MULTIPLE-CRITERIA DECISION ANALYSIS FOR PROACTIVE MANAGEMENT OF RISK OF WATER DISTRIBUTION SYSTEMS

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ABSTRACT

This article describes the development of a decision support tool based on multicriteria analysis, which uses the results of a risk analysis to evaluate and compare risk reduction measures. The literature contains a wide range of risk analysis techniques and we used the combined risk analysis method that is often used in water distribution systems. The multicritera decision analysis employed considers five of the methods most often applied to water resources problems: weighted sum, TOPSIS, ELECTRE I and III, and the Analytic Hierarchy Process (AHP).

A method was developed that integrates the risk and multicriteria decision analysis applicable to a water distribution network. The main steps of this approach are: first, to identify the pipes that are expected to be more constraining, i.e. pipes with a relatively high probability of failing and/or producing an extreme effect in the event of failure; second, to consider measures which could reduce the likelihood and/or consequences of the occurrence of these events; third, to analyse these measures through multicriteria decision analysis to identify the most effective technical and economic solution.

INTRODUCTION

Risk analysis has been used to assess the levels of safety and service provided to consumers by water supply systems. It is possible to classify the risk analysis in qualitative or quantitative ones (Tuhovcak et al., 2006). The basic idea of a qualitative risk assessment is to evaluate the risk without having to use quantitative measures. Qualitative risk assessment is commonly used in risk classification using risk matrixes. These present the categories of the probability of failure on the vertical axis, and the categories of consequences on the horizontal axis. The classification of hazard through risk matrixes is easily implemented but has some limitations that can be overcome by means of more sophisticated techniques such as quantitative approaches. The qualitative risk classification that uses risk matrixes is sometimes referred to as semi-quantitative if numerical scores are assigned to probability and categories of consequences, perhaps through risk-level values calculated by multiplying the probability values by the consequence levels (Menaia *et al*., 2010).

Because this is a straightforward approach that is often used for the risk analysis of water distribution systems, we will use a semi-quantitative method: Combined Risk Analysis published by the *TECHNEAU* project is reported in publications such as Lindhe *et al.* 2008, Lindhe *et al*. 2010 and Menaia et al. 2010. The main objective was to develop decision support tools based on multiple-criteria decision analysis using the results of a previous risk analysis to evaluate and compare risk reduction measures.

METHODOLOGY

The first step is to perform a risk analysis of a water distribution network, which will result in the identification of the most important pipes, i.e. pipes with a relatively high probability of failure and/or that they might produce an extreme effect if they rupture. This work concerns failure through the spontaneous rupture of pipes because of wear or extraneous influences.

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Combined Risk Analysis

The risk associated with a “ruptured pipe" scenario can be defined by the probability of occurrence and of one or more consequences. A rupture can cause a set of n different results, which can also be associated with k different risks ($R_k, k = 1,2,..., n$), whose value is calculated via the following equation:

$$R_{k,i} = P_i \times C_{k,i} \tag{1}$$

Where:

P_i is the category of probability of failure in pipe i and $C_{k,i}$ the category of consequence, of type k, arising from the occurrence of the scenario "rupture of pipe i”.

Thus, if we assign a score to the risk and consequence (see Table 1), we can evaluate the risk level $R_{k,i}$ associated with a given scenario (adapted from Lindhe et al. 2008).

Table 1: Categories of probability and consequence and their values, P_i and $C_{k,i}$.

Category of Probability	Frequency	P_i	Category of Consequence	Damage	$C_{k,i}$
P_1	Rare	1	**C_1**	Insignificant	1
P_2	Unlikely	2	**C_2**	Minor	2
P_3	Moderate	4	**C_3**	Moderate	4
P_4	Likely	8	**C_4**	Major	8
P_5	Almost certain	16	**C_5**	Catastrophic	16

Once the categories of probability and consequence have been defined, the next step is to set risk acceptance levels. For this we apply the ALARP principle (As Low As Reasonably Practicable). The ALARP principle applies two acceptance limits. An upper acceptance limit, indicating that the solution being analysed is definitely unacceptable if the risk is above this limit, (see red area, Figure 1). In this case the risk must be reduced or eliminated. The second is a lower limit, below which risks are considered acceptable and do not need to be further investigated (see green area, Figure 1) (Lindhe et al. 2008).

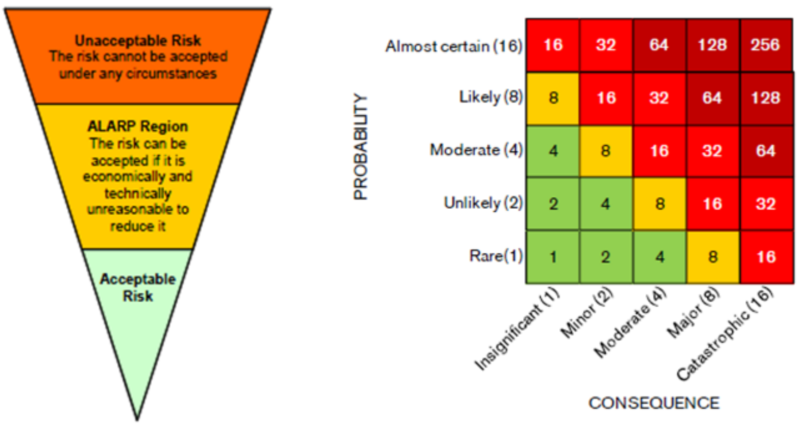

Figure 1: Risk matrix, acceptable (1-4), ALARP region (8), unacceptable (16-256), (Lindhe et al. 2008)

However, risks between these two limits, in the so-called "ALARP region", (yellow area), should be investigated further and be reduced "as far as reasonably practicable". This means that risk reducing measures should be investigated and their cost-effectiveness be evaluated. Unless a risk reducing measure is unreasonably expensive relative to its effect on the risk, it should be implemented. Risk reduction should therefore be discussed systematically for any risk in the ALARP region (Lindhe et al. 2008).

The vertical axis of the risk matrix displays the categories of probability and the horizontal axis displays the categories of consequence defined as shown in Figure 1. The values assigned to the matrix elements are determined by applying equation (1), i.e. by multiplying the scores given to different categories of probability and consequence (adapted Lindhe et al. 2008).

Categories of probability

In this study the categories of probability of failure in a pipe are expressed as a function of the number of breaks predicted per km per year. A comprehensive review of failure prediction models for water pipes was undertaken by Rajani and Kleiner; (Rajani and Kleiner 2001) and (Kleiner and Rajani 2001). These reviews identified two types of failure prediction models: statistical and physical models.

The case study described below uses a new and purely fictional distribution network, and so we are faced with two fundamental problems: first we have a new network without any reported history of ruptures, and therefore a statistical model cannot be used in this approach; second, because it is a fictitious network and lacks detailed information about the structural properties of the pipes or environmental conditions and loads that they are subjected to, a physical model cannot be used. In these circumstances, as the processing of statistical models is less complex, it was decided to use a duly adapted statistical regression model, using data history from a similar existing network.

Accordingly, and after thoroughly researching regression models that can handle a large number of available parameters (input of a larger set of parameters should lead to more realistic predictions of failure rates), we decided to use the nonlinear regression model reported in Tabesh *et al*. 2009 to predict pipe failure rates. Note that, in this model, the regression coefficients of the equation below are determined based on data from a history of failures of a real network described in that article. The following equation is proposed (Tabesh et al 2009):

$$\lambda_l = -0.4197 \cdot \left(D_l^{0.3762}\right) + 0.4168 \cdot \left(L_l^{0.0872}\right) + 0.2813 \cdot \left(P_l^{0.5668}\right) + 0.0903 \cdot \left(H_l^{-1}\right) + 0.7408 \cdot \left(Ag_l^{0.4281}\right) \quad (2)$$

Where λ_l is the failure rate of pipe i (based on the number of breaks/km/year); D_l is the diameter of pipe i in mm; L_l is the length of pipe i in km; P_l is the hydraulic pressure of pipe i in atm; H_l is the installation depth of pipe i in m; and Ag_l is the age of pipe i in years.

The categories of probability assignment to the pipeline network's elements is based on the values shown in Table 2.

Table 2: Relation between categories of probability and the failure rate $C_{k,i}$.

Range of Values Failure rate [ruptures/km/year]		Category of Probability
-	0.2	**C1**
0.2	0.5	**C2**
0.5	1	**C3**
1	2	**C4**
2	-	**C5**

Categories of consequence

Four consequences arising from a rupture in one of the network's pipes were evaluated (the evaluation is performed for all of them): 1. Total deficit; 2. Required minimum pressure; 3. Public image; and 4. Direct costs.

A pressure driven version of EPANET hydraulic simulator (Pathirana 2010) was used to simulate ruptures in each of the pipes and ascertain the consequences of each "rupture of pipe i" scenario. These consequences involve:

I. Total Deficit of consumption

This is the total volume of water no longer provided if the pipe ruptures. To evaluate this a minimum value of a required pressure of 25 m in all network nodes was established, a threshold below which there is a deficit and therefore the demand will not be totally satisfied.

The assignment of categories of consequence to the different pipes is based on the percentage of deficit of consumption obtained by the ratio between the total deficit of water observed for each scenario and the design demand.

II. Required Minimum Pressure

The objective is to know which node is most directly affected when a pipe bursts. As mentioned in the previous point, there is a threshold of pressure of 25 meters, below which there will be a deficit.

The assignment of categories of consequence is based on the number of nodes where the observed hydraulic pressure is lower than the minimum required pressure (25 meters of column of water), i.e. the number of nodes with a supply deficit.

III. Public Image

The consequences mentioned so far are only related to the supply deficit observed in the network nodes and do not take into account the type of infrastructure that they supply. The public image criterion overcomes this gap, capturing the degree of public sensitivity to supply deficit in infrastructure such as industries, schools, homes or hospitals. Bearing in mind that a fictitious water distribution network is going to be form the case study, it is necessary to decide on the nature of the infrastructure supplied by each node.

IV. Direct Costs

The direct costs entailed by a ruptured pipe are determined by identifying the nearby infrastructure and estimating the potential costs of repairing both the pipe(s) and infrastructure(s). The cost of damage to different infrastructure such as roads, dams or historic buildings is estimated. As the case study is a fictional network, a hypothetical framework related to the type of infrastructure in the vicinity of each of the network pipes must be created.

Table 3 shows the correspondences between the four categories of consequence and the set of values/assignments for each consequence.

Table 3: Correspondence between categories of consequence and the different consequences

Consequence Category	Total Deficit of Consumption Percentage	Required minimum pressure Number of affected nodes	Public Image Type of Customer to be Supplied	Direct Costs Infrastructures near to pipe
C1	<2	0	Residential Area (RA)	Standard (Std)
C2	2 - 4	1 - 2	Industrial Area (IA)	min Local Rods (LR)
C3	4 - 8	3 - 4	Risk Industries (RI)	Historic Areas (HA)
C4	8 - 16	5 - 6	Schools and Residential Homes (S,RH)	Collector Roads (CR)
C5	>16	≥7	Hospitals (H)	Monuments and Dams (MD)

Initial levels of risk

The risk analysis ends with the calculation of the initial risk levels, $R_{k,i}$, using equation (1). It is possible to identify the most important pipes. To apply this equation, we have to transform the categories of consequence into quantitative values, $C_{k,i}$. This transformation takes into account the assumptions shown in Table 1.

After the most constraining pipes have been identified, and to take a proactive approach towards risk, measures should be considered that will induce robustness in the network by reducing the risk levels associated with a possible break in one of the pipes. However, any strategy must reconcile the technical benefits with social and economic burdens. A pre-defined set of risk reduction measures will thus be analysed via multiple-criteria decision analysis techniques, to classify their performance and so identify the most effective measure(s) in technical, social and economic terms.

Multiple-criteria decision analysis

The multiple-criteria decision analysis process begins with the choice of a finite set of alternative measures and a set of evaluation criteria that are used to measure the performance of those alternatives.

Definition of alternative measures and criteria

For this particular case, measures have been identified with a view to reducing the levels of risk associated with a break in the pipes. These measures constitute the various alternatives of the multiple-criteria decision analysis model. As the network is a new one and therefore the initial design will satisfy the demand, it is easy to see that the only alternative measures considered will be resizing the diameters of the pipes. We will use the following five criteria to evaluate the various alternative measures:

I. Risk Reduction (with the implementation of the measure j) for the (risk) "total deficit";
II. Risk reduction in relation to "required minimum pressure";
III. Risk reduction in relation to "public image";
IV. Risk reduction in relation to "direct costs"; and
V. Ensuing cost increase.

Determination of the performance of the alternative measures in relation to the criteria
This subsection explains how the performance of each alternative for each criterion is determined.

i. Performance with regard to risk reduction

After the implementation of each alternative measure, new categories of probability and consequences for the different risks are estimated, resulting in a new value for risk exposure $R_{k,i}$. With this new score we calculate the risk reduction, $\Delta R_{k,i,j}$, given by the alternative measure , j for each risk and each " rupture in pipe i" scenario:

$$\Delta R_{k,i,j} = R_{k,i} - R_{k,i,j} \quad k \in \{\text{I, II, III, IV}\} \tag{3}$$

Where:

$R_{k,i}$ is the initial level of risk k for the scenario "rupture of pipe i" before any risk reduction measure is implemented and $R_{k,i,j}$ is the end level of risk k for the scenario "rupture in pipe i" after implementation of measure j.

Finally, the benefit of risk reduction for each risk k is obtained through the following sum (m is the number of scenarios):

$$\Delta R_{k,j} = \sum_{i=1}^{m} \Delta R_{k,i,j} \, , \; k \in \{\text{I, II, III, IV}\} \tag{4}$$

where $\Delta R_{\text{I},j}$, $\Delta R_{\text{II},j}$, $\Delta R_{\text{III},j}$ and $\Delta R_{\text{IV},j}$ are respectively the benefits of risk reduction in relation to the total deficit "total deficit of consumption", "required minimum pressure", "public image" and "direct costs".

ii. Performance in relation to the cost increase

The implementation of risk reduction measures in a new network implies increased investment costs. Accordingly, the cost increase, ΔC_j, associated with each of the proposed alternative measures is based on the cost difference between the new (larger diameter) and original pipes.

iii. Filtering of alternative measures

Of all possible alternative measures to be examined, there is one for which evaluation is unnecessary. Therefore, and before entering the multiple-criteria analysis, solutions which are considered to be dominated and/or inadmissible are eliminated. For this, we employ the dominance and connective methods.

iv. Ranking of alternative measures through multiple-criteria decision analysis techniques

Our methodology ends with the direct application of a series of multiple-criteria decision analysis methods to rank the alternative measures and help to ascertain which is/are the best alternative measure(s) to apply. Of these techniques, which are widely used in water resources problems, the following were chosen, as examples: weighted sum method, TOPSIS, ELECTRE I and III and Analytic Hierarchy Process. The application of more than one method enables the sensitivity of results to be tested, i.e. seeing which alternatives provide the best performance for the techniques used.

APPLICATION TO A CASE STUDY

The methodology presented was applied to a water distribution network often used in scientific benchmarking.

Network description

Figure 2 shows the network to which the method was applied. It is a new water distribution network fed by gravity, consisting of 33 pipes and 16 nodes, whose characteristics are presented in Tables 4, 5 and 6. The initial design for the implementation of this method corresponds to the peak flow scenario presented in Cunha & Sousa (2010).

It should be recalled that this is a fictitious network and it was therefore necessary to define the type of infrastructure that each node would supply. It was decided, on a purely arbitrary basis, that node 7 directly supplies a hospital, nodes 14 and 3 supply schools or dwellings and that node 16 supplies a risk industry. In addition, and based on a hypothetical use of real estate, nodes 10, 11 and 12 supply industrial zones and the remaining network nodes supply domestic households.

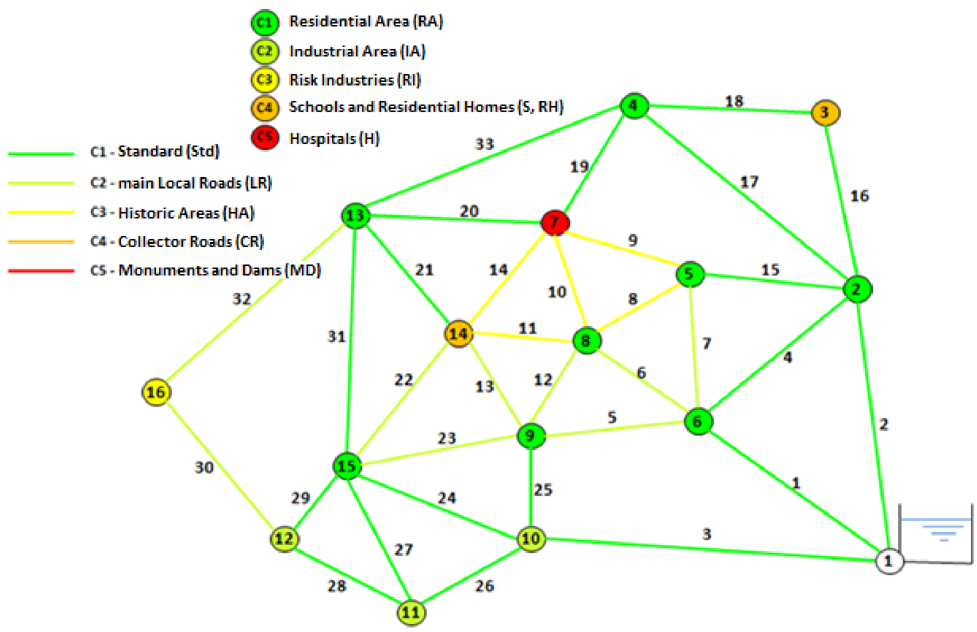

Figure 2: Network schema showing the infrastructure/areas supplied and nearby infrastructure network (adapted Cunha & Sousa 2010)

Table 4: Pipe characteristics

Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Upstream Node	1	1	1	2	9	8	5	5	5	8	14	9	9	14	2	2	2
Downstream Node	6	2	10	6	6	6	6	8	7	7	8	8	14	7	5	3	4
Length [m]	3660	3660	3660	2740	1830	1830	1830	1830	1830	1830	1830	1830	1830	1830	1830	1830	2740
Diameter [mm]	200	500	600	100	100	100	100	250	250	100	100	100	100	100	400	250	250

Pipe	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
Upstream Node	3	4	13	14	15	15	10	10	10	15	12	15	12	15	13	13
Downstream Node	4	7	7	13	14	9	15	9	11	11	11	12	16	13	16	4
Length [m]	1830	1830	1830	1830	1830	1830	1830	1830	1830	2740	1830	1830	1830	1830	3660	3660
Diameter [mm]	100	100	100	100	250	100	500	250	200	100	125	350	300	250	100	100

Table 5: Node characteristics

Node	1	2	3	4	5	6	7	8
Consumption (l/s)	0	43,89	43,89	43,89	43,89	43,89	43,89	43,89
Pressure (Water column)	55,00	44,81	38,89	37,16	40.93	36,43	36,49	36.49
Node	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Consumption l/s	43,89	43,89	43,89	43,89	43,89	43,89	43,89	43,89
Pressure (Water column)	40,36	47,37	36,51	39,15	37,39	37,58	43,28	36,98

Table 6: Available diameters and unit costs

Diameter (mm)	100	125	150	200	250	300	350	400
Unit Cost (€/m)	12,052	16,881	34,326	48,079	48,079	63,317	79,911	97,763
Diameter (mm)	**450**	**500**	**600**	**700**	**800**	**900**	**1000**	
Unit Cost (€/m)	116,793	136,933	180,332	227,595	278,439	332,637	390,000	

Risk analysis

The quantitative risk analysis of the water distribution network described below results in the identification of the most relevant pipes, i.e., those with a relatively high probability of failing and/or of producing a potentially extreme effect if they do fail. As stated earlier, the failure being studied is the spontaneous rupture of pipes.

Determination of categories of probability

Equation (2) is used to determine the rate of failure for each pipe, assuming an age Ag_l of 20 years and a depth H_l of 1.20 m for all of them. This decision may also be interpreted as a 20-year prediction, taking into account the set of parameters consisting of the diameter, the length and the hydraulic pressure. The resulting burst rates are given in Table 7. Then, based on Table 2, the corresponding categories of probability are assigned for each pipe.

Table 7: Probability and Risk indicators

		Probability	Total Deficit of Consumption	Required minimum pressure	Public Image	Direct Costs
		Failure index	Total Deficit of Consumption	Number of affected nodes	Type of Customer to be Supplied	Infrastructures near to pipe
Rupture in Pipe	**1**	0,87	1,58%	1	RA	Std
	2	-0,40	31,14%	7	H	Std
	3	-0,71	45,69%	11	H	Std
	4	1,48	0,00%	0	-	Std
	5	1,43	0,00%	0	-	LR
	6	1,39	0,00%	0	-	LR
	7	1,43	0,00%	0	-	LR
	8	0,46	1,61%	1	-	HA
	9	0,46	1,60%	1	RA	HA
	10	1,39	0,00%	0	H	HA
	11	1,40	0,00%	0	-	HA
	12	1,43	0,00%	0	-	LR
	13	1,43	0,00%	0	-	LR
	14	1,40	0,00%	0	-	HA
	15	-0,16	10,53%	4	-	Std
	16	0,49	5,04%	1	H	Std
	17	0,50	2,75%	1	S, RH	Std
	18	1,42	0,00%	0	RA	Std
	19	1,40	0,00%	0	-	Std
	20	1,40	0,00%	0	-	Std
	21	1,40	0,00%	0	-	Std
	22	0,48	1,63%	1	-	LR
	23	1,45	0,00%	0	S, RH	LR
	24	-0,49	22,12%	6	-	Std
	25	0,51	1,66%	1	S, RH	Std
	26	0,78	2,69%	1	RA	Std
	27	1,47	0,00%	0	IA	Std
	28	1,21	0,00%	0	-	Std
	29	0,02	9,72%	2	-	Std
	30	0,20	5,50%	1	RI	LR
	31	0,48	2,14%	1	RI	Std
	32	1,43	0,00%	0	RA	LR
	33	1,43	0,00%	0	-	Std

Determination of categories of consequence

Four consequences arising from the occurrence of burst pipes in different network pipes are studied in this work: 1. total deficit; 2. required minimum pressure; 3. public image; and 4. direct costs.

Probability and Risk indicators

Analysing Table 7 we can conclude that if pipe 24, 2 or 3 ruptures the consequences will be devastating in terms of the volume of water that is not provided to customers and also in terms of the number of connections that do not receive the minimum pressure required for demand to be fully met. A rupture of pipe 2, 3, 9 or 15, will produce severe consequences since there will be a supply shortage at node 7 (see Figure 2), responsible for supplying a hospital. So, assuming the situation illustrated in Figure 2 and Table 3, a category of consequence can be assigned to each risk scenario based on the type of infrastructure located in the vicinity of the pipe where the rupture occurs.

Initial risk levels and arrays

Based on Tables 1 and 3, we can transform the categories into quantitative values using equation (1). Finally, on the basis of this equation, the level, n, associated with each scenario "rupture in pipe i" is estimated for each risk.

Table 8:- Determination of levels of risk associated with each of the considered scenarios

Initial Risk ($R_{k,i}$) for the different types of risk ($R_{k,i} = C_{k,i} \times P_i$)	Rupture in pipe i																
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
I.	4	16	16	8	8	8	8	2	2	8	8	8	8	8	8	8	8
II.	8	16	16	8	8	8	8	4	4	8	8	8	8	8	4	4	8
III.	4	16	16	8	8	8	8	2	32	8	8	8	8	8	16	16	4
IV.	4	1	1	8	16	16	16	8	8	32	32	16	16	32	1	2	4

	18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
I.	8	8	8	8	2	8	16	4	8	8	8	8	8	4	8	8
II.	8	8	8	8	4	8	8	8	8	8	8	2	4	4	8	8
III.	8	8	8	8	16	8	8	4	8	8	8	4	8	2	8	8
IV.	8	8	8	8	4	16	1	4	4	8	8	1	4	2	16	8

The results in Table 8 identify the most relevant pipes. It is possible to conclude, for example, that if pipe 2 or 3 breaks, although the likelihood is low (see Table 7) the overall risk level is high due to the disastrous consequences that would ensue.

Multiple-criteria analysis

Because this is a fictional distribution network it was again necessary to create a hypothetical framework, this time related to possible measures to reduce risk exposure.

Alternative measures

It should be noted that the choice of the different resizing options took into account the following assumptions: mitigating the negative effects of a possible rupture in pipe 2 (alternatives 1 to 4); mitigating the negative effects of a possible rupture in pipe 3 (alternatives 5 and 6); mitigating the negative effects of a possible rupture in pipe 2 or 3 (alternatives 7 to 9); mitigating the negative effects on direct costs, focusing principally on the absence of any unacceptable risks in the corresponding risk matrix, i.e. risks marked in red in the “direct costs” risk matrix (alternative 10); mitigating the negative effects on direct costs, focusing principally on the sole existence of acceptable risk in the corresponding risk matrix, i.e. risks marked in green in the “direct costs” risk matrix (alternative 11); mitigating the negative effects of a possible rupture in pipe 9, 15 or 24 (alternative 12); combination of alternatives 4 and 10 (alternative 13); combination of alternatives 6 and 10 (alternative 14); combination of alternatives 9 and 10 (alternative 15); combination of alternatives 10 and 12 (alternative 16); combination of alternatives 4 and 11 (alternative 17); combination of alternatives 6 and 11 (alternative 18); combination of alternatives 9 and 11 (alternative 19); combination of alternatives 11 and 12 (alternative 20); sole existence of acceptable risks in the four risk matrices (alternative 21); sole existence of acceptable level one risks (1) with the lowest possible associated cost (alternative 22).

Performance and filtering of alternative measures in relation to the criteria

Table 9 shows the performance of each of the 22 alternatives for each criterion. Highlighted in green are the alternative measures that are then evaluated through multiple-criteria decision analysis, while the rest are eliminated because they are inadmissible and/or dominated alternatives, in which case any alternative with a negative score in any given criterion is considered to be inadmissible.

Table 9: performance of alternative measures

	Initial Sit.	1	2	3	4	5	6	7	8
Δ $R_{I,j}$	-	24,0	27,0	31,0	36,0	29,0	33,0	35,0	53,0
Δ $R_{II,j}$	-	22,0	23,0	31,0	42,0	37,0	45,0	40,0	52,0
Δ $R_{III,j}$	-	-12,0	-11,0	53,0	72,0	23,0	57,0	4,0	61,0
Δ $R_{IV,j}$	-	9,0	11,0	27,0	31,0	20,0	36,0	19,0	34,0
ΔC_j [€]	Ci=3.172.759	419.809	482.846	523.607	728.000	894.597	935.359	741.681	1.079.763
	Initial Sit.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
Δ $R_{I,j}$	-	66,0	73,0	153,0	65,0	86,0	95,0	103,0	
Δ $R_{II,j}$	-	64,0	48,0	118,0	60,0	82,0	86,0	96,0	
Δ $R_{III,j}$	-	72,0	82,0	158,0	99,0	118,0	110,0	124,0	
Δ $R_{IV,j}$	-	42,0	128,0	208,0	60,0	113,0	92,0	98,0	
ΔC_j [€]	Ci=3.172.759	1.304.53	523.880	1.415.041	713.871	1.129.595	1.336.954	1.624.605	
	Initial Sit.	**16**	**17**	**18**	**19**	**20**	**21**	**22**	
Δ $R_{I,j}$	-	119,0	163,0	167,0	169,0	167,0	181,0	225,0	
Δ $R_{II,j}$	-	101,0	143,0	155,0	157,0	140,0	169,0	213,0	
Δ $R_{III,j}$	-	139,0	177,0	209,0	211,0	180,0	223,0	267,0	
Δ $R_{IV,j}$	-	156,0	185,0	184,0	186,0	216,0	212,0	264,0	
ΔC_j [€]	Ci=3.172.759	1.115.46	1.909.390	2.202.947	2.379.232	1.793.468	2.426.032	3.820.230	

Each method requires the use of some additional parameters; these parameters are presented in the following table:

Table 10: weights and thresholds for each method

		I.	II.	III.	IV.	V.
SAW	Weights	0,200	0,075	0,175	0,050	0,500
TOPSIS	Weights	0,200	0,075	0,175	0,050	0,500
ELECTRE I	Weights	0,200	0,075	0,175	0,050	0,500
ELECTRE III	Weights	0,200	0,075	0,175	0,050	0,500
	Limit of Preference	30	30	30	30	100.000
	Limit of Indifference	15	15	15	15	50.000
	Veto Limit	100	100	100	100	1.000.000
AHP	Priority Vector	20,2%	7,5%	17,5%	5,1%	49,7%

Simple Additive Weighting

The first technique is Simple Additive Weighting (SAW). This is a popular decision rule because of its simplicity. It uses the additive aggregation of the criteria outcomes that is represented by the following equation:

$$A_i = \sum_{k=1}^{n} x_{ij} \times w_i \tag{5}$$

Where A_j is the alternative measure j, x_{ij} the performance of the alternative j in criterion i and w_i is the weight of criterion i. But first the evaluation matrix has to be normalized, for which we use a linear normalization. Criteria I, II, III and IV are benefit criteria and as such equation (6) is used:

$$x'_{ij} = \frac{x_{ij} - xmin_i}{xmax_i - xmin_i}, \qquad i \in \{I, II, III, IV\} \tag{6}$$

For the cost criterion V (Arising cost increase) the normalization equation is:

$$x'_{Vj} = \frac{x_{Vj} - xmax_i}{xmin_V - xmax_V} \tag{7}$$

The final ranking of the SAW is presented in Table 16.

TOPSIS

This method is based on reference points and requires a vector normalization. The original scores x_{ij} are transformed into x'_{ij} using equation (8):

$$x'_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{8}$$

With this matrix it is possible to calculate the ideal and anti-ideal solution. The ideal solution consists of the best score (of all alternative measures) for each criterion and the anti-ideal is the worst score of each criterion.

Table 11: Ideal and Anti ideal solution

	I.	II.	III.	IV.	V.
A+	0,09140	0,03630	0,08054	0,02224	0,04032
A-	0,01259	0,00528	0,01599	0,00227	0,29418

The next step consists of calculating the distance of each measure, for each criterion, to the ideal solution using the two following equations:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \tag{9}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \tag{10}$$

The resulting distances are presented in Table 12:

Table 12: Distance for each measure to ideal and anti-ideal solution

	3	10	11	12	16	17	18	19	20	21	22
Distance to Ideal Solution	0,10835	0,08860	0,08327	0,08935	0,07661	0,11378	0,13314	0,14613	0,10477	0,14843	0,25385
Distance to Anti-Ideal Solution	0,25385	0,25472	0,19549	0,24007	0,21352	0,16269	0,14628	0,13553	0,17169	0,13662	0,10835

To calculate the final score of we use equation (11):

$$T_i = \frac{S_i^-}{S_i^+ - S_i^-} \qquad (11)$$

The final scores are given in Table 13:

Table 13: Final scores of measures TOPSIS

3	10	11	12	16	17	18	19	20	21	22
0,70087	0,74194	0,70129	0,72877	0,73594	0,58846	0,52351	0,48117	0,62102	0,47928	0,29913

ELECTRE I

ELECTRE I is a so-called outranking method and we use vector normalization here as well. In this method we perform pairwise comparisons and for the concordance matrix we ascertain if one alternative is at least not worse than another alternative, for each criterion. For the discordance matrix we ascertain if the alternative has a worse score. The method is not described in detail here for reasons of brevity. One important detail is that the limits for concordance and discordance were set as the average of the concordance and discordance matrix respectively. The outcome is presented in Figure 3:

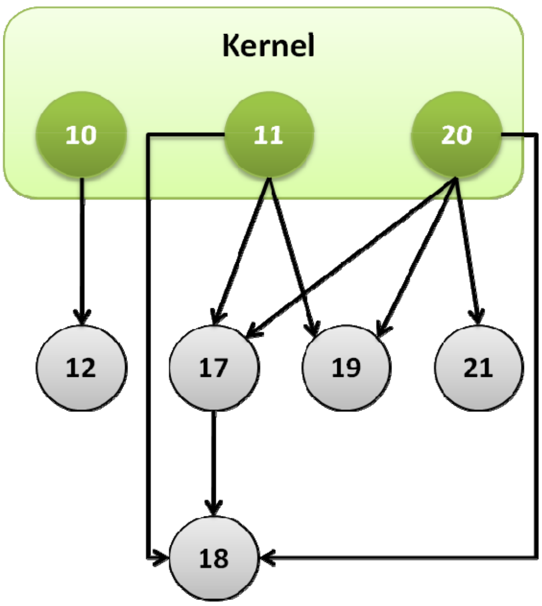

Figure 3: Final evaluation of ELECTRE I

ELECTRE III

This method is similar to ELECTRE I but uses thresholds to establish absolute and weak preference (see Table 10). As with ELECTRE I this method is not fully described in this paper. It has two orders (ascending and descending distillations) which are combined to obtain the final ranking (see Figures 4, 5 and 6).

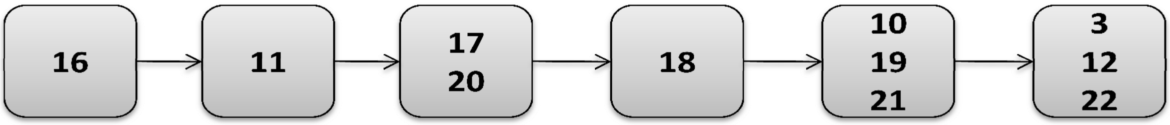

Figure 4: Ascending distillation

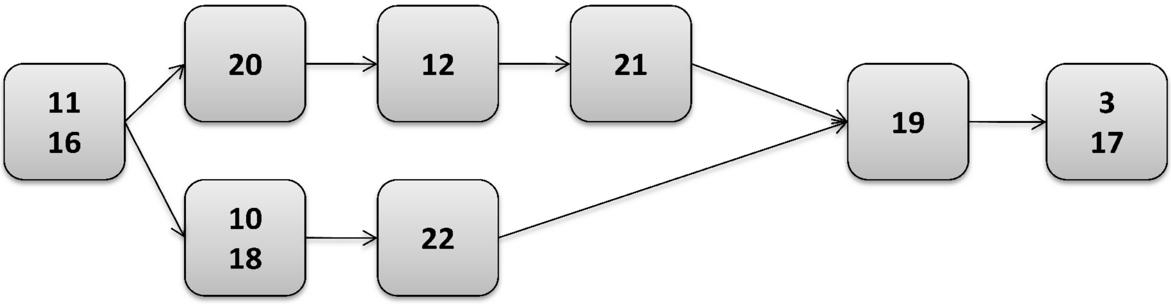

Figure 5: Descending distillation

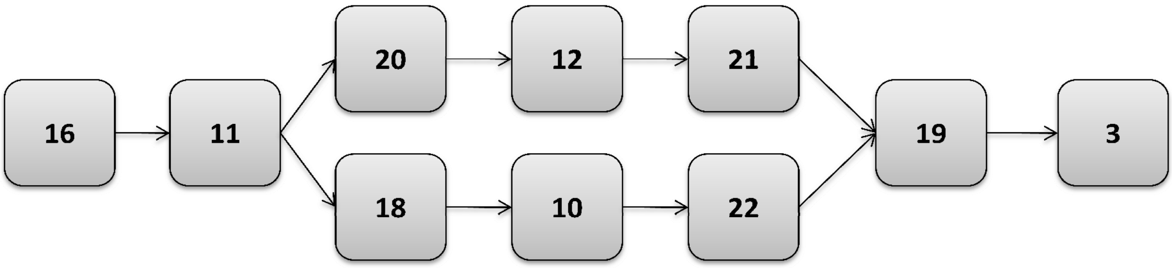

Figure 6: Final ranking ELECTRE III

ANALYTICAL HIERARCHY PROCESS

The AHP is a well known method to assist decision making. The structure is given in Figure 7:

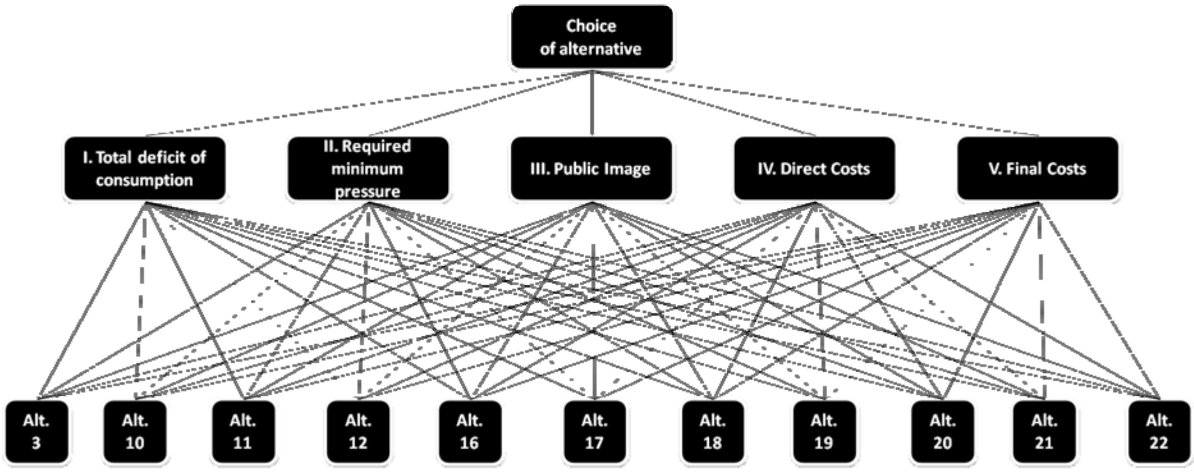

Figure 7: Hierarchy structure AHP

In this method the alternative measures are compared with each other individually for each criterion using the following scale:

Table 14: Pairwise comparison scale for AHP

Numerical Value	Verbal Scale	Explanation
1	Equal importance of both elements	Two elements contribute equally
3	Moderate importance of one element over another	Experience and judgement favour one element over another
5	Strong importance of one element over another	An element is strongly dominant
7	Very strong importance of one element over another	An element is very strongly dominant
9	Extreme importance of one element over an other	An element is favoured by at least on order of magnitude
2,4,6,8	Intermediate values	Used to compromise between two judgments

If a score is attributed the inverse comparison receives the inverse score. This method does not use any weights but does use the above comparison scale for the same purpose. It weights one criterion against another, which enables the priority vector to be calculated (see Table 10), which has a similar function as the weights.

It is easily noted that the resulting priority vector has similar values to the weights. This was intentional so that the end would have a better starting point for assessing the results from different techniques. AHP is also not described in full in this paper. After making all the pairwise comparisons of each criterion we obtain the following final scores:

Table 15: Final Scores

	I	II	III	IV	V	Final Score
3	1,36%	1,38%	1,48%	1,47%	22,45%	**11,87%**
10	1,96%	1,69%	1,96%	1,95%	22,45%	**12,12%**
11	7,19%	7,14%	6,29%	15,86%	7,38%	**7,57%**
12	3,02%	3,06%	3,31%	3,19%	15,12%	**9,10%**
16	5,61%	5,52%	6,23%	5,99%	11,56%	**8,69%**
17	10,45%	10,33%	10,35%	7,81%	5,06%	**7,61%**
18	10,45%	10,33%	11,07%	8,52%	3,11%	**6,81%**
19	10,82%	10,33%	11,07%	8,85%	2,98%	**6,83%**
20	10,82%	10,33%	8,52%	13,40%	6,15%	**8,19%**
21	16,71%	16,26%	16,35%	13,40%	2,47%	**9,37%**
22	21,62%	23,63%	23,37%	19,57%	1,25%	**11,85%**

Final Rankings

As mentioned earlier, the study ends with the direct application of a set of multiple-criteria decision analysis to achieve an ordered classification of alternative measures that helps us to see which are the best alternatives.

Table 16: Ranking of the alternative measures for the different MCDA techniques applied

SAW	
11	0,64
20	0,62
16	0,62
17	0,60
10	0,59
21	0,59
18	0,59
19	0,59
12	0,57
3	0,56
22	0,51

TOPSIS	
10	74,19%
16	73,59%
12	72,88%
11	70,13%
3	70,09%
20	62,10%
17	58,85%
18	52,35%
19	48,12%
21	47,93%
22	29,91%

ELECTRE I	
10	**Accept**
11	
20	
12	**Reject**
17	
18	
19	
21	
3	**No Classification**
16	
22	

ELECTRE III	
16	
11	
18	20
10	12
22	21
19	
3	
Incomparable	
17	

AHP	
10	12,12%
3	11,87%
22	11,85%
21	9,37%
12	9,10%
16	8,69%
20	8,19%
17	7,61%
11	7,57%
19	6,83%
18	6,81%

CONCLUSIONS

Analysis of the results presented in Table 16 clearly shows that some alternatives take precedence over the others, in particular alternatives 10, 11, 16 and 20. Such alternatives must be analysed with particular care by the decision-maker. The factor which would most likely be decisive in choosing the final alternative would be the budget available for the implementation of the project, since it is clear that any alternative whose final cost exceeded the available budget would be automatically disregarded.

The difficulty in reaching an equivalent (or at least similar) ranking in all methods is due to the fact that the various techniques involve several kinds of assumptions, information requirements and evaluation principles. So choosing an appropriate technique to handle situations in general is a matter that remains open; the choice of a method from those that exist is itself an issue for multiple-criteria decision analysis.

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