Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 119 (2015) 1231 – 1240

Procedia Engineering

www.elsevier.com/locate/procedia

13th Computer Control for Water Industry Conference, CCWI 2015

A multicriteria approach for a phased design of water distribution networks

João Marques[a]*, Maria Cunha[b], Dragan Savić[c]

[a]Departamento de Engenharia Civil, Faculdade de Ciências e Tecnologia da Universidade de Coimbra, 3030-788, Portugal.
[b]Departamento de Engenharia Civil, Faculdade de Ciências e Tecnologia da Universidade de Coimbra, 3030-788, Portugal.
[c]Centre for Water Systems, College of Engineering, Computing and Mathematics, University of Exeter, EX4- 4KF, United Kingdom.

Abstract

Water distribution networks are key infrastructure that provide essential water supply to communities. Planning water distribution networks involves many actors, including water companies, governments, environmentalists, consumers and financing institutions, and they tend to have conflicting perspectives. This work proposes a multi-criteria decision analysis (MCDA) as a useful tool for providing decision support in such circumstances. A phased planning horizon scheme is proposed that identifies the design for the first time interval while considering possible future conditions that the network might have to cope with. The results identify the best ranked phased design solutions.

Peer-review under responsibility of the Scientific Committee of CCWI 2015

Keywords: Water distribution networks; multicriteria analysis; phased design; optimization

1. Introduction

The rehabilitation and reinforcement of water distribution networks are generally costly and the high reliability and safety requirements of these infrastructures mean that a thorough study must be undertaken to support decision making. Researchers have been working on methods in this area for quite a number of years [1].

Efficient solutions for a water network that take social, economic and environmental dimensions into account and assume an uncertain planning horizon should be found with the help of appropriate tools. Multi-criteria decision

* Corresponding author.
E-mail address: jmarques@dec.uc.pt

Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.983

analysis (MCDA) is a structured and transparent approach that can be used in coherent decision making [2]. This is missing in most approaches used in the past. The application of MCDA to water infrastructures has been proposed by [2], [3] and [4] for the strategic rehabilitation of water networks. In [4] the results find the best ranked strategies for annual pipe replacement percentages that will perform well under a set of scenarios. Here, we use MCDA to solve a different problem. Some water networks work over their capacity and need to be reinforced to provide a good service. We propose using MCDA to identify the best ranked reinforcement design solution that embraces a phased planning horizon. There is little in the literature on the use of MCDA for the phased implementation of alternative solutions. A phased intervention scheme allows decision makers to deal with uncertainty and lets water companies implement short term upgrades and prepare for future conditions like network expansions [5]. Networks have to be constantly adapted to new circumstances and their design should therefore be flexible enough to cope with them. Flexible design is what enables the designer to dynamically manage or further develop the configuration of the water infrastructure down the line, to adapt it to changes in supply, demand, or the economic environment.

The objective here is to identify and rank a set of alternative designs and give decision makers a coherent relationship between different solutions to help select the best option. Multicriteria methods include TOPSIS [6], ELECTRE [7], AHP [8] and PROMETHEE [9]. We used the preference ranking organization method for enrichment of evaluations (PROMETHEE) developed by [9]. This method is easy to understand compared to other methods and is widely used in practice. A literature review about using PROMETHEE in water infrastructures can be found in [10]. This method uses an outranking principle to rank alternatives that is based on pairwise comparisons and requires the identification of different alternatives, criteria and weights for the decision making procedure. The results are represented in an evaluation matrix by the rank of the alternatives. PROMETHEE is also the most widely used program for supporting MCDA in terms of data management and visualization [2].

This study proposes a new decision approach for identifying the most efficient phased design solution to water networks. The remainder of this work is organized as follows: section 2 includes the methodology, section 3 explains the application and the results of the MCDA and finally section 4 contains the conclusions and indications for future work.

2. Methodology

2.1. Outline

Managing water distribution networks involves coping with conflicting interests and many stakeholders. These interests require the use of methodologies such as MCDA that can aggregate all preferences in a single flexible solution. The methodology is divided into 3 steps, shown in Fig. 1.

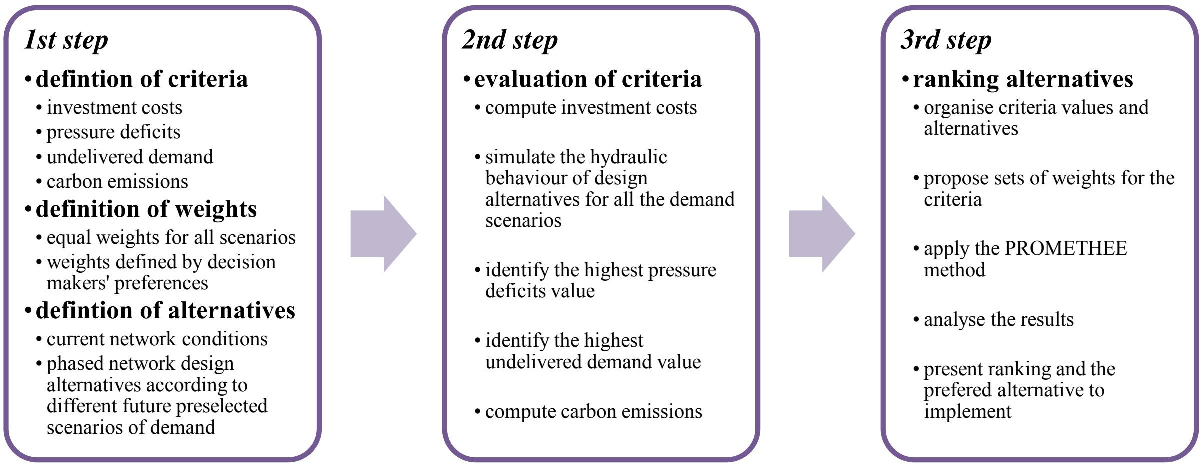

Figure 1: Multicriteria decision analysis steps

The first step establishes the criteria, weights and alternatives. The second step involves evaluating the criteria for each phased design alternative by assessing the alternative's behaviour under a set of different random generated scenarios. Finally, the third step ranks the alternatives. The idea is to identify how a water distribution system can be reinforced under a phased scheme in order to guarantee flexible investment in the water network over the planning horizon.

2.2. Establishing criteria, weights and alternatives

2.2.1. Criteria

Four criteria are analysed to evaluate the cost of investment, pressure deficits, undelivered demand and carbon emissions. The investment cost is given by the sum of the cost of pipes to all design phases (Eq. 1).

$$CI = \sum_{t=1}^{NPH} \left(\sum_{i=1}^{NPI} \left(Cpipe_i(Dc_{i,t}) \times L_i \right) \frac{1}{(1+IR)^{Y_t}} \right) \quad (1)$$

CI – cost of investment *(USD)*
NPH - number of phases into which the planning horizon is subdivided
NPI - number of pipes in the network
$Cpipe_i(Dc_t)$ - unit cost of pipe *i* as function of the commercial diameter $Dc_{i,t}$ adopted *(USD/m)*
$Dc_{i,t}$ – commercial diameter of pipe *i* installed in time phase *t (mm)*
Li - length of pipe I *(m)*
IR - annual interest rate for updating the costs;
Y_t - year when costs will be incurred for time phase *t*

Expression (Eq. 1) computes the investment costs of pipes to be installed. Water utilities usually have limited budgets that must be carefully managed. This cost criterion is used to classify economic viable solutions and is given by the unit commercial diameter cost multiplied by the length of the pipe.

To provide an adequate service, water networks should have enough hydraulic capacity to deliver the demand at adequate pressure. Pressure drops below the desirable pressure can lead to reduced water supply. One criterion for pressure deficits and another for undelivered demand are used to classify the water network in terms of quality of service. A pressure driven hydraulic simulator is used here to give an accurate prediction of pressures and flows. Furthermore, to evaluate the alternatives, a set of scenarios with different demand conditions is proposed. The hydraulic simulator identifies the nodes and the amount of pressure deficits for each scenario. The aim is to simulate the hydraulics and identify the highest pressure deficit scenario given by Eq. 2.

$$\begin{aligned} PD_{max} &= \max_{s}^{NS}\left(PD_s\right) \\ PD_s &= \sum_{t=1}^{NPH}\sum_{n=1}^{NN} max\left\{0;\left(Pdes_{\min,n} - P_{n,t,s}\right)\right\} \end{aligned} \quad (2)$$

PD_{max} – maximum pressure deficit *(m)*
NS - number of scenarios
PD_s – pressure deficits of scenario *s (m)*
NN - number of nodes
$Pdes_{min,n,}$ - minimum desirable pressure at node *n (m)*
$P_{n,t,s}$ - pressure at node *n* for time phase *t* in scenario *s (m)*

The Eq. 2 aims at computing the maximum pressure deficits considering the set of demand scenarios. The pressure deficits are obtained by summing the difference between the minimum desirable pressure and the effective simulated pressure for all network nodes, and for all time phases. The undelivered demand criterion is given by a similar procedure. A pressure driven hydraulic simulator is used to identify the nodes with delivered water flow below the required demand. The aim is to identify the highest undelivered demand given by Eq. 3.

$$UD_{max} = \max_{s}^{NS}\left(UD_s\right)$$
$$UD_s = \sum_{t=1}^{NPH}\sum_{n=1}^{NN} max\left\{0;\left(ND_n - C_{n,t,s}\right)\right\} \tag{3}$$

UD_{max} – maximum undelivered demand *(m^3/s)*
UD_s – undelivered demand of scenario *s* *(m^3/s)*
NN - number of nodes
$ND_{n,}$ - nodal demand at node *n* *(m^3/s)*
$C_{n,t,s}$ - consumption at node *n* for time phase *t* and in scenario *s* *(m^3/s)*

The maximum undelivered demand is computed by Eq. 3 considering a set of demand scenarios. The undelivered demand is determined by summing the difference between the required demand and the simulated delivered water for all network nodes, and for all time phases. Finally the last criterion is given by the carbon emissions arising from pipe construction and is explained in Eq. 4. This criterion is used because of the widely recognized importance of reducing carbon emissions, given that water networks contribute significantly to carbon emissions.

$$CE = \sum_{t=1}^{NPH}\left\{\sum_{i=1}^{NPI}\left(CEpipe_i(Dc_{i,t}) \times L_i\right)\right\} \tag{4}$$

CE – carbon emissions *($TonCO_2$)*
$CEpipe_i(Dc_t)$ - unit carbon emission of pipe *i* as function of the commercial diameter $Dc_{i,t}$ installed *($TonCO_2/m$)*

The carbon emissions computed by Eq. 4 are given by the total emissions for all the installed pipes over the planning horizon. The process described in [11] is used to compute the carbon emissions caused by constructing pipes the traditional way, for the available commercial pipe diameters. The emissions are calculated for the whole life cycle, including the extraction of raw materials, transport, manufacture, assembly, installation, disassembly, demolition and/or disposal.

2.2.2. Weights

Weighting of criteria is subjective and has a direct influence on the ranking of alternatives. There are two main methods of weighting criteria: ranking order methods (e.g. SIMOS [12]) or equal weights. The alternatives are quantitatively evaluated by Eqs 1 to 4. To compare the alternative performances qualitatively and combine them in a single common unit, weight factors are associated with criteria to represent the relative preference. For each criterion the decision maker's preference is given by a weight factor expressed as a value from 0 to 1, where 0 represents the least preferable and 1 the most preferable criterion. The sum of weights for all the criteria is equal to 1 (Eq. 5).

$$W_{sum} = \sum_{c=1}^{NC} W_c = 1 \tag{5}$$

W_{sum} – sum of weight factors
NC - number of criteria
W_c – weight factor of criterion c

2.2.3. Alternatives

A set of future demand scenarios for the phased planning horizon is used to handle demand growth uncertainty. After generating different demand scenarios, a particular set of reference scenarios is selected to represent the whole spectrum. Then the network is sized, using an optimization model to minimize the cost implementation of the phased design for each reference scenario that takes minimum pressure requirements into account. The corresponding results will be considered the alternative reference network designs.

2.3. Compute criteria

The criteria evaluation is given by Eqs 1 to 4 assuming the phased design scheme. The alternative reference network designs previously built will be evaluated for all the generated scenarios. The investment costs are found from the net present cost of the pipes to be installed, and the carbon emissions that are also function of the installed pipes. To identify the pressure deficits and the undelivered demand of the alternatives, a hydraulic simulator is used to compute the hydraulics of the network design alternatives for the set of demand generated scenarios.

2.4. Ranking alternatives

The objective here is to rank the network design alternatives and provide the decision maker with a comprehensive comparison between solutions. We can find the application of various multicriteria methods in the literature. We used Visual PROMETHEE [13] to rank the alternatives. This program is based on the PROMETHEE method [9]. The advantages of using PROMETHEE are reported in [10] and [2]. It is intuitive, auditable and is widely used in practice due to the mathematical properties and the particular friendliness of use. Furthermore, it has been successfully employed to solve real problems in water resources, environmental management and water infrastructures.

3. Application and results

3.1. Case study

The application of the method is illustrated by means of a case study based on the work of [14] to reinforce the New York tunnels water system. The network uses large diameter pipes and the reinforcement consists of increasing the capacity by constructing a pipeline parallel to the existing one to enable the systems to meet the increased water demands. The layout of the network can be found in [14].

The lack of capacity and the possible population increase confirm the need to reinforce the network. The original design assumed a single demand condition for which minimum heads had to be satisfied. The minimum heads for each node and the nodal demand are given in [14]. Current demand applied to the existing network shows that there are nodes with heads below the acceptable values. The original problem requires specifying the size of pipe diameters to meet the minimum head requirements, chosen from the set of 15 diameters in Table 1, and also the alternative of not duplicating the existing pipe. The cost and carbon emissions (in tonnes per meter) of the discrete diameters are also included in Table 1. The carbon emissions are those for traditional pipe construction per meter of pipe laid and computed according to the methodology proposed by [11]. Furthermore, we propose a phased design strategy for a planning horizon of 60 years. The traditional single phase design is replaced here by a three-phase design carried out over the 60 years, subdivided into 20-year phases.

The pipes' characteristics can be found in [14]. The Hazen-Williams coefficient of pipes is considered to decrease at a fixed rate of 2.5 per decade [15]. This rate depends on many factors and is also time dependent. But for simplification, a fixed rate was assumed for the entire planning horizon.

Table 1. Commercially available diameters

Diameter (mm)	Unit pipe cost (*USD*/m)	Reference diameter (inches)	Carbon emissions (tonnes CO_2/m)
0	0.00	0	0.0
914	306.75	36	0.4
1 219	439.63	48	0.6
1 524	577.43	60	1.0
1 829	725.07	72	1.3
2 134	875.98	84	1.8
2 438	1 036.75	96	2.8
2 743	1 197.51	108	3.3
3 048	1 368.11	120	4.5
3 353	1 538.71	132	6.1
3 658	1 712.60	144	9.7
3 962	1 893.04	156	13.5
4 267	2 073.49	168	18.9
4 572	2 260.50	180	26.4
4 877	2 447.51	192	37.0
5 182	2 637.80	204	51.7

3.2. Demand scenarios

The original problem consists of minimizing the construction costs of pipes considering a single demand pattern and minimum nodal heads that have to be satisfied. A different situation is considered here by using a set of demand patterns generated for three design phases. All demand patterns have the same initial value as the original case study, which is considered to be the year zero of the planning horizon. A set of 102 demand patters (Fig. 2) are detailed according to a demand increase between 0 and 10% per design phase of the planning horizon.

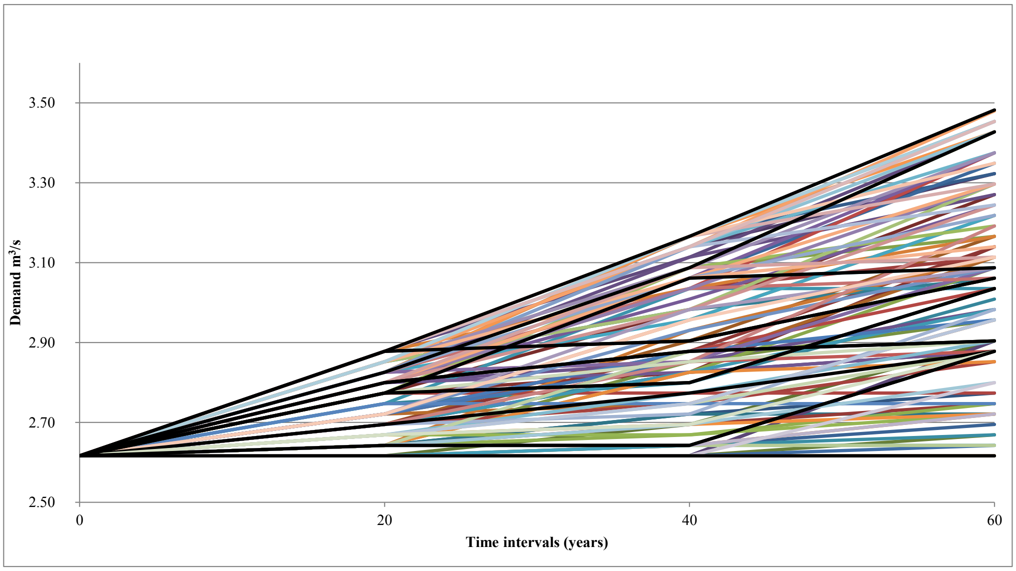

Figure 2: Demand growth patterns for a particular network node with a base demand equal to $2.62m^3/s$

The 102 scenarios are generated to test the hydraulic behaviour of the alternative network designs. In detail, one scenario with a constant demand increase of 10% is considered and represented by the top black line in Fig. 2. In this case the demand will increase 10% in the first phase, 10% in the second phase and 10% in the third phase. The total demand in the third phase grows into approximately 33%. Another particular scenario, with a zero demand growth, is considered and represented by the bottom black line in Fig. 2. There is no demand increment in this case, and the initial demand remains unchanged over the entire planning horizon. For the other 100 scenarios, the demand growth is randomly obtained and is assumed to be variable from phase to phase, but equal in terms of percentage of demand increase from node to node.

3.3. Network reinforcement alternatives

In the original network problem, pipe costs are minimized for a single demand scenario and considering minimum nodal heads that have to be satisfied. Here, we aimed to find alternative solutions for the network that satisfy the minimum nodal heads for the demand scenario considered in the original problem (year 0 of the planning horizon), but that also handle a 60-year planning horizon. Altogether 9 design alternatives are obtained considering the particular demand conditions, shown in Fig. 2 by black lines. These demand conditions are selected to represent the whole range of scenarios. The alternative designs for the network are obtained by using a simulated annealing method [16] to minimize the investment cost of designs. The design is subdivided in phases. At the first stage (year 0) it is necessary to install pipes (laid in parallel to existing pipes) to meet pressure constraints at this phase. For the subsequent phases, it may be necessary the increase network capacity due to demand growth and additional parallel pipes need to be installed to meet pressure constraints at these phases. The pressure constraints are verified with an EPANET extension for pressure-driven analysis [17] that simulate the hydraulics of the network. The solutions obtained for the 9 design alternatives are given in Table 2. The alternative designs include the pipe diameters (in mm) to be installed in each time interval, the pipe costs for each phase and the total cost for each design alternative. Alternative design 1 corresponds to the top black line demand pattern in Table 2 and has the highest cost. Alternative design 9 corresponds to the bottom black line demand pattern and has the lowest cost. The other 7 alternative designs are for the rest of the black line demand patterns. The network designs are optimized for these specific demand scenarios and thus the consideration of other scenarios would identify other alternatives.

3.4. Evaluation criteria

The investment costs and the carbon emissions criteria are computed by Eq. 1 and Eq. 4 for the pipes given by the design alternatives shown in Table 2. To evaluate the maximum pressure deficits and the maximum unsupplied water criterion, the design alternatives shown in Table 2 are tested with the set of all phased demand patterns in Fig. 2. The results are given in Table 3 to the 4 evaluation criteria valuations for each of the 9 network design alternatives. Design 1 is the most expensive but has no pressure deficits and no undelivered demand. Design 2 has the highest carbon emissions although construction costs are lower than design 1. Design 9 has the highest pressure deficits and undelivered demand but costs the least and has the lowest carbon emissions. All these design alternatives meet the minimum pressure requirements for the base nodal demand condition (year 0).

3.5. Ranking alternatives

We used a PROMETHEE method to address the problem of assigning the set of alternatives to define ranks according to the evaluation of criteria. To perform the MCDA, the weights have to be defined. The criteria weights can be determined based on decision makers' preferences and using appropriate procedures such as SIMOS [12]. The more important criteria are assigned greater weights. In this study we used three distinct weight sets (WS), as shown in Table 4. The WS1 has the same weights for all the criteria, thus all have the same importance. In WS2 the investment cost is the most important criterion and the carbon emissions the least important. In WS3 the unsupplied demand is the most important criterion and the investment costs and carbon emissions have the least importance.

The PROMETHEE method gives decision makers rankings for the alternatives. Three preference terms are computed to evaluate each alternative with respect to all the rest. The leaving flow (Phi+) is a measure of the strength of one alternative with respect to the rest. The entering flow (Phi-) measures the weakness of an alternative with respect to the rest. The net flow (Phi) measures the balance between (Phi+) and (Phi-) and each preference flow encourages a ranking in the set of alternatives. The best alternatives have high (Phi+) values (close to 1) and low (Phi-) values (close to 0) and thus a high positive net value (Phi).

Table 2: Network design alternatives for the case study

	Design 1			***Design 2***			***Design 3***		
Pipe	**Year 0**	**Year 20**	**Year 40**	**Year 0**	**Year 20**	**Year 40**	**Year 0**	**Year 20**	**Year 40**
1	0	0	3 658	0	0	1 219	0	0	0
2	0	0	3 048	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	5 182	0	5 182	5 182	0	0	2 438
13	4 572	4 572	4 572	0	0	5 182	0	5 182	5 182
14	4 267	4 267	4 267	4 572	4 572	4 572	2 438	2 438	2 438
15	4 267	4 267	4 267	4 572	4 572	4 572	4 267	4 267	4 267
16	2 134	2 134	2 134	2 438	2 438	2 438	2 438	2 438	2 438
17	2 743	2 743	2 743	2 743	2 743	2 743	2 743	2 743	2 743
18	2 743	2 743	2 743	2 438	2 438	2 438	2 438	2 438	2 438
19	1 829	1 829	1 829	2 134	2 134	2 134	2 134	2 134	2 134
20	0	0	0	0	0	0	0	0	0
21	2 438	2 438	2 438	2 134	2 134	2 134	2 134	2 134	2 134
Partial Costs	$ 78,486,848	$ -	$ 5,022,452	$ 63,437,724	$ 4,477,388	$ 4,359,635	$ 54,697,932	$ 8,844,676	$ 802,488
Total cost			**$ 83,509,295**			**$ 72,274,744**			**$ 64,345,097**

	Design 4			***Design 5***			***Design 6***		
Pipe	**Year 0**	**Year 20**	**Year 40**	**Year 0**	**Year 20**	**Year 40**	**Year 0**	**Year 20**	**Year 40**
1	0	0	0	3 353	3 353	3 353	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	914	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	3 658	1 219	1 219	1 219
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
13	0	0	4 267	0	0	0	0	0	4 572
14	4 267	4 267	4 267	0	2 743	2 743	0	1 829	1 829
15	4 267	4 267	4 267	5 182	5 182	5 182	5 182	5 182	5 182
16	2 438	2 438	2 438	2 438	2 438	2 438	2 743	2 743	2 743
17	2 743	2 743	2 743	2 743	2 743	2 743	2 743	2 743	2 743
18	2 134	2 134	2 134	2 134	2 134	2 134	2 438	2 438	2 438
19	1 829	1 829	1 829	1 829	1 829	1 829	2 134	2 134	2 134
20	0	0	0	0	0	0	0	0	0
21	2 134	2 134	2 134	2 134	2 134	2 134	2 134	2 134	2 134
Partial Costs	$ 59,544,632	$ -	$ 3,315,249	$ 54,311,340	$ 3,519,294	$ 1,043,998	$ 53,295,872	$ 2,128,660	$ 3,456,310
Total cost			**$ 62,859,878**			**$ 58,874,633**			**$ 58,880,842**

	Design 7			***Design 8***			***Design 9***		
Pipe	**Year 0**	**Year 20**	**Year 40**	**Year 0**	**Year 20**	**Year 40**	**Year 0**	**Year 20**	**Year 40**
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	3 658	3 658	3 658
8	0	0	0	0	0	0	0	0	1 524
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
13	0	2 743	2 743	0	0	0	0	0	0
14	0	0	4 267	0	0	5 182	0	0	0
15	4 572	4 572	4 572	3 658	3 658	3 658	0	0	0
16	2 134	2 134	2 134	2 134	2 134	2 134	2 438	2 438	2 438
17	2 438	2 438	2 438	2 743	2 743	2 743	2 438	2 438	2 438
18	2 438	2 438	2 438	2 134	2 134	2 134	2 438	2 438	2 438
19	1 524	1 524	1 524	1 829	1 829	1 829	2 134	2 134	2 134
20	0	0	0	0	0	0	0	0	0
21	2 134	2 134	2 134	2 134	2 134	2 134	1 829	1 829	1 829
Partial Costs	$ 44,773,344	$ 4,019,667	$ 2,777,972	$ 43,230,624	$ -	$ 3,534,114	$ 40,470,840	$ -	$ 459,069
Total cost			**$ 51,570,983**			**$ 46,764,737**			**$ 40,929,908**

Table 3: Evaluation criteria for the 9 alternative designs

Alternatives	Investment cost (USD)	Max. pressure deficits (m)	Max. undelivered demand (m^3/s)	Carbon emissions (Tonnes CO_2)
Design 1	83,509,295	0.000	0.000	2,483,992
Design 2	72,274,744	0.675	0.022	3,168,075
Design 3	64,345,097	8.856	0.258	1,948,213
Design 4	62,859,878	14.218	0.443	1,436,632
Design 5	58,874,633	22.128	0.680	1,321,623
Design 6	58,880,842	15.051	0.424	1,803,152
Design 7	51,570,983	34.236	1.061	1,151,789
Design 8	46,764,737	30.375	0.892	1,502,480
Design 9	40,929,908	51.328	1.503	391,878

Table 4: Weight sets for criteria

	Criteria			
Weight Sets	Investment cost	Pressure deficit	Unsupplied demand	Carbon emissions
WS1	0.25	0.25	0.25	0.25
WS2	0.35	0.20	0.30	0.15
WS3	0.15	0.20	0.50	0.15

The PROMETHEE ranking method is based on the net flow (Phi). It is used here taking linear preference functions [9] for all the four criteria evaluated. Given the alternatives, the criteria and the weights, the Visual PROMETHEE program [13] is implemented and the results are shown in Table 5.

Table 5: Alternative design rankings for three weight groups identified by Visual PROMETHEE [13]

	WS1				WS2				WS3			
Rank	Altern.	Phi	Phi+	Phi-	Altern.	Phi	Phi+	Phi-	Altern.	Phi	Phi+	Phi-
1	**Design 6**	0.101	0.156	0.055	**Design 6**	0.109	0.162	0.053	Design 3	0.162	0.212	0.051
2	Design 4	0.100	0.161	0.061	Design 3	0.083	0.172	0.089	Design 1	0.133	0.310	0.177
3	Design 3	0.087	0.172	0.084	Design 4	0.080	0.152	0.072	**Design 6**	0.133	0.172	0.039
4	Design 5	0.044	0.134	0.091	Design 5	0.033	0.129	0.096	Design 4	0.128	0.172	0.044
5	Design 8	0.001	0.166	0.165	Design 8	0.030	0.189	0.159	Design 2	0.118	0.297	0.180
6	Design 1	-0.073	0.221	0.294	Design 2	-0.044	0.215	0.258	Design 5	0.013	0.118	0.105
7	Design 9	-0.086	0.310	0.396	Design 7	-0.089	0.131	0.219	Design 8	-0.099	0.119	0.218
8	Design 2	-0.086	0.214	0.299	Design 9	-0.090	0.304	0.394	Design 7	-0.223	0.084	0.307
9	Design 7	-0.088	0.131	0.219	Design 1	-0.113	0.221	0.334	Design 9	-0.364	0.186	0.550

We can draw some conclusions from the results in Table 5. The best ranked alternative is network design 6 (in bold) for the WS1 and WS2. For WS3 the best ranked alternative is design 3 and design 6 is in the third position. In WS1, the results were obtained using the same weight to all criteria. Design 6 and design 4 have practically the same value of Phi and thus are preferred alternatives to implement. In WS2, the results were obtained with an investment cost weight of 0.35 (the highest weight). This can explain why the worst ranked design solution is the one with the highest cost (design 1). In WS3, the unsupplied demand was deemed the most important criterion and the worst ranked solution, design 9, has the highest undelivered demand (1.503 m^3/s). In fact, the objective is to choose a solution that minimizes all criteria which makes network design 6 the best compromise between the criteria. Comparing design 6 with the other designs, it can be seen, from table 3, that the investment cost (USD 58,880,842) is midway between the cheapest (design 9) and the most expensive (design 1). In terms of undelivered demand (0.424m^3/s) and pressure deficits (15.051m), these values are similar to design 4, which has a higher investment cost (USD 62,859,878) and finally, in terms of carbon emissions, design 6 (1,803,152TonCO_2) is high compared with design 5 (1,321,623TonCO_2), which has a similar investment cost.

The alternatives for the water network design were defined in a phased reinforcement scheme. The design alternative (design 6) has highest value of (Phi) for two weight sets and if implemented, the network interventions that have to be made now (year 0) are to construct parallel pipes in the network links: 7, 15, 16, 17, 18, 19 and 21. In the next stages more two network links (13, 14) are projected to be reinforced. However, this will depend on future circumstances. The phased intervention scheme makes it possible to review the process and take better decisions as new information becomes available.

4. Conclusions

This work presents an MCDA for the phased design reinforcement of water distribution networks. The proposed methodology includes 4 criteria and 9 decision alternatives. The framework includes a PROMETHEE method solved by Visual PROMETHEE to rank the alternatives. The application of the methodology was illustrated in a case study to highlight the most important steps of the MCDA process. For the case study, results show that the favoured alternative is design 6 for weight sets WS1 and WS2. For the weight set WS3, design 6 is ranked on the third position. Design 6 has an investment cost of USD 58,880,842, but relatively low pressure deficits (15.051m) and unsupplied demand (0.424m^3/s). Visual PROMETHEE proved to be able to handle with this problem. This methodology can be very useful to help water utilities identify the best ranked strategies when intervention in water networks is required. Future work will focus on an enhanced sensitivity analysis of the results and comparisons between the results obtained by a traditional design and the phased design scheme proposed here.

Acknowledgements

This paper is based on research conducted under the DESAFIO project (www.desafioglobal.org). DESAFIO is funded by the Seventh Framework Programme of the European Union for research, technological development and demonstration under grant agreement no. 320303. The information contained in this work reflects only the opinion of the authors and the European Union is not responsible for the use which may be made of the information contained therein.

References

[1] S.J.T. Pollard, J.E. Strutt, B.H. Macgillivray, P.D. Hamilton, S.E. Hrudey, Risk Analysis and Management in the Water Utility Sector, Process Saf. Environ. Prot. 82 (2004) 453–462.
[2] H.E. Mutikanga, S.K. Sharma, K. Vairavamoorthy, Multi-criteria Decision Analysis: A Strategic Planning Tool for Water Loss Management, Water Resour. Manag. 25 (2011) 3947–3969.
[3] R. Baur, P. Le Gauffre, S. Saegrov, Multi-criteria decision support for annual rehabilitation programmes in drinking water networks, 3 (2003) 43–50.
[4] L. Scholten, A. Scheidegger, P. Reichert, M. Mauer, J. Lienert, Strategic rehabilitation planning of piped water networks using multi-criteria decision analysis., Water Res. 49 (2014) 124–43.
[5] J. Marques, M. Cunha, D. Savić, Using Real Options in the Optimal Design of Water Distribution Networks, J. Water Resour. Plan. Manag. 141 (2015) 04014052.
[6] K. Yoon, A Reconciliation Among Discrete Compromise Solutions, J. Oper. Res. Soc. 38 (1987) 277–286.
[7] B. Roy, Classement et choix en présence de points de vue multiples, RAIRO - Oper. Res. - Rech. Opérationnelle. 2 (n.d.) 57–75.
[8] R.W. Saaty, The analytic hierarchy process—what it is and how it is used, Math. Model. 9 (1987) 161–176.
[9] J.P. Brans, P. Vicke, A PREFERENCE RANKING ORGANISATION METHOD, Manage. Sci. 31 (1985) 647–657.
[10] M. Behzadian, R.B. Kazemzadeh, A. Albadvi, M. Aghdasi, PROMETHEE: A comprehensive literature review on methodologies and applications, Eur. J. Oper. Res. 200 (2010) 198–215.
[11] J. Marques, M. Cunha, D.A. Savić, Using real options for an eco-friendly design of water distribution systems, J. Hydroinformatics. 17 (2015) 20.
[12] J. Figueira, B. Roy, Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure, Eur. J. Oper. Res. 139 (2002) 317–326.
[13] Y. Mareschal, B. and De Smet, Visual PROMETHEE: Developments of the PROMETHEE & GAIA multicriteria decision aid methods, in: Ind. Eng. Eng. Manag. 2009. IEEM 2009. IEEE Int. Conf., 2009: pp. 1646–1649.
[14] J.C. Schaake, D. Lai, Linear programming and dynamic applications to water distribution network design, 1969.
[15] D.W. and S.D. DWSD, Summary Report - Comprehensive Water Master Plan, Detroit, 2004.
[16] J. Marques, M.C. Cunha, J. Sousa, D. Savić, Robust optimization methodologies for water supply systems design, Drink. Water Eng. Sci. Discuss. 5 (2012) 173–192.
[17] M.S. Morley, C. Tricarico, Pressure Driven Demand Extension for EPANET (EPANETpdd), 2008.