Barcelona, 02nd July 2019

WATER NETWORK RENEWAL STRATEGY: A CASE STUDY OF AIGÜES DE BARCELONA

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Number of words: 5675 words

Number of figures and tables: 4 figures and 5 tables

Abstract

This paper presents a consistent and transparent methodology for the prioritization of the pipeline sections to be renewed among the whole Aigües de Barcelona urban water network. The Prioritization Index for Pipeline Renewal (PIPR) serves to evaluate the risk impact, in terms of sustainability, of each section of pipeline in the water distribution network, for the purpose of its eventual renewal. Thus, the sections with higher prioritization indices should be proposed as the first to be renewed. This methodology represents a meaningful step towards a sustainable and reliable management of water assets. Different economic, environmental and social aspects were considered through a probabilistic multicriteria decision framework and analytic hierarchy process (AHP) was used to conciliate all stakeholder interests. The case study conducted for Aigües de Barcelona, a Spanish utility company dedicated to services, distribution and treatment of water, is presented in this article, showing how this method performs accurate, consistent, and repeatable evaluations.

ICE KEYWORDS: Sustainability – Environment – Water supply

LIST OF NOTATIONS:

- B_i: factor that allows the function to be maintained within the range 0-1
- c: proportionality constant
- C_d: discharge coefficient
- C_i: approximates the x-axis of the inflection point
- CI: Consistency Index
- CR: Consistency Ratio
- D: pipe diameter

d_o: original hole diameter

E: elasticity modulus

g: gravity acceleration

H: medium pressure of the pipeline

IV_i: value function

Ki: approximates the ordinate of the inflection point

n: size of the pairwise comparison matrix

P_i: form factor that defines whether the curve is concave, convex, linear or an "S" shape

P_x: each pipeline section

Q_f: flow rate through a round hold in a pipe

RI: Random Index

t: pipe wall thickness

w_{C_y}: criteria weights

w_{I_j}: indicators weights

w_{R_t}: requirement weights

X: quantification of the indicator under evaluation (different or otherwise, for each intervention)

X_{min_i}: minimum x-axis of the space within which the interventions take place for the indicator under evaluation

λ_{max}: largest eigenvalue

ρ: Fluid density

AB: Company name Aigües de Barcelona

ADT: Average Daily Traffic

AHP: Analytic Hierarchy Process

APTV: Average Pedestrian Traffic Volume

CBA: Cost-Benefit Analysis

CEA: Cost-Effectiveness Analysis

DMA:	District Metering Area
FA:	Financial Analysis
IRR:	Internal Rate of Return
IRRM:	Internal Rate of Return Mix
MAUT:	Multi-Attribute Utility Theory
MCA:	Multi-Criteria Analysis
MCDM:	Multi-criteria Decision Making
MIVES:	Integrated Value Model for Sustainable Assessment
PIPR:	Prioritization Index for Pipeline Renewal
WHO:	World Health Organization

1- INTRODUCTION

The private sector is increasingly challenged to achieve sustainable and reliable development, as the gap between available funding and investment needs widens (Pujadas et al. 2017).

This is the case of Aigües de Barcelona (AB), a Spanish utility company dedicated to services, distribution and treatment of water which, after a process of internal reflection, has recently published a Strategy Action Plan. The initiative reflects the wish of the company to strengthen its position as a global reference in the management of the integral water cycle, while contributing to the sustainable development of the environment.

As part of this Strategy Action Plan, the company sought to implant a sustainable risk-management methodology for the prioritization of the renewal of the water pipeline network. Limited resources mean that the selection of all the proposed renewal investments (in this case, renewal of the distribution pipeline network) is quite obviously impossible. Consequently, managing risk effectively requires making sensible decisions under uncertainty (which sections should be renewed) subject to the constraints of knowledge and resources. Hence, identifying the most sustainable pipeline renewal investments becomes a critical activity. Utility companies such as AB therefore aim to develop methodologies, in order to assure rational and systematic decision-making based on economic, social, and environmental grounds.

Decision-making in the private sector is usually based on Cost-Effectiveness Analysis (CEA), where the costs of different homogeneous alternatives (same asset type) are compared. The alternative monetary-based decision-making techniques are: Financial Analysis (FA) and Cost-Benefit Analysis (CBA).

It should be taken into account that monetary-based techniques consider social and environmental aspects that are identified as relevant impacts and are often (but not always) valued with various limitations on both their methods and their accuracy. However, they might in some circumstances be sufficient to change the resulting order (Dodgson et al. 2009). In these circumstances, where accuracy is important, Multi-Criteria Analysis (MCA) can be very useful.

A number of multi-criteria methodologies have been developed over time, with the aim of providing a systematic framework in which to consider the multidimensional nature of real-world problems. MCA implies that each problem is broken down into its constituent parts, in order to understand the evaluation process (Cafiso et al. 2001). A detailed and comprehensive review of the MCA methodologies for ranking homogeneous alternatives developed over the last twenty years can be found in Kabirb, Sadiq and Tesfamariam (2013).

Hajkowicz and Collins (2007) found that MCA is used for water policy evaluation, strategic planning, and infrastructure selection where a broad spectrum of MCA methods are currently in use. From their comparative studies of MCA methods used in water management applications, Gershon and Duckstein 1983, Ozelkan and Duckstein 1996, Eder *et al*. 1997 all arrived at a general finding that no single MCA technique is inherently better than another.

Over the past few years, MCA methods are becoming an important tool for the incorporation of non-monetary aspects in decision making. Sustainability is a key issue in water management, to ensure the efficient management of a limited and increasingly valuable resource. The sustainability concept has its origin in the Brundtland Report of 1987. The Brundtland definition of sustainable development was framed as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". True sustainability can only be achieved through economic, environmental, and social aspects of well-being that are simultaneously interlinked.

The main objective of this paper is to describe the MIVES methodology – Integrated Value Model for Sustainable Assessment – that has been developed to assist decision-makers in finding strategies for the prioritization and selection of the pipeline sections which should be renewed every year throughout the whole water distribution network. To do this, a specific decision framework is defined as the contribution of the different stakeholders. The methodology solves the asset managers' challenge of prioritizing the assets with a reduced budge without compromise the reliability of the network. MIVES is a Multi-Criteria methodology originally developed for the assessment of sustainability in construction (San Jose and Cuadrado 2010; Aguado et al. 2012; Pons et al. 2012; Pujadas et al. 2018) and the prioritization of homogenous (Aguado et al. 2017; de la Fuente et al. 2017) and heterogeneous (Pardo-Bosch and Aguado, 2016; Pujadas et al. 2017) alternatives. Its main contribution is that it combines Multi-criteria Decision Making (MCDM) and Multi-Attribute Utility Theory (MAUT), incorporating the value function concept (Alarcón et al. 2011) and assigning weights using the Analytic Hierarchy Process (AHP) (Saaty 1980). This methodology provides rational sustainability and resilience-based reasoning for the decision criteria.

The company, AB, expresses a strong commitment to sustainable development and aligns all of its strategic decisions in that direction. It therefore needed to introduce the sustainable development strategy into its decision-making process; an objective that in practice required an internal review of the attributes and impacts of a sustainable pipeline network. The MIVES methodology was selected as the most appropriate MCA method, because it responds to three challenging end-purposes. The first is the unique index value that the MIVES framework defines; in this case, the prioritization index for pipeline renewal. The second is the way that unique index is established through a series of different units and quantitative and qualitative values that are combined in MIVES using different indicators. The methodology includes Multi-Attribute Utility Theory (MAUT) that standardizes the differences between (e.g. social and technical) indicators. The final end-purpose was to meet stakeholder expectations and to encourage them to participate in the decision-making process. Stakeholder interests are parametrized in the model to show the reasoning behind each decision process.

2.- MIVES MULTI-CRITERIA ANALYSIS

All classification and sorting techniques require a realistic framework through which to consider the multidimensional nature of the real-world problem. Consequently, the methodology in use should include all three (ecological, financial, and social (United Nations 2005)) sustainability dimensions in the prioritization processes. All of those dimensions can be considered in the MIVES approach.

The problem in MIVES is structured within a multi-criteria analysis framework in which different investment projects may be prioritized according to pre-established criteria, in order to satisfy a pre-defined sustainable objective. A 3-level MIVES framework is developed here, in order to set the pre-established criteria. The three levels range from the most general to the most specific: requirements, criteria, and indicators.

The weights are assigned by decision-makers using the Analytic Hierarchy Process (AHP), to reflect the relative importance of each requirement, criterion and indicator for the purposes of the prioritization. The AHP, originally devised by Saaty (1980), is a linear additive model that converts subjective assessments of relative importance into a set of overall scores or weights that are respectively based on pairwise comparisons between criteria and between options. Thus, for example, in assessing weights, the decision-maker is asked a series of questions, each of which inquires into how important one particular criterion is in relation to another for the decision that is addressed. Further details on the AHP process of creating the comparison matrix, checking the consistency of the assessments and the calculation of the final weights of the variables, may be found in Appendix A.

From the three levels of the framework analysis, indicators are the only concepts that are evaluated during the prioritization process. Such an evaluation can be done using qualitative or quantitative variables, and different units and scales depending on the indicator. The value function (Alarcón et al. 2011) is a single mathematical function that converts the qualitative and quantitative variables of the indicators, with their different units and scales, into a single scale from 0 to 1. These respective values represent the minimum and the maximum degree of satisfaction of the decision maker. In MIVES this value function (eq. 1, for growing functions) depends on 5 parameters, the variations of which generate four function curves: concave, convex, lineal, or S-shaped, according to the weighting attached to the decisions that are taken. A complete description of the definition of the function values may be found in Appendix B.

$$IV_i = B_i * \left[1 - e^{-Ki*\left(\frac{|X - X_{min_i}|}{C_i}\right)^{P_i}} \right] \quad (1)$$

Previous MIVES frameworks were always developed for the evaluation and/or prioritization of homogeneous alternatives. This fact allows the direct application of the MIVES framework to all the alternatives under study, and its latter evaluation and ranking.

3.- FRAMEWORK FOR THE PRIORITIZATION INDEX FOR PIPELINE RENEWAL

3.1- System boundaries

The framework presented in this paper was designed for the Network Renewal Area of Aigües de Barcelona (AB), responsible for developing the renewal management strategy for the renewal of the water pipeline network of the company. In the past, multiple sections of pipeline were chosen every year on the basis of a monetary-based methodology that only took account of the Internal Rate of Return (IRR). Here a broader decision framework is defined in which apart from the IRR, other resilient and sustainable risk-criteria are considered.

The water pipeline network system is composed of 4678 km of primary and secondary pipelines which supplies 23 cities with 2892313 inhabitants. The secondary pipeline system, from now on called water distribution network, is composed of 4134 km (around 120000 section pipelines) and represents the largest part of the system. The secondary system represents de 88,3% of the total network, the work presented in this paper is focused in the distribution network (secondary system).

The definition of a suitable decision framework for a proper assessment is of great importance. To that end, the most significant and discriminatory variables (see table 1) were chosen in consultation with experts from the network renewal area management team.

3.2- Decision framework

The Prioritization Index for Pipeline Renewal (PIPR) serves to evaluate the risk impact, in terms of sustainability, of each section of pipeline in the water distribution network, for the purpose of its eventual renewal. Thus, the sections with higher prioritization indices should be prioritized and consequently renewed.

Risk impact evaluation can be either qualitative, using a descriptive approach, or quantitative, using numeric estimations. In the latter, risk is defined as a product of the probability of occurrence of a particular event and the consequences of that event actually occurring. The assessment of the probability of failure occurrence and its consequences are therefore another key step in the risk assessment method.

The probability of pipeline failure at any particular point is essential to risk management for pipeline operators. Categorical causes of pipe failure have been identified by a number of authors (Morris 1967; Shamir and Howard 1979; Kelly and O'Day 1982; Goulter and Kazemi 1988; Petit-Boix et al. 2016). They reported the variety of factors that can alter this probability of failure: the material properties, age over the expected lifetime, pipeline pressure, and the length and the diameter of the pipeline section. In this paper the probability of failure was determined with a reliability analysis method.

The consequences of no renewal are assessed here with regard to sustainability. The concept of sustainability, as applied to a water distribution network, is the ability of the pipeline network to continue to function with levels of service quality that the community desires, without restricting the options available to present and future generations and without causing adverse impacts both inside and outside the urban perimeter and the network.

Thus, all aspects of the economic, environmental, and social consequences of no renewal of each pipeline section will be considered here. The coherence, representativeness, and objectivity of the risk-criteria and risk-indicators under consideration in each requirement will guarantee the goodness and the credibility of its results.

With this purpose in mind, the most significant discriminatory indicators were exclusively considered. Table 1 shows the detailed list of the decision framework, constituted by the 3 aforementioned requirements, 5 criteria, and 8 indicators. In Table 1, an example of weights assigned to each requirement is presented in brackets (corresponding to case – DS_2 presented later on in section 4), as well as, the 2017 stakeholders contribution average of weights assigned to each criterion and indicator. Each indicator aims to measure the sustainability risk impact (the product of the probability of occurrence and the consequences) of renewal. It is also important to mention the participatory AB design process, to which engaged AB stakeholders – the clients, the city councils, the regulatory administration and the company committee – had the opportunity to contribute to setting the final weights.

The decision framework as well as the methodology used to evaluate the risk impact of the indicators was introduced to the stakeholders to prepare them to the participatory process. Owing to the variety of stakeholders the collaborative process to collect the weights was adapted to each collective. In this sense, two questions were added to the annual survey of the company to collect the clients relative importance's. On the other hand, the city councils, the regulatory administration and the company committee were called separately to participate in specific workshops through which the weights were collected. The company relay on external experts of the Polytechnic University of Catalunya lead the process to ensure transparent and consistent decisions.

Table 1. Decision framework for the Prioritization Index for Pipeline Renewal

REQUIREMENTS	CRITERIA	INDICATORS
R1. Economic ($\mathbf{w}_{R1}$=33.3%)	C1. Internal Rate of Return Mix or IRRM with Criticality (100%)	I1. Internal Rate of Return Mix or IRRM with Criticality (100%)
R2. Social ($\mathbf{w}_{R2}$=33.4%)	C2. Service Improvement (53%)	I2. Continuity Service Improvement (68%)
		I3. Water organoleptic perception improvement (32%)
	C3. Surrounding Impacts (47%)	I4. Mobility disruptions (100%)
R3. Environmental ($\mathbf{w}_{R3}$=33.3%)	C4. Loss of water (60%)	I5. Water loss [m3] (25%)
		I6. Water loss per lineal meter [m3/ml] (75%)
	C5. Loss of energy (40%)	I7. Energy loss [kWh] (25%)
		I8. Energy loss per lineal meter [kWh/ml] (75%)

Value Functions

A value function is proposed for each indicator, so that each assessment is transformed into a number from 0 to 1, thereby defining equivalences between the different units of the indicators. The decision-making satisfaction criterion of each indicator in the present study can be satisfactorily represented by either decreasing (D) or increasing (I) functions: linear (Lr), concave (Ce), convex (Cx), or S-shaped (S). Accordingly, table 2 shows the data and the form of each value function (A complete description of the parameters involved in the definition of the value function can be found in Appendix B).

Table 2. Parameters and coefficients for each indicator value function

INDICATORS	X	X_{min}	X_{max}	P_i	C_i	K_i	B_i	Shape
I1. Internal Rate of Return or IRR with criticality	IRRC	0.0	0.6	2.25	0.04	0.065	1.000000	I-S
I2. Continuity Service Improvement	SCI	0.0	4.7	6.0	3.0	0.6	1.000140	I-S
I3. Water Organoleptic Perception Improvement	WOPI	0.0	6.0	5.0	1.7	0.3	1.000000	I-S
I4. Mobility Disruptions	MDi	0.0	8.0	0.5	0.2	1.0	1.001794	I-Cx
I5. Water loss [m3]	WL	0.0	4900	2.00	500	2.15	1.000000	I-S
I6. Water loss per lineal meter [m3/ml]	WLm	0.0	19	2.00	3.15	1.25	1.000000	I-S
I7. Energy loss [kWh]	EL	188.5	1590	2.00	250	2.25	1.000000	I-S
I8. Energy loss per lineal meter [kWh/ml]	ELm	1.47	6.50	1.00	2.50	2.00	1.000000	I-S

It is worth highlighting that the values proposed in Table 2 respond to the degree of satisfaction and the criteria of Aigües de Barcelona technicians in particular (2017), and may vary according to the experience of each decision-makers which are in charge of selecting the values.

Economic Requirement

The Economic Requirement is calculated using the Internal Rate of Return Mix (IRRM), which is obtained with the IRR and then up-dated by taking account of the density of the critical connections.

A comparison of two hypothetical scenarios of the same section of pipeline is presented: renewal and no renewal. The difference between the cost, the asset value, and tax savings are calculated over a 50-year lifespan. Finally, the IRR is calculated from the difference between the cash flows of the renewal and the no renewal scenario.

Apart from the classical financial benefit-cost analysis, which covers the profitability aspect of the project at the enterprise level, technical data are also used to define the economic model. Knowing that the condition of the pipelines may be good, the connections might have different failure probabilities, because of the service life and service pressure. Were the condition of the pipeline connections not considered, then a high repair cost associated with connection failures would be overlooked.

In the economic model used in this paper, pipeline sections with critical connections are identified. The critical connections fulfil pressure and age conditions. These weaker connections therefore increase the value of their IRR and the IRRM. Further research is expected, in order to improve the IRRM, including a proper estimation in the IRR model of the connection repair costs, in case critical connections have to be renewed.

Social Requirement

Service Improvements and the Surrounding Impacts compose the Social Requirement. The Service Improvement is based on the Continuity Service Improvement and the Water Organoleptic Perception Improvement. On the other hand, the Surrounding Impacts are due to Mobility Disruptions.

The Water Organoleptic Perception (WOP) Improvement is measured in terms of materials that can disturb the organoleptic perception. Grey cast iron is the only material in the entire network that has this effect. It is considered by the World Health Organization (WHO) as an indicative parameter, so the values are recorded during the complete analysis and the parameter was selected as a possible indicator of organoleptic perception. Despite the fact that the iron parameter as an indicative parameter has no upper limit value, a recommended maximum value of 600 µg/L is cited by the WHO. Much lower values that the recommended upper limit were recorded, so a value of 100 µg/L was established as the limit value in this study. The statistical information was determined on the basis of that limit and with the information on customer complaints of changes to the organoleptic perception and the changes recorded in representative iron values. Using that statistical information, an estimation of grey cast-iron pipe aging and its concentration in each District Metering Area (DMA) was determined. Two steps were followed for attaching a value to each pipeline section: first, a base value was assigned according to the previously determined concentration within each DMA; subsequently, additional values were assigned to the relative positions of the pipeline sections within the DMA. Additional values were also assigned to the pipeline sections entering the DMA and the dead-end pipeline sections of the network, due to their higher impact on the remainder of the system. In addition, those pipeline sections in the same area as one of the pipelines with higher values, due to their entering or ending position, were assigned this additionally higher value. The relative position inside the DMA is not straightforward to determine, due to the available information on energy loss.

The Continuity Service Improvement is composed of the maximum between the risk associated with potential incidents and historical incidents. The risk associated with a potential incident is the estimation of its probability and the quantification of the damage that it would cause. Historical incidents are used to quantify previous historical damage and the estimated probability of recurrent incidents. This criterion depends on an enclosed network, defined by the number of valves that have to be shut to isolate a sub-system of pipeline. The risk associated with potential incidents takes into account the number of people, the critical customers, and the large-scale consumers who would be affected by a possible incident, before isolating a damaged section of pipeline for repair (implying that all the above-mentioned customers are supplied by the same pipeline). The risk associated with historical incidents is obtained using the five-year records of customer complaints. Renewal was needed whenever the reasons for the customer complaints were directly linked to the connection rather than to the pipeline.

For the avoidance of Mobility Disruption, due to unexpected incidents, information from the local councils was used to define strategic zones with the highest population densities and transit zones in the city; for example, high-density commercial zones, central services such as key healthcare facilities and large inter-modal hubs. The mobility levels of pedestrian and motorized traffic were also considered. These estimates were possible with the data from each council available in their Urban Mobility Plans. In fact, one aim of the model was to cross-validate the network pipeline vector information with the mobility vector information, so that the geographic network of pipelines could be adapted to mobility patterns in the event of incidents. Ideally, the vector information on Average Daily Traffic (ADT) and Average Pedestrian Traffic Volume (APTV) would be used, but if unavailable, other information such as high-density pedestrian areas and hierarchy transportation could be considered. The main goal is to guarantee proper pipeline network conditions, thereby minimizing the risk of unmanageable incidents in areas and streets defined as critical by the city council.

Environmental Requirement

The criteria used to define the Environmental Requirement are Water and Energy loss. The level of water loss is important to estimate the energy loss; in the event of a leakage, the higher the altimetric level, the greater the energy that is lost raising the water to the leakage point.

<u>Water loss</u> can be due to latent leak and other leaks. Latent leakage of water is directly associated with pressure in the pipeline that causes stress to the pipeline connections and walls. Pressure is therefore crucial to pipeline failure and leakage that affects pipes that are beyond their service life or made with low strength materials.

An ideal pipeline network with no seniority is used to estimate the flow rate. The flow rate is modified depending on the pipeline condition and the DMA, which is given by the energy efficiency department of the company. The flow rate through a round hole in a pipe was calculated with the following theoretical work (eq. 2) proposed by the Water Research Group at the University of Johannesburg (Greyvenstein B. *et al*, 2007):

$$Q_f = C_d \frac{\pi d_o^2}{4} \sqrt{2g} \left(H^{0.5} + \frac{2c\rho g D}{3tE} H^{\frac{3}{2}} + \frac{c^2 \rho^2 g^2 D^2}{9t^2 E^2} H^{\frac{5}{2}} \right) \qquad (2)$$

The pressure in the pipeline section is conditioned by whether it has a connection. Besides the connections, the status of the connection (value control or otherwise) is also necessary to estimate the minimum and maximum pressure. The pressure values depend on whether the pipeline section is controlled by district metering area or whether it is directly connected to a transportation pipeline, the piezometric level of the corresponding DMA, the daily evolution of the water demand, the location of the section of pipeline in relation to the entrance of the DMA, the existence of pressure regulation valves in the entrance, and the altimetric level of the pipeline section.

The efficiency control department of AB is in charge of providing a correlation table with the DMA and energy consumption levels. Using the estimated total leakage of water associated with each pipeline section and knowing the corresponding DMA of each pipeline section, the total Energy losses could be calculated as well as the loss of energy per unit length, provided that the length of each pipeline section is known.

Prioritization Index for Pipeline Renewal (PIPR)

The final result of the PIPR for each pipeline section is calculated according to equation 3 as the weighted sum of each indicator, IVj(Pi,x); see eq. 3. As previously mentioned in section 2, the relative weights of each indicator(w_{I_j}), criterion (w_{C_y}) and requirement (w_{R_t}) were calculated by means of the Analytic Hierarchy Process (AHP), and the indicator IVj(Pi,x) with function values (see Appendix A and B, respectively).

$$\mathrm{PIPR}\ (\mathrm{P}_x) = 100 \cdot \sum \mathrm{w}_{\mathrm{R_t}} \cdot \mathrm{w}_{\mathrm{C_y}} \cdot \mathrm{w}_{\mathrm{I_j}} \cdot \mathrm{IV_j}(\mathrm{P}_x) \qquad (3)$$

The PIPR values ranging between 0 (low priority) and 100 (high priority), prioritize all the pipeline sections under evaluation. A qualitative assessment may be assigned to each project according to the five PIPR categories presented in table 3 (Pardo-Bosch, F. and Aguado, A., 2015). The maximum and the minimum contributions to sustainability are represented by levels A and E, respectively. According to Pardo-Bosch, F. and Aguado, A. (2015), investment projects will hardly ever score over 80, due to the highly demanding requirements of MCA. Following the same logic, projects with an E level score are in all likelihood directly rejected beforehand, because of their very low contribution to sustainable development. Therefore, the projects will generally be classified at the A, B, C, and D levels.

Table 3. Levels of PIPR, ICE (2010) and ASCE (2013)

Level A	Level B	Level C	Level D	Level E
$100 \leq PIPR < 80$	$80 \leq PIPR < 60$	$60 \leq PIPR < 40$	$40 \leq PIPR < 20$	$20 \leq PIPR < 0$

4.- SENSITIVITY ANALYSIS

The feasibility, robustness, and coherence of the PIPR - MIVES multi-criteria approach are assessed in this section.

The model includes a budget that is five-times higher than in previous years, so that the management team of the annual pipeline renewal plan can consider the full array of pipelines available on the market. Finally, the line manager also prepares a list of water distribution pipelines for renewal in the network in the following year, so that all the sustainability information is fed into the model for each section of pipeline, contributing a reserve of corporate knowledge for the city development plans and future urban planning.

The results with all the weights for each requirement give a detailed picture of the maximization of the indicators of each requirement. The results also show three different weight distributions corresponding to the three branches (economic, social and environmental) of Sustainable Development. Table 4 analyzes the weights under consideration (DS_ECO, DS_SOC, DS_ENV, DS_1, DS_2 and DS_3) and figures 1, 2, 3 and 4 display the results of the principal indicators for each case study, considering the exceptionally higher budget. The method which has been used so far to prioritize is equal to consider only the economic requirement (consideration DS_ECO).

Table 4. Requirement weight [%] distribution of each case study

Consideration/Requirements	Economic (w_{R1})	Social (w_{R2})	Environmental (w_{R3})
DS_ECO	100	0	0
DS_SOC	0	100	0

DS_ENV	0	0	100
DS_1	50	30	20
DS_2	33.3	33.4	33.3
DS_3	40	40	20

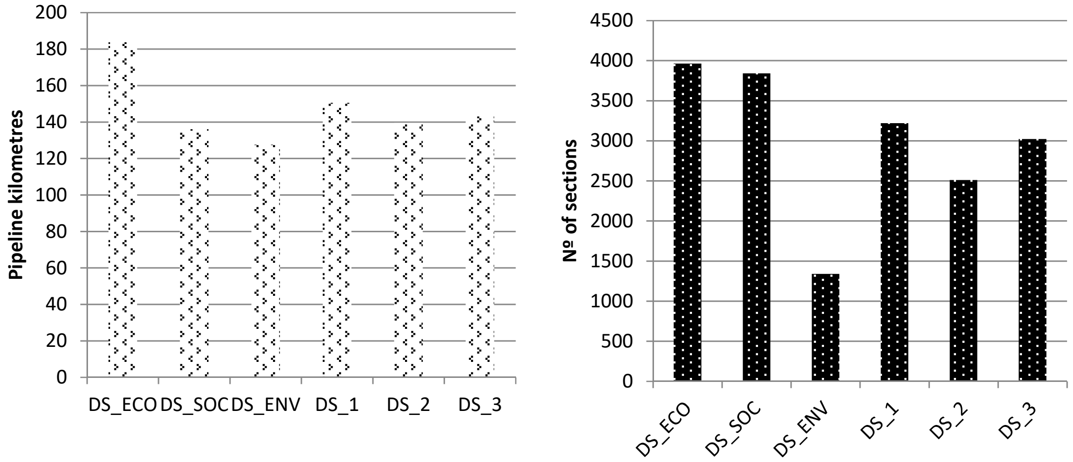

Fig. 1. Pipeline kilometres and number of sections selected for renewal

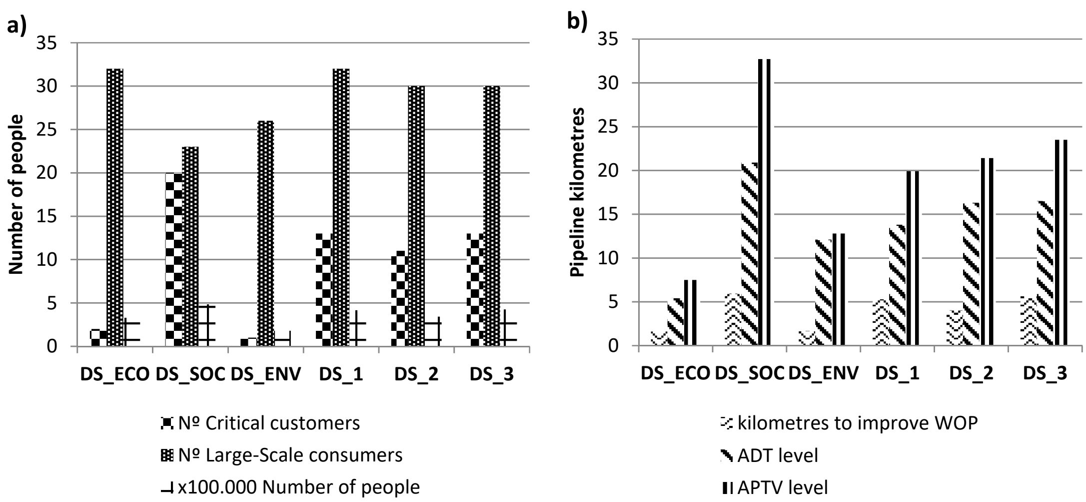

Fig. 2. Social requirement indicators: a) number of people and b) pipeline kilometres

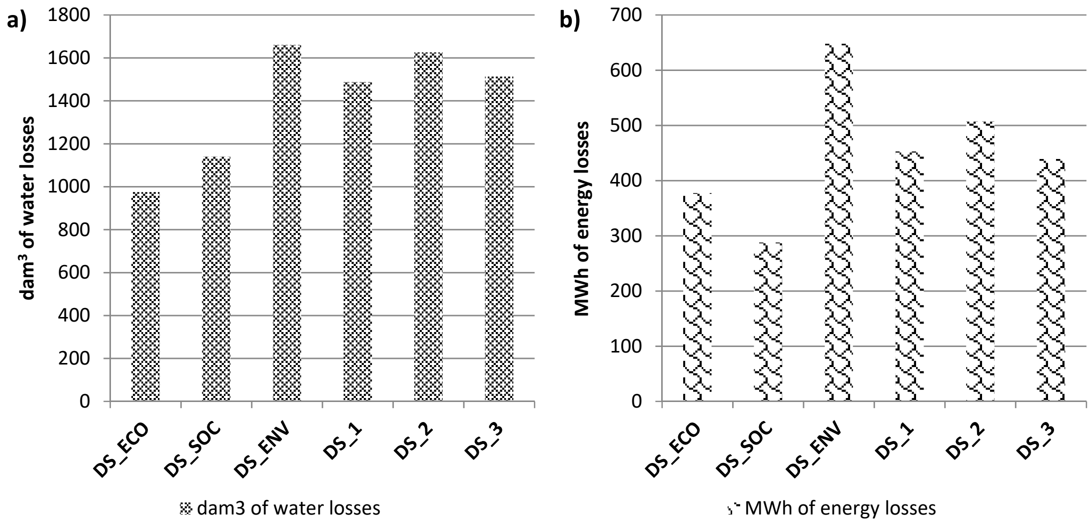

Fig. 3. Environmental requirement indicators: a) dam3 of water losses and b) MWh of energy losses

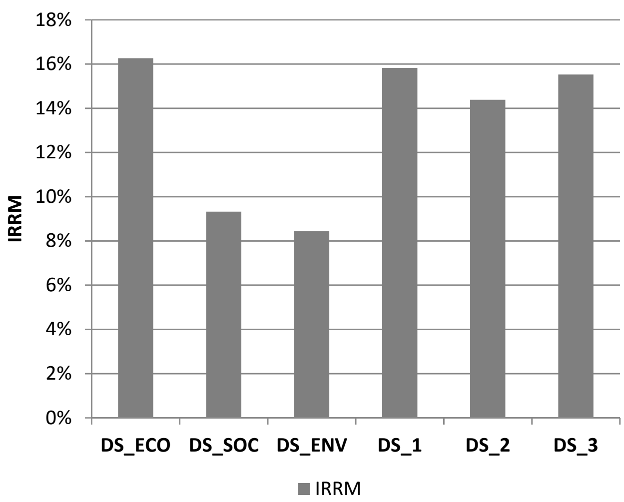

Fig. 4. Economic requirement indicator

The analysis of the results, on the one hand, takes account of only the economic requirement, which has been used over recent years and, on the other, the results of the model considering all 3 requirements of sustainable development (case – DS_1). A slight decrease in the total length of Km of pipeline proposed for renewal is observed with the sustainable development models compared with the economic model (case – DS_ECO).

However, there is an increase in the critical customers, the large-scale consumers, and the number of people benefitting from this renewal, implying that the benefits more people and the disruptions due to possible incidents would affect fewer people. Additionally, there is a significant six-fold increase in the critical customers (hospitals, dialysis facilities etc.). The IRRM of the renewal network remains almost the same, considering the sustainable development method, and profitability is the same when taking into account either the sustainable development model or only the economic requirement. The renewal of pipeline sections by kilometre to improve the organoleptic perception is almost double the same figure with the economic model, and the reductions in water and energy wastage are greater using the sustainable development model.

As expected, the criteria in the composition of the requirements are maximized by taking each requirement into account separately. Nevertheless, the sustainable development approach maximizes all the criteria involved. The social requirement mainly affects the improvement of customers and people benefitting from the pipelines selected for renewal; unlike the environmental requirement that prioritizes the renewal of pipeline sections to reduce water loss and energy wastage. The maximization of kilometres of renewable pipeline was only observed as a benefit when using the economic requirement, although this advantage is also achieved using the sustainable development model.

5.- CONCLUSIONS

The simple and straightforward methodology presented in this paper has taken a step forwards, towards sustainable renewal management of the water pipeline network, in which decisions are taken according to clear, consistent, and transparent criteria. The MIVES methodology is a proven approach for consideration of the main economic, environmental and social risks in the decision framework. Moreover, the involvement of stakeholders and company staff achieves higher degrees of transparency and objectivity than might otherwise be the case.

The paper highlight that considering the three pillars of sustainable development in the decision framework maximizes the social and environmental benefits without compromising the economic benefits which remain similar.

The case study has yielded very satisfactory results, consistent, and repeatable evaluations can be performed. Decision-makers can adapt the method simply by changing the criteria and modifying the weights and the value functions that are assigned at each level. Moreover, the robustness of the proposed approach would make it easily applicable to other cities.

Appendix A.: Analytic Hierarchy Process

Construction of the pairwise comparison matrix

The decision maker is asked to rate the importance of one particular criterion in relation to another in the context of the decision that is addressed, in order to build the pairwise comparison matrix,

Checking the consistency of the pairwise comparison matrix.

Typically, some inconsistencies may arise during the assessment of the comparison of each alternative (which may cause errors and uncertainty over logical results). The AHP incorporates an effective technique for checking the consistency of the evaluations made by the decision maker when building each of the pairwise comparison matrices involved in the process. In this sense, Saaty introduced the Consistency Ratio (CR) for the pairwise consistency matrix. If the CR exceeds 10%, it is recommended that the decision-maker revise the elicited preferences. The CR may be calculated using the Consistency Index (CI) and the Random Index (RI), according to eq. A.1.

$$CR = \frac{Consistency\ Index}{Random\ Index} = \frac{CI}{RI} \tag{A.1}$$

Saaty proposed to compute the Consistency Index (CI) by means of the largest eigen value (λ_{max}) and the size (n) of the pairwise comparison matrix, according to eq. A.2.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{A.2}$$

The Random Index, i.e. the consistency index when the entries of the comparison matrix [A] are completely random. The values of RI for small problems (n ≤ 10) are shown in Table A.1.

Table A.1 RI values

Matrix size n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Calculate the weights of the variables

A number of methods can be used to estimate the set of weights that are most consistent with the relativities expressed in the pairwise comparison matrix. Saaty's basic method of identifying the value of the weights depends on relatively advanced ideas in matrix algebra and calculates the weights as the elements in the eigenvector associated with the maximum eigenvalue of the matrix.

A more straightforward alternative, which also has some theoretical grounding, is to: (1) calculate the geometric mean of each row in the matrix; (2) total the geometric means; and, (3) normalize each of the geometric means by dividing each one by the total calculated in the preceding step. The weights estimated by the two different methods (taken to a number of significant figures for greater accuracy) are not identical, but it is common for them to be very close.

Appendix B.: Value Function

The parameters that define the type of function are: Ki, Ci, X max., X min. and Pi. The value of B that appears in equation 1 is calculated on the basis of the 5 earlier values (Equation B.1).

$$IV_i = B_i * \left[1 - e^{-Ki*\left(\frac{|X - X_{min_i}|}{C_i}\right)^{P_i}}\right] \qquad (B.1)$$

where:

X_{min} is the minimum x-axis of the space within which the interventions take place for the indicator under evaluation.

X is the quantification of the indicator under evaluation (different or otherwise, for each intervention).

P_i is a form factor that defines whether the curve is concave, convex, linear or an “S” shape: concave curves are obtained for values of Pi < 1, convex and “S” shaped forms for Pi > 1 and almost straight lines for values of Pi = 1. In addition, Pi gives an approximation of the slope of the curve at the inflection point.

C_i approximates the x-axis of the inflection point.

K_i approximates the ordinate of the inflection point.

B_i is the factor that allows the function to be maintained within the value range of 0 to 1. This factor is defined by equation B.2.

$$B_i = \left[1 - e^{-Ki*\left(\frac{|X_{max_i} - X_{min_i}|}{C_i}\right)^{P_i}}\right]^{-1} \qquad \text{(B.2)}$$

where: X_{max} is the x-axis of the indicator that generates a value equal to 1 (in the case of functions with increasing values).

Alternatively, functions with decreasing values may be used: i.e. they adopt the maximum value at X_{min}. The only difference in the value function is that the variable X_{min} is replaced by the variable X_{max}, adapting the corresponding mathematical expression.

Acknowledgments

The authors would like to thank the company, Aigües de Barcelona, for material and technical assistance and, particularly, Xavier de Fuentes, Aleix Sanjuan, and Hector Papavassiliu for their initiative, active collaboration, and constant support throughout the project. Likewise, the authors are thankful for the IT contribution of Alex Gasulla and Dani Gavaldà from Innovartium, and Francesc Simon and Josep Maria Gil from Aldebaran for the vector information. Finally, the authors especially acknowledge the support and the data made available from Barcelona City Council, and the local councils of Badalona, Montcada i Reixac, Cornellà de Llobregat, Esplugues de Llobregat, l'Hospitalet de Llobregat, Sant Feliu de Llobregat, Sant Just Desvern, el Papiol and Sant Climent de Llobregat.

Conflict of Interest – None

Limitations

Due to the sensitivity of the data information some calculations cannot be presented in this paper. Also, the availability of the data is an issue to adapt the methodology to other utilities, however, some changes in the decision framework could be done to adapt the methodology to other data sets.

Finally, further research in determining the probability of failure is needed. Authors are considering Machine Learning as a solution due to the fact that currently this technic is being used for prediction events on water field (Yaseen, Z.M., et al 2019).

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