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:

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

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):

$$T_i = \frac{S_i^-}{S_i^+ - S_i^-} \tag{11}$$

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:

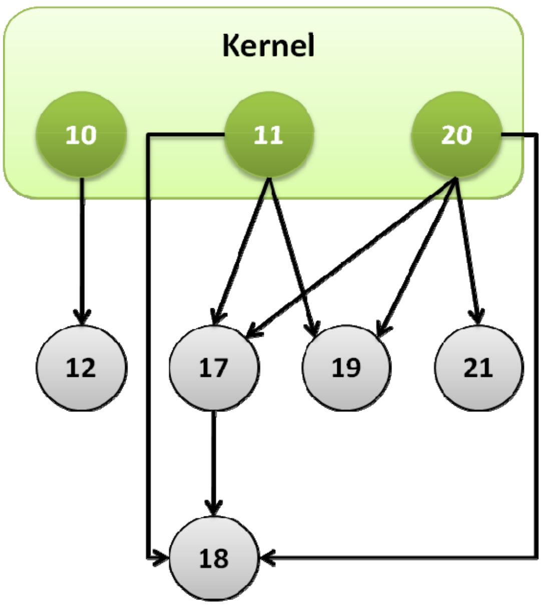

Figure 3: Final evaluation of ELECTRE I

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).

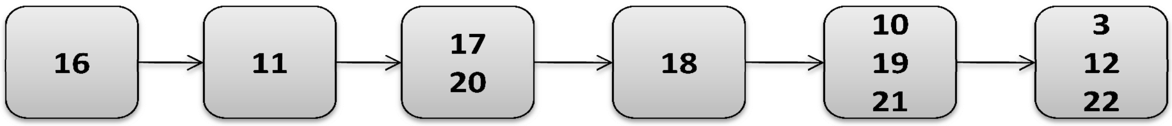

Figure 4: Ascending distillation

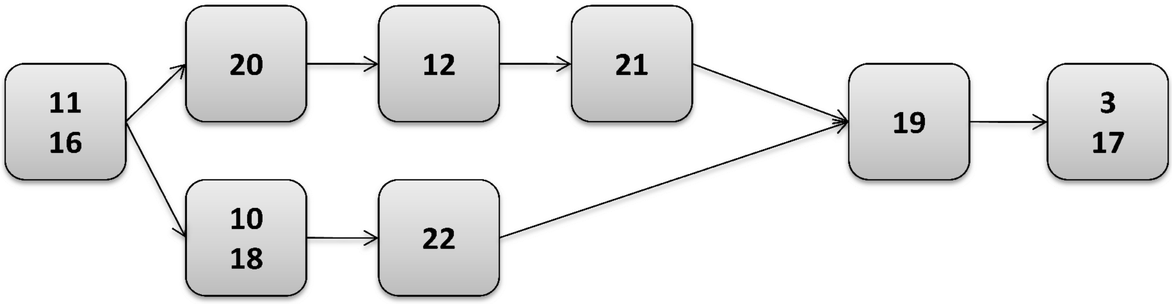

Figure 5: Descending distillation

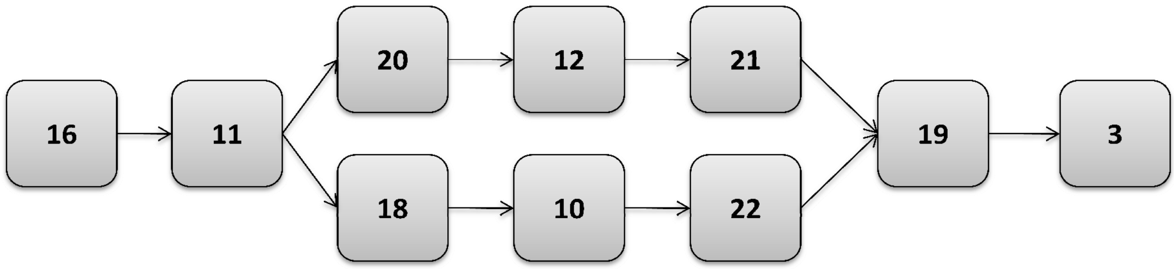

Figure 6: Final ranking ELECTRE III

ANALYTICAL HIERARCHY PROCESS

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

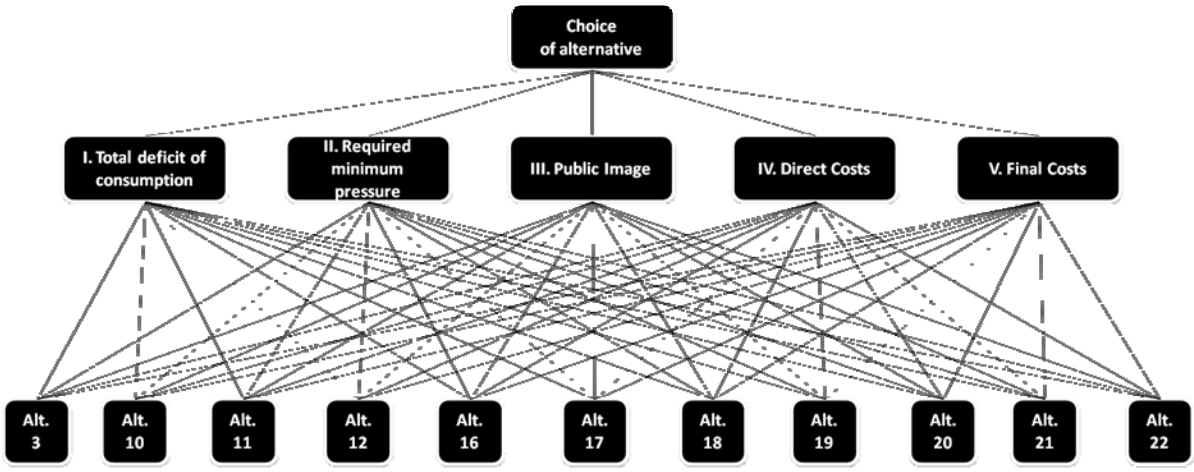

Figure 7: Hierarchy structure AHP

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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