be aggregated using the attributes of a criterion and weighting them in different time steps. The results obtained in this study showed that the best alternative is A_3 which consists of the construction of a new pipe for 60 hm^3/year abandoning the existing pipe. When the cost criteria have a lower weight, or is not considered in the analysis, the ranking order will change but keeping as best alternative A_3.

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