A practical decision scheme for the prioritization of water pipe replacement

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ABSTRACT

Most water distribution networks are assemblies of buried elements which makes their diagnosis complex and requires implementing an asset management (AM) policy of actions performed in the short, medium and long terms. To implement such an AM, decision makers must diagnose the condition of the asset by developing specific tools for establishing priorities between assets and plan the actions needed to maintain or improve their condition. This study focuses on two topics. (i) The implementation of a spatiotemporal analysis of the propagation of pipe breaks. This innovative approach inspired by criminality analysis allows focusing on hotspot zones in order to discriminate critical assets. We have designed a new 'clustering' criterion that can be used as a prioritization criterion for asset sorting. (ii) The second part addresses the issue of multi-criteria decision making concerning the classification of pipe renewal candidates by comparing two kinds of aggregation method: (i) an unsophisticated approach by using adapted weighted sum methods; and (ii) a sophisticated approach by using the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) and the 'Elicitation Et Choix Traduisant la Réalité' (ELECTRE III). The underlying reason for comparing these methods is to know whether the unsophisticated methods ensure reliable replacement policy compared to the sophisticated one.

Key words | aggregation, clustering, decision making, prioritization, policy, rehabilitation replacement

SUBSCRIPTS

PROMETHEE Preference Ranking Organization Method for Enrichment Evaluation
GAIA Geometrical Analysis for Interactive Aid
AM Asset management
ANN Artificial neural network
GIS Geographic information system
NRW Non revenue water
NNA Nearest neighbour analysis
NNI Nearest neighbour index
PCA Partitional clustering algorithm
HCA Hierarchical clustering algorithm
NNH Nearest neighbour hierarchical algorithm
MCDM Multi-criteria decision making
DMs Decision makers
EC Evaluation criteria
MCA Multi-criteria analysis
CP Compromise programming
AHP Analytic hierarchy process
HNWS Harmonized and normalized weighted sum

NOTATION

$\text{NND}_R$ the expected value of the nearest neighbour distance in a random pattern.
$\text{NND}$ nearest neighbourhood distance
$n$ number of failure points
$A$ size of the study area
NNI nearest neighbour index
Minpts minimum points
ε \quad \text{epsilon}

n \quad \text{time horizon}

k \quad \text{criteria}

i \quad \text{pipe}

j \quad \text{criterion}

g() \quad \text{assessment function}

w_i \quad \text{weight value}

BR \quad \text{breakage rate: b/km/year}

HC \quad \text{hydraulic capacity}

RC \quad \text{replacement cost}

RT \quad \text{residual lifetime, year}

IC \quad \text{important customer demand}

CL \quad \text{clustering}

CS \quad \text{cost saving}

DI \quad \text{diameter, m}

NC \quad \text{number of contiguities}

PM \quad \text{pipe material}

p_j(a, b) \quad \text{the preference of option } a \text{ with regard to option } b \text{ on each criterion } j,

d_j(a, b) \quad \text{the difference between evaluation } a \text{ and } b \text{ on each criterion}

q \quad \text{indifference threshold}

p \quad \text{preference threshold}

s \quad \text{intermediate value}

\Pi(a, b) \quad \text{global preference index}

\Phi_+ \quad \text{positive outranking flow}

\Phi_- \quad \text{negative outranking flow}

\Phi(a) \quad \text{net outranking flow}

M \quad \text{max } (g_j(a))

WS(a) \quad \text{weighted sum of option } a

C \quad \text{criterion expressed as the sum of the breaks divided by the total replaced length}

\Delta B \quad \text{difference of avoided breaks between replacements } i \text{ and } i + 1

\Delta L \quad \text{difference of the replaced length between replacements } i \text{ and } i + 1

INTRODUCTION

Asset management (AM) of drinking water systems is an approach that tracks the status of the buried asset and anticipates actions to be performed to ensure its efficient operation during its service lifetime. It is a managerial approach aimed at maintaining the user’s water service at a required level of quality and quantity under optimal technical and financial conditions. In most cases, the budget for renewal is fixed in advance and the works to be performed must fall within financial constraints. Firstly, AM tends to improve knowledge of networks by implementing inventories of items of equipment and checks of components. The status of the asset is established in the present, i.e. today, so the current status of the network depends on policies implemented earlier by the network manager. To improve this current status, AM requires the use of a specific decision scheme to help utility managers to establish priorities for network rehabilitation. The multi-criteria decision methods provide an interesting means of achieving this aim by defining criteria and indicators for assessing the level of asset condition. Two kinds of methods can be cited: (i) sophisticated methods with consistent scientific bases, and (ii) unsophisticated methods with empirical bases. Here, the challenge is to assess the capacity of the water utility manager to understand the scientific basis of multi-criteria methods and how it can implement them. This is considered by most of utilities as a major advance.

In practice, it is almost impossible to rehabilitate the whole system immediately. Thus, it is necessary to identify the most deteriorated parts and rank them according to their level of deterioration. Deterioration implies a decrease of the condition of the asset that can be physical or functional. This depends on contradictory criteria that can be environmental, technical, managerial and economic. It appears that two main stages should be taken into account to define a robust rehabilitation policy: (1) the definition of relevant criteria, and (2) weighting and aggregating criteria by through selection and using an adequate multi-criteria method. Therefore our work tends to help the decision maker to answer the following questions: What are the criteria for renewal? What is the weight of each criterion and how can we assess it? Are multi-criteria methods complex to implement? Do unsophisticated multi-criteria methods give reliable results? How much is it going to cost? What are the possible savings?

Based on these considerations, the aim of our paper is to answer the questions raised regarding network renewal. It is organized in two complementary parts. The first concerns
the prioritization criteria for water pipe renewal. As explained previously, the definition of an efficient rehabilitation policy requires identifying critical pipes and assessing the impact of their renewal. A new criterion is defined in the current paper, based on a spatiotemporal analysis. Spatial aggregation of breakages, i.e. clustering, based on past failure records, is performed in order to identify critical pipes belonging to hotspot zones. As we cannot consider all the pipes in the network, clustering allows us to identify ‘hotspots’ indicating the areas of the network where failures are concentrated, hence a pipe that belongs to a hotspot zone is considered to be critical.

The second part provides a discussion on how to aggregate criteria for pipe renewal and select multi-criteria methods for sorting pipes. This part benchmarks existing multi-criteria methods based on outranking methods considered as ‘sophisticated methods’ against methods based on weighted sums considered as ‘unsophisticated’. Specific indicators are used for this benchmarking. The following paper is arranged in five sections. The first provides an analysis of the context through a review of the literature on existing criteria for pipe prioritization. The second section introduces the spatiotemporal approach by explaining the principle, the objectives and the algorithm used. The third section presents the main multi-criteria approaches cited in the literature. The fourth section presents the implementation of the approach in a real case study and the significant results. Finally, the last section presents an initial evaluation of the approach, the results and further work.

DECISION MODELS FOR ASSET MANAGEMENT: STATE OF THE ART

Several decision support systems for prioritizing water pipes have been developed: Utilnets, Caree-W (Le Gauffre & Haidar 2008); Kanew, Riva, Sirocco, Prams, Water Gems (Nafi & Werey 2009). Most researchers (Dridi et al. (2006), Halfawy et al. (2008) and Giustolisi & Berardi (2009)) have proposed a non-exhaustive list of various criteria and encouraged water utilities to obtain better knowledge of their assets by collecting new data and updating.

Eisenbeis (1994) described failure events using the Proportional Hazard Model (PHM) (Link PHM: http://www.weibull.com/acceltestweb/proportional_hazards_model.htm) proposed by Andreou (1986), while assuming that the time between breaks was described by a Weibull function. The model took into account endogenous and exogenous variables related to both the pipe and its environment. The impact of these variables on the pipe deterioration process was expressed by covariates. The model was designed to predict pipe status given a set of variables.

Werey (2000, 2002) proposed scheduling pipe replacement using a PHM model that assessed failure probabilities involved in an objective function, and which took into account direct and social costs related to a break in the network. Two alternatives were considered in the event of a break: repair and wait for renewal, or replace the broken pipe with a new and similar pipe.

Kleiner (1996) described the evolution of breaks on pipes over time using the model proposed by Shamir & Howard (1979), but considered more rehabilitation alternatives and hydraulic constraints in the optimization process, whereas Kleiner (1996) and Werey (2000) used dynamic programming to propose optimal scheduling of renewal.

Le Gauffre et al. (2004) proposed a multi-criteria analysis to determine classes of deteriorated pipes in a network. The ELECTRE-TRI method was employed using criteria linked to pipe characteristics and environments to classify and prioritize pipes for replacement. However, it appears that the link between hydraulic operation and structural deterioration was not sufficiently established in this model.

In their approach to evaluating renewal technologies, Halfawy & Baker (2008) embraced the notion of condition index and the possibility of soil loss. The structural capabilities of pipe renewal categories were identified on the basis of the pipe’s structural condition and the possibility of soil loss. The authors also integrated the concept of cost/benefit to optimize the choice of renewal methods. According to Halfawy & Baker (2008), an assessment of benefits should consider the impact of post-rehabilitation of a renewal method and the different categories of failures and believe that there is no way of accurately calculating the improvements expected. Obviously, the development and validation of such a model would require extensive and generally unavailable pre and post-rehabilitation data. Their approach was based on the profit estimate in terms of
improvement of condition (or recovery) by deducting certain values from the condition index.

Cheng et al. (2009) developed a qualitative model that combines an Artificial Neurone Network (ANN) with a geographic information system (GIS) to provide decision makers with an alternative analysis of pipe failure problems in water distribution networks.

The innovative approach in their research was to add the factor of number-magnitude earthquake to determine the decision making priorities. Obviously this theory is only valid in countries where the phenomenon of earthquake and severe natural events are frequent.

Saldarriaga et al. (2010) submitted a prioritization scheme for water network rehabilitation based on the following performance measure criteria: (i) a new conceptualization of the resilience index proposed by Todini (2000) by including the flow and pressure variation due to leakage; (ii) the unitary power of the pipe; and (iii) the reduction of the non revenue water (NRW) to identify the point at which, according to the criteria used, the pipe replacement process should be stopped.

Tabesh et al. (2010) built a subroutine that links GIS and a hydraulic simulation software application. The renovation scheme was based on several indices like pipe breaks, leakage analyses, hydraulic and quality performance and the mechanical reliability of the network, including the parameters of pressure, velocity and residual chlorine. Then the performance of each node, pipe and entire network was evaluated and represented in the GIS map of the network.

Even if the proposed criteria are relevant, not enough account is taken of the spatial dimension and ‘network scale’. Indeed, the prioritization criteria identified in the literature are assessed at pipe scale and allow discriminating between pipes. Some criteria are difficult to quantify or require too much and often unavailable input data. In reality, criteria used most often for pipe rehabilitation are pipe age, breakage history, pipe size, pipe criticality and roadworks or planned works on adjacent networks such as gas, electricity and sewers.

However pipe condition depends on both structural and functional deterioration. As for pipe criticality, it depends on the pipe’s location in the network topology among other factors. The scale of analysis should therefore be both that of the pipe and of the whole network. In addition, analysis across the network refers to a spatial dimension that takes into account not only the pipe scale but also the whole system in terms of break trends, a factor generally omitted. Often, the pipe is a record in a database identified by a key; nothing is known of its location in the network during its selection or of its links with other pipes. This leads to a loss of important information and can penalize the prioritization of pipes to be chosen for renewal. The spatial analysis of the network shows clusters of breaks which are more crowded in certain areas of the water network. Empirically, it has been observed that breaks tend to cluster spatially and temporally, where the first break is an independent event followed by breaks that occur in close proximity in terms of location and time (Goulter & Kazemi 1988).

Therefore, we explore the construction of pipe prioritization criteria based on grouping pipe breaks in ‘clusters’ in order to discriminate areas of high break density called ‘hotspots’ surrounding areas characterized by low break density or ‘noise breaks’ that does not reflect a potential concentration of failures. This approach is inspired by the notion of areas of concentrated crime formulated by Levine (1996) and Levine et al. (1995a, 1995b) and through which individual pipes within a hotspot will subsequently be prioritized.

### A NEW PRIORITIZATION CRITERION: CONSIDERATION OF SPATIAL AND TEMPORAL DIMENSIONS

A pipe renewal program requires the implementation of a proactive approach for failure prediction and the definition of relevant criteria for the selection and prioritization of pipes to be renewed. In general, prioritization criteria can be classified as follows:

- **Hydraulic criteria:** surplus pressure or deficit, demand satisfaction, hydraulic capacity, reliability, resilience.
- **Economic criteria:** replacement cost, opportunities and economy of scale, direct and indirect costs, social costs, cost of water loss, repair cost, benefit.
• Social criteria: customer dissatisfaction, number of complaints, externalities.
• Structural criteria: number of breaks or leakage, breakage rate, linear index of loss, red water.

Beyond these criteria, we propose building additional indicators to characterize hotspots and their evolution over time. This implies a spatial analysis of failures through clustering according to historical failure data.

The knowledge of the trend of failures, occurrences and their spatial distribution within the network remains essential before carrying out any prioritization task. Discrimination of failure concentration will enable focusing on the most vulnerable pipes belonging to high failure density zones and thus avoid early renewal of pipes having just undergone noise breaks. This helps to better target the renewal works and achieve significant savings.

**Principle of clustering: distance analysis**

In this section, we analyze how clustered or dispersed the breaks are. Based on the nearest neighbour approach, the analysis put us on track for identifying and understanding hotspots. We used distance analysis techniques to know how dispersed the breaks are and identify hotspots highlighted by areas where breaks concentrate. Several distance measurement methods exist. In the following section we describe the Nearest Neighbour Analysis (NNA). It compares the mean distance to what would have been expected in a random nearest neighbour distribution (Equation (1)) and measures the distance of each point to its nearest neighbour (Equation (2)). NNA determines the mean distance between neighbours (Equation (3)). We can also control whether to compare each point to its single nearest neighbour or to run the process for the second-nearest, third-nearest, and so on. The NNA allows calculating the Nearest Neighbour Index (NNI) (Chang & Kang 2008). In the NNI, a score of ‘1’ would indicate absolutely no discrepancy between the expected distances in a random distribution and the measured distances in the actual distribution. Scores lower than ‘1’ indicate that incidents are more dispersed than would be expected in a random distribution. The NNI calculation process is given by:

\[
\text{NND}_R = \frac{1}{2\sqrt{n/A}} \tag{1}
\]

\[
\text{NND} = \frac{\sum_{i=1}^{n} \text{NND}}{n} \tag{2}
\]

\[
\text{NNI} = \frac{\text{NND}}{\text{NND}_R} \tag{3}
\]

where: \(n\) is the number of failures. Each failure is spatially represented by a point, the failure location. \(A\) is the size of the area analyzed, NNI the ratio of the observed distance over the expected distance, NND is the distance between each failure location and its nearest neighbour, \(\text{NND}\) is the observed mean distance between nearest neighbours, and \(\text{NND}_R\) the expected value of the nearest neighbour distance in a random pattern.


Clustering is the process of creating a collection of similar data within the same group and dissimilar data when they belong to different groups. It is an unsupervised classification, which means one without predefined classes. These methods are widely used in risk and crime spread analysis. A good clustering method ensures high ‘within-group’ similarity and allows ‘inter-group’ dissimilarity and these are characteristics on which the analysis of the spatial distribution of pipe breaks will be based. There are four major clustering approaches. **Partitional Clustering Algorithms (PCA)** usually construct predefined clusters. **Hierarchical Clustering Algorithms (HCA)** create a hierarchical decomposition which can be represented as a dendrogram. **Density-based partitioning Algorithms** search for regions that are denser according to a predefined threshold. **Grid-based Algorithms** are based on multiple-level granularity by quantizing the search space into a finite number of cells (Abdulvahit Torun & Düzgün 2006). In this study we use **Neighbour Hierarchical Spatial Clustering (NNH)** (Wong &
Lane 1981; Levine 1996; Smith & Bruce 2008) (Link: http://www.slidefinder.net/c/crimestat_iii_workbook_powerpoint/crimestat_iii_workbook_powerpoint/27801438) and Evakikandi & Mirzaei (2010). The NNH is an algorithm used to identify areas containing a high percentage of a studied phenomenon and thus it distinguishes clusters of incidents. In order to display the clusters the NNH proceeds as follows:

1. The NNH builds on NNA (NNA determines if a particular event was more clustered than might be expected by random chance).
2. NNH takes the analysis to the next level by identifying these clusters.
3. NNH creates ‘first order’, ‘second order’, etc. clusters.
4. NNH continues until it cannot locate any more clusters.

The failure clustering in the network was based on two parameters: (i) the maximum neighbourhood radius (search radius) that separates a basic break point from other breakage points ‘ε’; and (ii) the minimum number of breaks in a neighbourhood (minimum breaks per cluster), ‘MinPts’.

**Methodology**

In this section, we analyze the spatial and temporal trend of pipe breaks to understand how the size of clusters evolves over time. The temporal dimension is taken into account by analyzing the trend of past failures. This analysis divides the break history into decade time intervals (see step 1 below) in which we layer breaks corresponding to each horizon. This mapping considers the cumulative number of breaks per period of time, allowing us to describe the evolution of breaks. At the end of the break history, a cluster characterized by high break density forms a hotspot zone.

The proposed methodology includes six steps:

**Step 1:** break history (1962–2003) is partitioned into decade time intervals, thus we obtain four equivalent time intervals: [1962, 1973], [1974, 1984], [1985, 1995] and [1996, 2003].

**Step 2:** the network breaks corresponding to each time interval are plotted.

**Step 3:** the nearest neighbour index (NNI) is calculated for each horizon in order to detect the spatial distribution of breaks by using the NNA method.

**Step 4:** the network is divided into clusters using \( \text{NNH} \) to identify areas of high failure from surrounding areas of low breakage density (noise breaks), to understand and discern the break patterns in time. Many simulations have been performed to fix the clustering parameter values. Ben-David \( \text{et al.} \) (2002) and De Oliveira \( \text{et al.} \) (2010) demonstrated that clustering quality declines as the \( \varepsilon - \) distance increases and as the ‘\( \text{MinPts} \)’ parameter decreases. When the distance parameter increases, the clusters tend to be larger and less homogeneous. Clustering using a low \( \text{MinPts} \) parameter (say two or less breaks) will tend to produce a large number of small clusters non-conducive to effective renewal policy. Indeed, a large number of clusters prevents highlighting the notion break density in the network and does not allow distinguishing between clusters – also defined as small extension – De Oliveira \( \text{et al.} \) (2010b). Consequently, we set the parameter \( \text{MinPts} = 3 \) while the distance parameter was defined while considering that replacement will not be performed for arbitrarily long extensions of pipes but rather for shorter lengths. For instance, taking in account the longest pipe (410 m) and the shortest one (37 m), we used a distance \( \varepsilon \) or search radius equal to an average pipe length value of 225 m. This distance is not generated randomly and is meaningful for decision makers.

**Step 5:** Define criteria for giving a first ranking level and identifying which clusters form hotspot zones. A possible criterion is the breakage rate of a cluster. The pipes included in the clusters will be automatically prioritized once the classification of clusters has been set. A pipe contained in a cluster characterized by a high breakage rate has priority in comparison to another one belonging to a cluster with a lower breakage rate.

**Step 6:** Define prioritization ranking for each pipe or street into the clusters. Within each cluster, prioritization should not be applied only at pipe level but rather at that of streets or roads. Street level corresponds to a practical dimension instead of cluster which is only a means of focusing on hotspot zones. Thus establishing a link between a critical cluster and a street dimension provides a realistic way of defining the potential replacement worksites.

**Clustering analysis**

The methodology was applied to part of a real network consisting of 147 cast iron pipes with a diameter from 150 to 250 mm. For each time interval, we performed the cluster
analysis separately (Nearest Neighbour hierarchical clustering algorithm) with a fixed radius (or distance parameter of 223 m). One way of analyzing and observing the temporal trend of breaks was to display the clusters of the period \((t + 1)\) over those of the previous period \((t)\) through the different time intervals. This analysis is illustrated in Figure 1 which shows the clusters obtained for four periods of time considered separately. The *Nearest Neighbour Index* corresponding to periods is respectively 0.55, 0.53, 0.48 and 0.6 (less than 1) which denotes the clustering behaviour of breaks. We note that clusters tend to occur in the same location as in the previous period, they can be superposed, with the same deviation or also between two adjacent previous clusters. This could confirm the hypothesis mentioned at the beginning: breaks tend to be clustered over time. We observe that there are three main annotations: (i) appearance of new clusters, (ii) evolution of clusters from one or more other clusters, and (iii) above all, the overlapping of new clusters over old ones. In particular these clusters seem to be the most critical zones characterized by a higher density of breaks.

In other words, we observe that many scored clusters are close to, or have exactly the same location as, those in the previous period, which implies that a large number of breaks were concentrated exactly in the same location of the previous cycle and therefore encompassed. To perform this reasoning concerning hotspots, the analysis was also performed using the kernel density estimation function. Figure 2 shows practically the same hotspots and cold spots describing the breakage density in each raster. This confirms that zones A, B and C are the most critical zones in the study area, characterized by a high density of breakage, and will therefore be the prime targets for prioritization.

The encompassed clusters were then merged into larger ones to reach a second hierarchy through which it will be easier to identify sectors and streets for replacement. Indeed, the first level of clustering (pipe level) can provide an excellent indicator of breakage in small sections but does not allow working at a larger scale. Therefore merging small clusters into macro clusters will permit prioritizing replacement at street and road level.

**Analysis of results**

Here we analyze the cluster results to provide insight on the issues that spatial clustering can be used for infrastructure management decision-making. In this section we compare the information provided by the definition of (non-spatial) groups of pipe of similar age to the information provided by spatial clusters of pipes. Figure 3 shows that clustering based on the number of breaks per zone, zones A and B are the most critical despite the fact that they are equipped
with newer pipes (years of installation 1956–1958 and 1959–1960, respectively). Based on the breakage rate (breaks/km/year/cluster), we observe that the most critical zones are not those in which pipes were installed before 1955, but rather where most of the breaks are concentrated. Furthermore, the same pipe age may imply different levels of breakage density, which is one of the advantages of clustering (Figure 3).

In this case, the prioritization scheme within each cluster will be based only on the breakage rate of pipes, as pipes included in clusters are automatically classified. Besides, to compare the current methodology with a method based only on pipe breakage rate, noted ‘classical one’, we sort pipe networks according to breakage rate (high to low) and plot the curve describing the number of breaks avoided.
versus the cumulative percentage of pipe length renewed in the network (Figure 4). We split the time horizon from 1962 to 2003 in which breaks occurred, into two periods: a period of analysis from 1962 to 1995 and validation from 1996 to 2003. To compare the clustering methodology to a classic approach based only on breakage rate, we tracked the variation in the number of breaks (for the selected prioritized pipes corresponding to each methodology) in the validation period with the total length to be replaced. For us, for example, if pipe ‘i’ is selected for replacement in the observation or analysis period ([1962, 1995]), the number of breaks avoided corresponds to the failures that occurred in the validation period ([1996, 2003]). If we renew that pipe we will avoid ‘x’ breaks (avoided breaks) in the future.

According to Figure 4, the new criterion seems interesting because it allows focusing replacement on critical pipes and leads to fewer replacements with more avoided breaks compared to the classical approach. Fewer pipes are replaced (10.9 km vs. 11.3 km for the classic method), i.e. equivalent to 1.5% of the whole network, but the same number of future breaks is avoided (avoided breaks). Obviously, avoiding unnecessary replacements for 1.5% of the network would allow saving about €99,650 for the last 8 years which corresponds to an average amount of €14,230 per year for this small network. This saving is the percentage of pipe length saved for the validation period of the last 8 years (1996–2003), and it might be more advantageous for a longer period of time or for a larger network. Obviously, the accuracy of the results depends on breakage history or, more precisely, on the distance between breaks. Indeed, as the data necessary to accurately locate the ‘x’ and ‘y’ coordinates of the break points were unavailable, we divided the pipe length by the number of breaks and represented our point of breakage with the ‘ArcGis’ tool which, unfortunately, not does not reflect reality due to the lack of data. The quality and accuracy of the results could be improved by providing more precision for localization data.

This approach allowed us to add a new dimension regarding the water pipe renewal prioritization criteria. Obviously, it must be applied to several case studies with several combinations of training and validation periods to confirm its performance. Knowledge of the link between the spatiotemporal analysis ensured by ‘clustering’ and the hydraulic behaviour of the network could help the manager to check whether the hotspot zones affect the hydraulic operation of the network. This aspect deserves further exploration. In the present paper, we treat the hydraulic aspect by only considering the hydraulic capacity of pipes expressed by the Hazen Williams coefficient. By conserving classical criteria, breakage clustering behaviour will be included in the next section for a multi-criteria analysis for decision support tool in which we focus on the comparison of different aggregation and decision-making methods.

MULTI-CRITERIA DECISION MAKING (MCDM) FOR PIPE PRIORITIZATION

Definition of MCDM

The International Society on Multiple Criteria Decision Making defines the MCDM as ‘the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process’. According to Xu & Yang (2001), multiple criteria decision making refers to making decisions in the presence of multiple and usually conflicting criteria. Mutikanga et al. (2011) define the MCDM as a tool developed in the field of decision theory for resolving operational research problems with a finite number of decision options that decision makers (DMs) have to evaluate and rank using the weights of a finite set of evaluation criteria (EC). Hajkowicz & Collins (2007) liken the MCDM as a model which contains:

• a set of decision options which need to be ranked or scored by the decision maker;
• a set of criteria, typically measured in different units; and
• a set of performance measures, which are the raw scores for each decision option against each criterion.
MCDM in water management

Decision making in water management is a sensitive task requiring well recognized and documented performance criteria. A large number of decision options and unclear conflicting criteria typically require attributing both an ordinal (qualitative) and a cardinal (quantitative) weight to each criterion. All this makes the decision making issue more abstruse for decision makers and notably for the water utility manager. Hajkowicz & Higgins (2008) report disagreement between multi-criteria methods used for water resource management in several cases, especially when criteria are both ordinal and cardinal.

A recent review of the major MCDM techniques is available in Hajkowicz & Collins (2007). The same review mentioned that the most commonly applied methods were Fuzzy set analysis, compromise programming (CP), the analytic hierarchy process (AHP), ELECTRE and PROMETHEE with most applications used in water policy evaluation, water supply planning and infrastructure selection. The authors add that the reason for using MCA in water management is that it was found to provide transparency and accountability to decision procedures which may otherwise have unclear motives and rationales. Transparency in multi-criteria analysis (MCA) is achieved by explicitly stating and weighting decision criteria.

With regard to the prioritization of water mains for the replacement and management of water loss, Almeida & Costa (2007) proposed a group decision making model based on the PROMETHEE method for leakage reduction planning which takes into account the point of view of five decision makers of a water company. The task of the stakeholders was to identify the relevant criteria, the respective weights, the preference functions and the parameters required for their analysis. Taking into account the available budget as a constraint, and a combination of socioeconomic, environmental and technical aspects, the authors tried to pick out the appropriate alternative for leakage management.

Saldarriaga et al. (2010) submitted a prioritization scheme for water network rehabilitation based on the following performance measurement criteria: (i) A new conceptualization of the resilience index proposed by Todini (2000) that includes the flow and pressure variation due to leakage, (ii) the unitary power of the pipe, and (iii) the reduction of the non revenue water (NRW).

Mutikanga et al. (2011) involved a multi-criteria decision support framework for strategic planning of water loss management based on the PROMETHEE II method which includes a multidimensional scheme that considers environmental, social, technical and economic aspects for leakage management. The prioritization outline of leakage management strategies has led to ranking mains and service line replacement followed by pressure management as the two most cardinal options for water loss reduction.

Nonetheless, Hajkowicz & Higgins (2008) argue that the adoption of more sophisticated and more complicated techniques may not be beneficial if they are likely to confuse decision makers. The authors argue that if decision makers cannot understand the MCA technique and how it generates a result, they would be unlikely to use it.

In the present research, decision making is performed on pipe candidates for renewal with a view to implementing an asset management policy. Each pipe represents a potential option. The approach developed aims to establish priorities between various options-pipes networks in order to identify the most deteriorated pipes requiring rehabilitation actions. Sorting the set of options needs: (i) establishing cognitive interaction processes with the water utility manager to define the objective and criteria measured, (ii) determining the assessment function for the selected criteria, (iii) ranking and weighting the criteria according to the importance of each one in the prioritization, (iv) choosing and testing the multi-criteria method for criteria aggregation, (v) defining the thresholds for the methods tested, (vi) implementing the methods and aggregating the results.

This approach presents one main obstacle which concerns the difficulty of water utilities to understand the mathematical background of available methods and the complexity of implementing them in the utility information system (IS). It appears from our experience, that although typical water utilities are aware of the need to make the process of selecting pipes for renewal more transparent and efficient by implementing, for example, a multi-criteria approach, the mathematical complexity involved often discourages the use of a multi-criteria approach. In our opinion, the challenge is to propose a comprehensive method for tackling the difficulties of installing the MCM on the one hand, while ensuring
on the other hand the same reliability of sorting options. This entails that the method developed should be capable of sorting the options as robustly as other methods, which is why it is advisable to compare them by defining specific indicators. In this part, different aggregation methods were tested and compared, including non-sophisticated methods adapted from the weighted sum method: (i) a method based on evaluating the performance and score of pipe candidates for renewal; (ii) a method based on the Z score ranking. The sophisticated methods include: (iii) PROMETHEE with the Geometrical Analysis for Interactive Aid (GAIA) method, and (iv) the ELECTRE III method. For each of these methods, we describe how to calculate the evaluation function on which the aggregation technique is based and how to rank pipes. This section is organized as follows: in the first subsection we describe the main steps involved in building a comprehensive multi-criteria decision process which includes the choice of the decision makers, the construction of the criteria considered and the description of each aggregation method by underlining their evaluation functions. In the second subsection, we compare sophisticated and unsophisticated aggregation methods by using the following indicators: the avoided breaks, the ‘C’ parameter, the cost saving and the number of contiguities.

**THE MAIN STEPS FOR BUILDING A COMPREHENSIVE MULTI-CRITERIA DECISION PROCESS**

The approach we describe may be reproduced without great difficulty in any water utility. However, it must meet certain guidelines to avoid introducing a bias that may favour certain prioritization criteria or influence the manager in his decision. Beyond the choice of method and its implementation, a real challenge is involved in understanding and describing the decision process for selecting pipe candidates for rehabilitation. In fact, before implementing a new mode in a water utility, the team or the service responsible for asset management.

The success of the implementation of a decision process depends on the involvement of relevant stakeholders whose role in the definition of the renewal policy and renewal programs are clearly identified as part of their skills, directly or indirectly. Participant stakeholders can be chosen according to their involvement in strategic, tactical and operational decisions of both managerial and technical natures.

The ‘game’ proposed is a cognitive process in which we interact with decision makers in order to obtain better knowledge of decision makers’ opinions concerning important prioritization criteria. It was applied in interactive mode in a water utility in the central east part of France. Three stakeholders were identified: (i) the head of the utility, representing strategic and managerial aspects, (ii) the head of the water supply service, responsible for technical and operational aspects of the network, and (iii) the engineer responsible for renewal planning. These decision makers appeared relevant for building and choosing for prioritization criteria. The number of ‘players’ was not fixed in
advance, but depended on the context, the size of the utility and its organizational structure.

**Construction of criteria**

We submitted a non-exhaustive list of prioritizing criteria to decision makers. The goal was to choose the criteria that they considered relevant from a list and suggest others that were not included. The interaction with stakeholders yielded a list of eight criteria ($j \in [1,8]$) deemed relevant:

- **Breakage rate (BR):** the number of breaks observed per km per year.
- **Hydraulic capacity (HC):** this expresses the capacity of the pipe to operate, taking into account potential disruption due to a decrease of pipe section leading to the deterioration of the pressure or volume served. In our case we consider the Hazen Williams coefficient.
- **Residual lifetime (RT):** this is obtained by dividing the gradient between the theoretical service life (which is fixed a priori) and the age of the pipe (on the date of analysis) by the theoretical service life.
- **Component of a loop or a branch (LB):** this assesses the importance of a pipe in the operation of the network and the impact of a random event on the reliability of the service. Indeed, if a pipe is in a loop it will be less critical than another in a branch or at the end of the network.
- **Important customer demand (IC):** this reflects the degree of priority to be given according to the customers served in terms of both volume (large consumers) and activity (hospital, institution, restaurant, nursery, swimming pools and old people’s home). In our case, and given the unavailability of data, the capacity to supply demand is expressed in terms of the flow circulating in the pipe.
- **Clustering (the cluster to which a pipe belongs) (CL):** if a pipe is more critical and prioritized when it belongs to a cluster characterized by a high density of breaks (cluster breakage density).
- **Diameter (DI):** this can be a criterion for renewal; usually larger diameters have fewer failures than smaller ones.
- **Pipe material (PM):** the physical deterioration of a pipe depends on the nature of the pipe material. It is known that some types are more or less resistant. Pipes can be sorted according to their material.

In order to describe stakeholders’ perception of the importance of each criterion for prioritization, we pursue an interactive process by asking them to rank the criteria from most to least important. We asked the following question: ‘In your opinion what is the degree of importance of this criterion in the selection of a pipe candidate for renewal regardless of other criteria?’

To complete the interactive process, we need to define a clear way to assess selected criteria as well as define their relationship with the prioritization scheme (increasing breakage rate increases priority, etc.). As most (if not all) criteria are non-commensurate regarding their units, they must be mapped on a generic common scale. We propose the scale shown in Figure 5.

This experiment was not easy to perform since the instructions had to be clearly defined and in particular avoid influencing the responses of decision makers. In addition, it was very difficult to remain objective due to interference with other subjective criteria that often disturbed the respondents. We explained as much as possible that the instruction for each criterion to be considered each time was totally unique in the ranking process. The iterative process was performed three times, meaning once for each decision maker, so that decision makers could influence each other or the level or the function skews their responses. Once the responses of the decision makers were recorded, we identified the conflicting situations, that is to say the points on which the decision makers did not agree, and tried to understand the response of each one.

The ultimate importance of each criterion is that of the majority, that is to say it is similar to the response of two thirds of the respondents, i.e. those who gave the same response.

The answers of each participant having equal weight were compiled and analyzed. The final rank of criteria was as follows: $BR > HC = RT = LB = PM = CL > IC > DI$.

![Figure 5](https://iwaponline.com/ws/article-pdf/12/6/895/417082/895.pdf)
Table 1 gives information on the criteria, their characteristics and their degree of importance given by the decision makers.

One of the possible weighting profiles conforming to the final rank of criteria obtained from the interactive process with stakeholders is represented in Figure 6.

Assessment functions

After the criteria definition and ranking step, we established a transparent method of assessing each criterion according to specific set of data. We defined an assessment function per criterion, as shown in Table 2.

Criteria evaluation

The use of the assessment functions allows estimating the criteria values for each pipe considered in the analysis. In order to harmonize values and reduce the bias possibly due to the unit scale of each criterion, we use the same score scale as previously, by considering for the criterion assessed a worst value that corresponds to score ‘10’ and a best value that corresponds to score ‘0’ as shown in Table 5.

The values obtained were analyzed and submitted to the stakeholders in order to adapt the scale of scores from 0 to 10. A trade-off was obtained by defining the range of values per criterion. The following tables establish a link between observed or calculated values and the scale of scores.

Choosing an aggregation method

One of the main problems when using a multi-criteria approach is to ensure clear and unbiased aggregation and take into account the real influence of each criterion. This debate is not recent, and many works had been performed to show the advantage of using different methods. On the other hand, even if robust methods exist, the problem of integrating them in an existing Information System (IS), and how the decision maker can understand them, ensure their use and update them is not trivial.

Therefore, based on the rank of the criterion and the score values, we explore the use of simple and comprehensive aggregation methods that we call unsophisticated methods. We tested two of them: (i) the Z score ranking method, and (ii) the harmonized and normalized weighted sum. These methods had been compared with two multi-criteria methods identified in the literature as robust and widely used in several domains to tackle multi-objective problems. The implementation and updating of sophisticated methods requires specific skills and scientific knowledge.

### Table 1 | Prioritization criteria and degree of importance

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1st Decision maker</th>
<th>2nd Decision maker</th>
<th>3rd Decision maker</th>
<th>Score</th>
<th>Preference trend</th>
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<td>Increasing</td>
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<td>8</td>
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<td>3</td>
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<tr>
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<td>5</td>
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<td>Decreasing</td>
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<tr>
<td>Component of a loop or branch</td>
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<td>8</td>
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</table>

Figure 6 | The criteria weights.
to be implemented and updated, discouraging their use for practical purposes. We consider these methods as sophisticated and tested two of them: (iii) PROMOTHEE method and (iv) Electre III method.

Method based on the Z score ranking

This method (Mateu 2002) is based on the distance between options. The method aims to classify an option...
and obtain its relative position vis-à-vis the trade-off solution, the compromise option and the worst one, with a critical option for each criterion. This led us to use specific metrics. For a criterion $j$ and an option $a$, we define $z_j(a)$ as:

$$z_j(a) = \frac{g_j(a)}{g_j \text{(ideal)} - g_j \text{(worst)}}$$  \hspace{1cm} (4)

where $g_j(a)$ is the criterion evaluation of the option considered, $g_j \text{(ideal)}$ the best case value and $g_j \text{(worst)}$ the worst case value. This metric compares the value of the criterion to two extreme cases defined a posteriori by the stakeholders, the ideal pipe condition and the worst one. The option has greater priority (critical) if its distance from the ideal case increases and decreases from the worst one. In order to aggregate all the criteria values, we define the $Z(a)$ score per option $a$ as the weighting sum of all $z_j(a)$:

$$Z(a) = \sum_{j=1}^{k} w_j z_j(a)$$  \hspace{1cm} (5)

The set of pipes considered representing the options is sorted according to the $Z$ score value by increasing order, thus the pipes ranked first correspond to those most vulnerable.

**Harmonized and Normalized Weighted Sum (HNWS)**

This method is an adaptation of a classical weighted sum method. It allows improving two main shortcomings of the standard weighted sum which are: (i) the consideration of the preference trend of each criterion, (ii) the bias due to the variation of scales (hundred, thousands, etc.). When the preference trends of the criteria oppose each other (increase and decrease), it is not possible to interpret and use the value of the weighted sum obtained from non-harmonized criteria. Should they be sorted according to the high or low value of the sum? The adapted method is based on five main steps:

(a) Analyzing the preference trend, which consists in establishing the preference trend of each criterion, and definition of the dominant trend: decrease or increase.

(b) Harmonizing the preference trend of each criterion in the dominant trend. For an option $a$ assessed by function $g_j$ of criterion $j$, the harmonized value $g'_j$ is obtained by considering the inverse of the absolute value, as follows:

$$g'_j(a) = \frac{1}{g_j(a)}$$  \hspace{1cm} if $g_j(a) \neq 0$  \hspace{1cm} (6)

$$g'_j(a) = 0$$  \hspace{1cm} if not

(c) Normalizing the values in order to avoid the bias of scale in the aggregation process. Several metrics and values $M$ can be used. We consider $M = \max (g_j(a))$. Other values of $M$ can also be tested. The normalized values should be scaled according to a predefined scale: 0 to 1, 0 to 10, 0 to 100 or more. We note $S = \{1, 10, 100, 100, ..., N\}$ the scale factor. The normalized values $|g'_j(a)|$ are obtained as follows:

$$|g'_j(a)| = \frac{g'_j(a)}{M} \cdot S$$  \hspace{1cm} (7)

(d) Assessing the weighted sum $WS(a)$ of an option $a$ based on the normalized values and weight values:

$$WS(a) = \sum_{j=1}^{k} w_j |g'_j(a)|$$  \hspace{1cm} (8)

(e) Sorting the options according to the preference trend selected for the harmonization. If the trend chosen was ‘increased value’ the critical options are those with a high $WS$ value.

**Method based on the preference ranking organization method for enrichment evaluation (PROMETHEE)**

The PROMETHEE is a multi-criteria decision-making method developed by Brans & Vincke (1985) and Brans et al. (1986). It is well adapted to problems where a finite number of alternatives or options have to be ranked according to several conflicting criteria (Albadvi et al. 2007). The first step of the PROMETHEE method is the construction of the performance matrix. The basic principle of PROMETHEE is based on a pairwise comparison of alternatives along each criterion recognized. Alternatives are evaluated according to different criteria which have to be
maximized or minimized. This method requires the definition of a specific function for each criterion, the preference function which translates the difference between the evaluations obtained by two options – in our case the pipes – into a preference degree ranging from zero to one.

\[ P_j(a, b) = f_j(d_j(a, b)) \]  

(9)

where \( P_j(a, b) \) denotes the preference of option \( a \) with regard to option \( b \) on each criterion \( j \), as a function \( f_j \) of \( d_j(a, b) \).

\[ d_j(a, b) = g_j(a) - g_j(b) \]  

(10)

where \( d_j(a, b) \) denotes the difference between evaluation \( a \) and \( b \) on each criterion. In order to facilitate the selection of function \( f_j \), Brans & Vincke (1985) and Macharis et al. (2004) proposed six basic types: (i) usual criterion, (ii) U-shape criterion, (iii) V-shape criterion, (iv) level criterion, (v) V-shape with indifference criterion, and (vi) Gaussian criterion.

For each criterion, implementing PROMETHEE requires the calibration of threshold values: (i) indifference threshold \( q \), (ii) the value of a strict preference threshold, \( p \) and (iii) the value of an intermediate value \( s \) between \( p \) and \( q \) (Brans & Mareschal 1992). In each case, these parameters must have a clear significance for the decision maker.

In the current research, each pipe candidate for renewal represents an option to be ranked according to its value of the net flow or the outranking flow in the complete ranking process of PROMETHEE II. We recall that the calculation of the outranking flow is obtained via the following steps.

Calculation of the global preference index

\[ \forall a, b \in A: \pi(a, b) = \sum_{j=1}^{k} P_j(a, b)w_j \]  

(11)

where \( \Pi(a, b) \) of \( a \) over \( b \) (from 0 to 1) is defined as the weighted sum or preference function \( P_j(a, b) \) of each criterion \( j \) weighted by \( w_j \).

Calculation of the outranking flow: PROMETHEE I partial ranking

\[ \Phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \]  

(12)

\[ \Phi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \]  

(13)

where \( \Phi^+ \) and \( \Phi^- \) denote the positive and the negative outranking flow respectively for each alternative.

Calculation of the net flow

\[ \Phi(a) = \Phi^+(a) - \Phi^-(a) \]  

(14)

where \( \Phi(a) \) denotes the net outranking flow for alternative \( a \).

The results of the outranking are plotted for analysis by the GAIA to ensure global visual analysis.

Each criterion is represented by an axis, close criteria axes in the plane are similar while opposite criteria are in conflict. A specific \( \pi \) vector indicates the best direction for the compromise solution. More details about GAIA analysis are given in Maresch & De Smet (2009) and Macharis et al. (2004).

Electre III method

Electre III (Vallée & Zielniewicz 1994) is a multi-criteria analysis method which solves ranking problems. It relies on the definition of an outranking relation ‘\( S \)’ to compare two actions \( a \) and \( b \) separately. Considering a set of options \( A = \{a_1, a_2, \ldots, a_n\} \), the method classifies the actions by comparing them with peers. Each action is compared to others on the basis of the criteria considered. The evaluation of actions is performed by a real function; for each criterion we define the \( G \) set, \( G = \{g_1, g_2, \ldots, g_n\} \), containing the evaluation actions for all the criteria. The importance of the criteria in decision making is evaluated by a set of weights \( k \), \( k = \{k_1, k_2, \ldots, k_n\} \).

In this method, the preference, indifference and veto threshold are based on the evaluation of the action for each criterion. In the case of an action \( a \) assessed by \( g_i(a) \) for criterion \( j \), the indifference threshold is denoted \( q_j(g_i(a)) \), the preference threshold \( p_j(g_i(a)) \) and the veto threshold \( r_j(g_i(a)) \). The Electre III method is based on the following steps:
1. Calculation of the concordance and discordance indexes.
2. Calculation of the credibility index and definition of the relationship of fuzzy-ranking.

COMPARISON OF AGGREGATION METHODS

In this section, we compare sophisticated and unsophisticated methods used for aggregating renewal criteria with two simple and obvious mono-criterion procedures generally used by utility decision makers to sort pipes. It concerns the prioritization of pipes according to: (i) their total past failures; (ii) their age.

The objective of this second part is to provide decision makers with a simple and easy comparison calculation method that can be implemented on a standard application such as MS Excel.

The comparison is mainly based on the curves representing: (i) the number of future avoided breaks on the pipe to be replaced, (ii) the replacement cost with breaks per percentage of pipe to be replaced, and (iii) the criterion ‘C’ developed using the number of replacements. We also consider two other indicators: (iv) cost saving, and (v) the number of contiguousties. We define the ‘contiguity’ by a collection of connected pipes – at least two – that share at least one node and appear to undergo renewal at the same time. All the indicators used for the comparison are described in the following section:

- Avoided breaks: this parameter provides the sum of expected breaks $B_i$ (on a given time horizon) of pipe $i$ that will be avoided once the pipe is chosen for replacement. The higher the number of breaks, the more advantageous the aggregation method is.
- Replacement cost ($RC$): the breakage number per percentage of pipe $L$ to be replaced gives information on how many breaks will be avoided by percentage of pipe to be replaced. Since aggregation methods do not necessarily give the same ranking, the expected breaks $\sum B_i$ and the replaced pipe $\sum l_i$ are different. Hence, each avoided break per replaced pipe has a cost. The lower the replacement cost, the better the ranking method.
- The C criterion: another aspect that should be emphasized here is that a pipe $i$ that can be selected as prior could not break in the future so that will be replaced without having in return a benefit on the basis of avoiding breakages. This can be expressed by the following indicator:

$$ C = \frac{\sum_i B_i}{\sum_i l_i} $$

where $B_i$: Number of avoided breaks; $l_i$: Length to be replaced.
- Cost saving (CS): this indicator measures the potential saving offered by a renewal policy obtained with a given aggregation method. The cost saving (CS) of a renewal policy (RP) is equal to the difference between the cost of the most expensive renewal policy (Max ($RC$)) and the cost of that considered (RC). It is calculated by the following equation:

$$ CS(RP) = \text{Max}(RC) - RC(RP) $$

- The number of contiguousties (NC): the number of contiguousties indicates the potential worksites that enable economies of scale due to the adjacency of the pipes to be renewed. This indicator can be calculated for each renewal policy, by identifying the grouping of connected pipes among those selected for renewal. The number of contiguousties must be completed by the number of pipes in the contiguousties identified. The greater the number of pipes in the contiguousties, the higher the economies of scale will be.

RESULTS AND DISCUSSIONS

Case study

The comparison was applied to the same case study used for the clustering approach. It is a part of a real municipal network consisting of 147 cast iron pipes with a diameter from 150 to 250 mm installed from 1951 to 1960 and with an available breakage history for the years 1962–2003. As mentioned previously, we partitioned the time horizon from 1962 to 2003 into two periods: Analysis [1962, 1995] and validation [1996, 2003] on the basis of which the expected
number of breaks was established. The method was implemented in two steps: (i) the criteria for prioritization were assessed according to a pre-established list, and (ii) the different criteria were applied as described above. The aim was to compare the ranking obtained in order to see how significant the difference between the sophisticated and simple method is, and how this result can be used and recommended for practical application by decision makers to prioritize pipes to be replaced.

Results

Criterion based on the variation of the avoided breaks with linear to replace

The figure above allows the comparison between the ranking methods and a reference scheme consisting of an obvious mono-criterion prioritization scheme based on the number of observed breaks and pipe age.

The curves of the variation of the number of the avoided or predicted breaks versus the pipe to be renewed (up to 10% of the whole network) express the performance of these methodologies and indicate the advantage of each scheme in the prioritization. We assume that the ranking obtained by each method can be considered as a renewal scheduling between [1996, 2003].

Renewal concerns the pipes at the top of the list, but is it possible to know when to the selection should be stopped? Two ways can be applied. The first consists of an average effort of renewal per year, where not more than 1.5% of the total length is considered in our case. Therefore, over the time interval considered, the total length that can be renewed does not exceed 10% of the network. The second is to establish either an annual budget constraint or a constraint on the planning horizon, so the renewal will only concern the pipes at the top of the list, ensuring that the budget constraint is not violated.

The three first techniques, in particular, allow avoiding more breaks with the same percentage of network replaced (Figure 7). Simultaneously, the same methods give a lower replacement cost than other ones (Figure 8). Although the PROMETHEE method is adapted to multi-criteria decision problems, it appears to predict a much smaller number of breaks and a higher replacement cost. As we continue to renew pipes that will not break in the future, the expected number of breaks remains constant ($\Delta B = 0$), with an increase in the amount of pipe to be replaced. Consequently, the ‘C’ criterion is equal to zero and the total ‘C’ remains constant.

This can be expressed by the curve representing the variation of this parameter versus the number of replacements by considering that we will make 10 replacements per year (Figure 9).

In fact, for each aggregation methodology, a horizontal curve trend leads us to presume that we will replace pipes that will not break in the future. On the other hand, the
higher the value of the ‘C’ parameter, the better the method should be. Table 4 represents the ‘C’ value for each methodology.

According to Figure 9, the value of ‘C’ for the NHWS is 16.364, for the Z score it is 12.390 and for ELECTRE III it is 13.012.

| Table 4 | (a) The C parameter value. (b) Parameter C (bis) |
|------------------|------------------|------------------|------------------|
| Replacements     | NHWS             | Z score weighting | PROMETHEE         | ELECTRE III      |
|                  | Total avoided breaks | Total length (%) | Total avoided breaks | Total length (%) | Total avoided breaks | Total length (%) | C = ΔB/ΔL |
|                  |                   |                   |                   |                   |                   |                   |           |
| 1                | 1                 | 0.521             | 2.189             | 1                 | 1.657             | 2.150             |
| 2                | 2                 | 0.978             | 2.189             | 3                 | 2.587             | 2.150             |
| 3                | 2                 | 1.553             | 5.054             | 5                 | 4.746             | 6.757             |
| 4                | 2                 | 1.947             | 6.903             | 7                 | 5.309             | 8.862             |
| 5                | 3                 | 2.833             | 9.327             | 8                 | 5.784             | 10.045            |
| 6                | 4                 | 3.659             | 10.587            | 9                 | 6.629             | 10.045            |
| 7                | 6                 | 5.245             | 15.374            | 9                 | 7.550             | 10.045            |
| 8                | 8                 | 5.615             | 16.364            | 9                 | 9.467             | 12.390            |

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<tr>
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The methods tested give good results although PROMETHEE and the ranking by pipe age approach do not appear to be efficient. The efficiency of these aggregation and ranking processes can be better understood by examining the following table which shows the evolution of the \( C \) parameter \( C \) according to the number of replacements.

Analysis of the results given in the table above confirms that the use of a mono-criteria scheme for prioritizing pipes for renewal is inefficient. It appears that the reference score was ranked at the bottom according to the low value of the \( C \) parameter, which is equal to 11 (ranking by pipe age only). Hence the prioritization of water pipes for replacement must be a multi-objective optimization problem in which the optimal solution (ranking) is a result of considering several factors. It appears that multi-criteria methods dominate others and we note that simple methods like those used in the present case study can provide good results while also being easy to handle.

Cost saving

We perform a comparison with the methodology giving the highest replacement cost, by considering 10 replacements a year, i.e. PROMETHEE (\( RC = 5.09 \times 10^5 \) €). The cost saving was calculated for each technique as represented in the Figure 10.

The NHWS technique leads to the highest cost saving (\( 2 \times 10^5 \) €); then Electre III and ranking by pipe age respectively (\( 1.56 \times 10^5 \) €) and (\( 0.8 \times 10^5 \) €). The Z score method does not provide a ranking which saves on the pipe length and hence the replacement cost.

The number of contiguities

We consider the ‘the number of contiguities’ \( NC \) and the number of pipes belonging to contiguities to assess for possible savings (Table 5). Savings correspond to economies of scale due to the spatial proximity of pipes and mobilization cost due to grouping pipe replacements. We note that Z-score and Electre III are the best as they give three and two contiguities with seven and eight pipes respectively. However NHWS and PROMETHEE do not offer the same concentration of pipes in contiguities, as they group only four pipes in two contiguities.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>The number of contiguities for each aggregating method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technique</td>
<td># of contiguities (NC)</td>
</tr>
<tr>
<td>Electre III</td>
<td>2</td>
</tr>
<tr>
<td>Z-score</td>
<td>3</td>
</tr>
<tr>
<td>PROMETHEE</td>
<td>2</td>
</tr>
<tr>
<td>NHWS</td>
<td>2</td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSIONS

The rehabilitation of drinking water distribution networks is a crucial aspect of sustainable urban development. The mismanagement of water systems can engender not only the disruption of supply but also the degradation of water quality and increased operating and capital expenditures.

Decision making concerning the ranking of prioritized pipe candidates for renewal depends on the number of criteria used and the weight assigned to each criterion, making the aggregation task more complicated. Although the hydraulic operation of the network can represent an important renewal criterion, we explore other criteria for pipe prioritization. The present paper does not deal with the hydraulic performance of the network. Improving the present study by adding hydraulic aspects can be done easily by considering a comparison function that assesses the impact of renewals on the operation of the network. This can be achieved by coupling the current approach with a hydraulic simulator such as Epanet 2 (Rossman 2001). This has already been done in previous contributions (Nafi & Kleiner 2010; Kleiner & Nafi 2011).

This paper focused on two main analyses using data on water pipe failures to complete the study started by
Nafi & Kleiner (2010). Geostatistical analyses conducted with a scanning algorithm were addressed to discover not only the distribution of water pipe failures in space but also to indicate various spatial and temporal trends.

The breakage rate is calculated for each cluster at the first level of prioritization using the spatial, temporal and scanning process based on the nearest neighbour hierarchical clustering. This study indicates that a significant number of failures appear in geographic clusters. Notably, it shows point distribution with strong concentration of failures in some areas and low in others where it would be interesting to know their causes and typology. The approach proposed allows defining a new and original criterion for pipe prioritization by combining structural deterioration and its geographical spread on the whole network.

The second part of this research focuses on modelling the decision making process for pipe selection for renewal and the implementation of a non-sophisticated and transparent methodology for prioritizing pipe candidates for renewal. In practice, one of the obstacles of implementing is understanding the scientific background of the methods used and the complexity of implementing them. Thus testing sophisticated and non-sophisticated multi-criteria methods using a similar set of exhaustive criteria with the same data allowed us to show the disparity between methods. Although the results obtained cannot be generalized, it appears that the performance and results of non-sophisticated methods are acceptable and their contribution to decision making remains significant.

The current study shows the main steps involved in modelling the decision process and its implementation for pipe prioritization. It offers a new and original criterion for use in the multi-criteria decision model.

The use of non-sophisticated multi-criteria approaches like NHWS is very interesting because it required less effort by the water utility manager to understand it, and it can be easily implemented as a simple tool without the need for specific software. More applications and simulations are required to check the robustness and reliability of non-sophisticated methods to sort pipes for renewal. The result obtained is encouraging and offers a trade-off between ranking quality and the difficulty of implementation.

REFERENCES


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Xu, L. & Yang, J. B. 2001 Introduction to multi-criteria decision making and the evidential reasoning approach. Working Paper Series No. 0106, Manchester School of Management, University of Manchester Institute of Technology.

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