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# Using Real Options for an Eco-friendly Design of Water Distribution Systems

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*This paper presents a real options approach to handle uncertainty during the entire life cycle of water distribution systems design. Furthermore, carbon emissions associated with the installation and operation of water distribution networks are considered. These emissions are computed by taking an embodied energy approach to the different materials used in water networks. A simulated annealing heuristic is used to optimize a flexible eco-friendly design of water distribution systems for an extended life horizon. This time horizon is subdivided into different time intervals in which different possible decision paths can be followed. The proposed approach is applied to a case study and the results are presented according to a decision tree. Lastly, some comparisons and results are used to demonstrate the quality of the results of this approach.*

*Keywords: carbon emissions, optimization, real options, simulated annealing, uncertainty, water distribution networks,*

## 31 **1 Introduction**

32 Water supply and distribution systems represent a major investment for a  
33 society, whether it is in the construction of new systems or the maintenance and  
34 rehabilitation of ageing infrastructure. For example, the cost of replacing ageing water  
35 infrastructure in the USA could reach more than \$1 trillion over the next few decades  
36 (AWWA 2012). These systems also have to cope with future uncertainties, including  
37 growing populations, shifting consumption patterns and a climate change. Therefore,  
38 constructing and maintaining water infrastructure with the aim of improving reliability  
39 and reducing costs, is a difficult task and this is compounded by a number of associated  
40 environmental issues that should be addressed.

41 Concern about global warming is increasing. Nations will need to act to  
42 dramatically reduce greenhouse gas emissions (GHG), specifically those countries that  
43 have signed and ratified the Kyoto Protocol of 2009. 192 countries follow this protocol  
44 and have to limit and reduce carbon emissions over the coming decades. In Portugal, the  
45 most polluting industry is the electricity generation sector, based on (ERSE 2012).  
46 Between 2005 and 2010, this sector was responsible for 55% of total carbon emissions.

47 In this paper we propose an approach that both handles environmental impacts,  
48 and tries to find appropriate flexible solutions for the design and operation of water  
49 distribution systems. McConnell (2007) defined system flexibility as “the ability for a  
50 system to actively transform, or facilitate a future transformation, to better anticipate or  
51 respond to changing internal or external conditions”. These problems are challenging  
52 and very difficult to solve. The real options (ROs) approach could be very useful in this  
53 field. Black & Scholes (1973) and Merton (1973) are the works that define and solve

54 the financial option valuing problem. Inspired by them, Myers (1977) introduced ROs.  
55 This approach permits flexible planning, thus allowing decision makers to adjust  
56 investment according to new future information. ROs has already been utilized for:  
57 designing maritime security systems (Buurman *et al.* 2009); finding the optimal  
58 capacity for hydropower projects (Bockman *et al.* 2008); dam project investments  
59 (Michailidis & Mattas 2007); constructing a parking garage (De Neufville *et al.* 2006),  
60 and designing satellite fleets (Hassan *et al.* 2005). However, there are very few papers  
61 where ROs concepts are applied to water infrastructure: Woodward *et al.* (2011) used  
62 ROs for flood risk management and Zhang & Babovic (2012) used it for decision  
63 support in the design and management of a flexible water resources framework through  
64 innovative technologies. We propose a real options approach to define the design of  
65 water distribution networks under different possible future conditions and taking carbon  
66 emissions in to account.

67         Several definitions are being used for direct and indirect carbon emissions. Alker  
68 et al. (2005) makes the distinction between direct emissions, i.e. those from sources that  
69 are owned or controlled by water companies, and indirect emissions, which are a  
70 consequence of the activities of the water company but that occur at sources owned or  
71 controlled by another company and generated away from the water infrastructure site. In  
72 water supply systems, the source of a direct emission would be the excavation works for  
73 traditional pipe installation, because this process is under the water company's direct  
74 control. An indirect emission source would be the pipe manufacturing process, because  
75 this is controlled by another company.

76         In the last decade, objectives focused on environmental issues have started to  
77 feature in water distribution networks optimization works. The key work by Filion *et al.*,

78 (2004) has been followed by a vast body of literature. Some works analysed and  
79 compared the carbon emissions with different pipe material instalation (e.g. Dandy *et al.*  
80 (2006) and Shilana (2011)) in a single objective framework.

81 Wu *et al.* (2008) was the first work to introduce the goal of minimizing  
82 greenhouse gas emissions into the multiobjective optimal design of water networks. The  
83 works of Wu *et al.* (2010), Wu *et al.* (2011) and Wu *et al.* (2013) report some  
84 developments and comparisons based on the multiobjective approach.

85 Herstein *et al.* (2009) take the idea of concentrating diferent environmental  
86 impacts in a single measure and present an index-based method to evaluate the  
87 environmental impacts of water distribution systems. This environmental index aims to  
88 agregate multiple environmental measures calculated by an economic input-output life-  
89 cycle assessment model. However, some criticism of this methodology has emerged  
90 (Herstein and Filion, 2011a). Herstein *et al.* (2010) and Herstein and Filion (2011b)  
91 include different optimization models to minimize this index.

92 Water distribution networks are usually planned and constructed to be operated  
93 over a long planning horizon and so annual operating costs should be discounted.  
94 MacLeod and Filion (2011) and Roshani *et al.* (2012) study the effect of reducing  
95 carbon emission pricing and discount rates on the design and operation of water  
96 distribution networks. Finally, Oldford and Filion (2013) have reviewed the policy and  
97 research initiatives that have been used to incorporate environmental impacts in the  
98 design and optimization of water distribution systems. The aim is to develop a  
99 regulatory framework to limit these impacts during the design and operation of a water  
100 distribution system.

101           Our approach calculates carbon emissions using a different procedure. In the  
102 literature, carbon emissions associated with pipe installation only include those related  
103 to pipe manufacturing. In our work, emissions are calculated by considering the  
104 manufacturing of pipes and by computing the emissions of other materials required for  
105 pipe installation. The emissions from tank construction are also computed and carbon  
106 emissions from energy consumption are calculated for the whole of the planning  
107 horizon.

108           The remainder of this paper is organized as follows: section 2 sets out a  
109 methodology to compute the carbon emissions of a water network; next, the decision  
110 model is built, and then a case study is presented to examine the application of the  
111 methodology and to show some results. Finally, some comparisons are made and  
112 conclusions drawn.

## 113   **2 Carbon emissions of water distribution systems**

114   To incorporate carbon emission costs in the design and operation of the water networks  
115 it is necessary to quantify emissions from the very beginning of the extraction of the  
116 materials that are used until their final disposal. Water distribution infrastructure is built  
117 from and maintained with a range of materials. The most common are the steel used in  
118 pipes, accessories and pumps; reinforced concrete in civil construction works like tanks,  
119 manholes and anchorages; plastic in pipes and accessories; aggregates in pipeline  
120 backfill and asphalt for repaving. The carbon emissions of these materials can only be  
121 evaluated if the whole life cycle is involved, which includes the extraction of the raw  
122 material, transport, manufacturing, assembling, installation, dismantling, demolition  
123 and/or decomposition. The embodied energy is determined by the sum of the energy

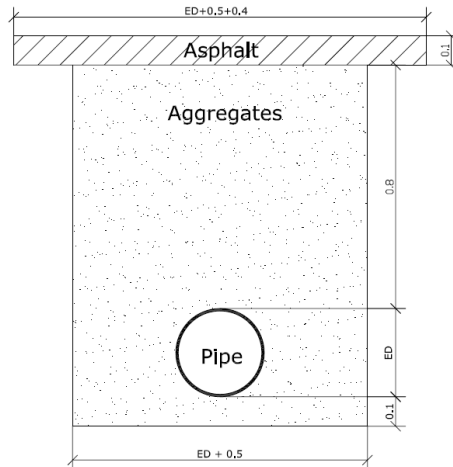
124 sources (fuels, materials, human resources and others) that are used for product  
125 manufacturing and its use. The embodied energy tries to compute the sum of the total  
126 energy expended during all the life cycle of the product. Hammond & Jones (2008)  
127 present the embodied energy for the life cycle of some materials. Table 1 shows the  
128 embodied energy of the most common materials used in water distribution  
129 infrastructure.

130 **Table 1:** Embodied energy of some materials used in water infrastructure

Material	Embodied energy	
	Mj/kg	KWh/kg
Ductile iron for pipes	34.40	9.56
Aggregates	0.11	0.03
Asphalt	6.63	1.84
Concrete	2.91	0.81
Structural steel	28.67	7.96

131

132 From the data collected from Hammond & Jones (2008) and presented in table  
133 1, it is possible to compute the total amount of embodied energy needed to build new  
134 pipes and reservoirs. The quantities of materials needed for pipeline installation are  
135 computed based on the scheme in Fig. 1. Some simplifications are assumed. The  
136 embodied energy to build the water network is determined from five materials: pipe  
137 material; aggregates to backfill pipes; asphalt for repaving, concrete and structural steel  
138 to build tanks. The units are expressed in KWh of energy per kg of material used.



139  
140

**Figure 1:** Scheme to compute quantities of materials (dimensions in meters)

141 To determine the embodied energy of pipe construction in the traditional way,  
142 the quantity of energy per meter of pipe is considered. The weight of the materials used  
143 to settle one meter of pipe must therefore be determined. Given the scheme in Fig. 1, we  
144 can calculate the volume of aggregates and asphalt needed for the settlement of each  
145 meter of pipe. The quantity of materials per meter is a function of the pipe's external  
146 diameter ( $ED$ ), since the excavation and repaving volumes increase the higher the pipe  
147 diameter  $ED$ . We assume ductile iron pipes and Eq. 1 is used to compute the embodied  
148 energy of the material:

$$EE_{pipe_{Dc}} = WDc \times EE_{iron} \quad (1)$$

149  
150

Where:

151  $EE_{pipe_{Dc}}$  - embodied energy of the pipe with commercial diameter  $Dc$

152 ( $KWh/m$ );

153  $WDc$  - weight of the commercial diameter  $Dc$  ( $kg/m$ );

154  $EE_{iron}$  - embodied energy of the ductile iron for pipes ( $KWh/kg$ ).

155 The quantities of aggregate are a function of the commercial diameter that is to  
156 be used. The width of the trench is to the same as the external diameter of the pipes plus  
157 0.5 m. The walls of the trench are assumed to be vertical and the entire trench is filled  
158 with aggregate. Based on this, the quantity of embodied energy of aggregates is  
159 computed by Eq. 2:

$$EE_{aggr_{Dc}} = \left\{ [(0.5 + ED_{Dc}) \times (0.1 + ED_{Dc} + 0.8)] \times 1 - \left( \frac{\pi \times ED_{Dc}^2}{4} \right) \times 1 \right\} \times W_{aggr} \times EE_{aggr} \quad (2)$$

161

162 Where:

163  $EE_{aggr_{Dc}}$  - embodied energy of aggregates to backfill a pipe with  
164 diameter  $Dc$  ( $KWh/m$ );

165  $ED_{Dc}$  - external diameter of the pipe with diameter  $Dc$  ( $m$ );

166  $W_{aggr}$  - weight of aggregates, equal to 2240 ( $kg/m^3$ );

167  $EE_{aggr}$  - embodied energy of the material ( $KWh/kg$ ).

168 Finally, the last material is asphalt. 0.2 m is assumed for the extra paving of each  
169 side of the trench. The embodied energy is computed by Eq. 3:

$$EE_{asphalt_{Dc}} = \left\{ [(0.5 + ED_{Dc}) + 0.2 + 0.2] \times 0.1 \times 1 \right\} \times W_{asphalt} \times EE_{asphalt} \quad (3)$$

170

171 Where:

172  $EE_{asphalt_{Dc}}$  - embodied energy of asphalt ( $KWh/m$ );

173  $W_{asphalt}$  - weight of the asphalt, equal to 2300 ( $kg/m^3$ );

174  $EE_{asphalt}$  - embodied energy of asphalt ( $KWh/kg$ ).

175 To determine the total embodied energy (Eq. 4) per meter of installed pipe, Eqs  
176 1, 2 and 3 are added together:



$$EE_{total_{Dc}} = EE_{pipes_{Dc}} + EE_{aggr_{Dc}} + EE_{asphalt_{Dc}} \quad (4)$$

177

178 Where:

179  $EE_{total_{Dc}}$  - total embodied energy of pipe installation ( $KWh/m$ ).

180 Now the embodied energy can be computed for the different commercial  
181 diameters, considering the contribution of the ductile iron pipes, aggregate to backfill  
182 the pipe and asphalt for repaving. The carbon emissions related to the total embodied  
183 energy can be computed through Eq. 5:

$$CE_{pipe_{Dc}} = EE_{total_{Dc}} \times CET \quad (5)$$

184

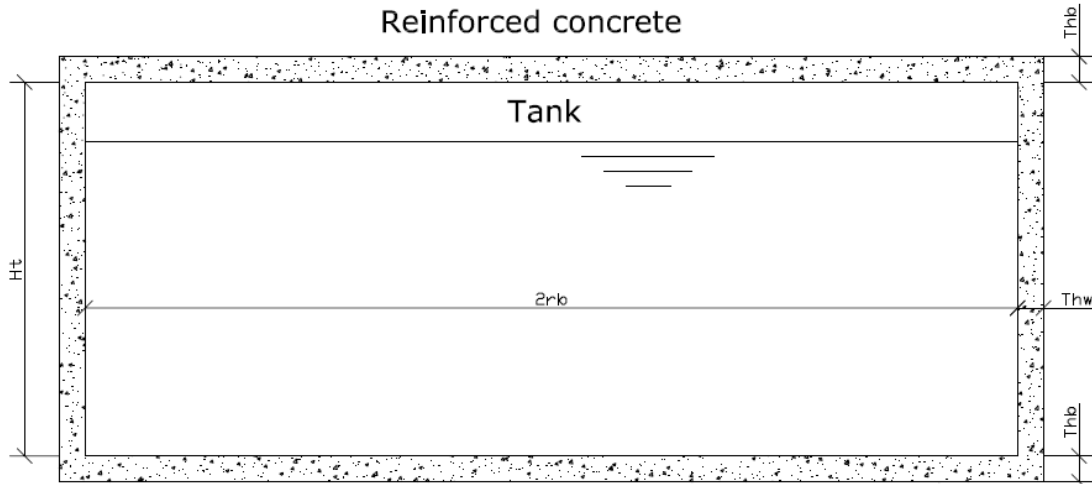
185 Where:

186  $CE_{pipe_{Dc}}$  - carbon emissions of installing pipes with commercial  
187 diameter  $Dc$  ( $tonCO_2/m$ );

188  $CET$  - total carbon emissions from energy generation ( $tonCO_2/KWh$ ).

189 Carbon emissions are computed assuming a value of  $CET=0.637 \times 10^{-3}$  tonCO2  
190 per KWh of energy produced by non-renewable means and obtained by a fuel mix of  
191 58% coal, 20% natural gas, 13% oil, 5% diesel and 4% of other means. This is a mean  
192 value of the carbon emissions of electricity generation sector by non-renewable means  
193 between 2005 and 2010 in Portugal (ERSE 2012).

194 This work also considered the carbon emissions related to the installation of new  
195 tanks in the network. New tanks are assumed to be cylindrical and have the same  
196 transversal area of 500 m<sup>2</sup>. For simplification, the walls and the slabs of the tanks are  
197 assumed to have the same thickness, Fig. 2:



198  
199

**Figure 2:** Scheme for computing the concrete used in tank construction

200 The amount of concrete is a function of the volume of the tank. The thickness of  
201 the slabs and the walls is taken to be  $Th_b = Th_w = 0.35$  m and the inner radius of the tank  
202 is  $r_b = 12.62$  m. Based on these conditions the quantity of embodied energy of concrete  
203 is computed by Eq. 6:

$$EET_{concrete,t} = \left[ \pi \times (r_b + Th_w)^2 \times Th_b \times 2 + \pi \times Ht_t \left\{ (r_b + Th_w)^2 - r_b^2 \right\} \right] \times W_{concrete} \times EE_{concrete} \quad (6)$$

204

205 Where:

206  $EET_{concrete,t}$  - embodied energy of concrete of the tank  $t$  (KWh);

207  $r_b$  - radius of the slab of the tank, 12.62 (m);

208  $Th_w$  - thickness of the walls of the tank, 0.35 (m);

209  $Th_b$  - thickness of the slabs of the tank, 0.35 (m);

210  $Ht_t$  - height of the tank (m);

211  $W_{concrete}$  - weight of concrete, 2500 (kg/m<sup>3</sup>);

212  $EE_{concrete}$  - embodied energy of concrete (KWh/kg).

213 The embodied energy of reinforcing steel bars for the concrete of the tanks is  
214 also considered. For this study, the quantity of steel is taken to be a percentage of the  
215 cubic meters of concrete used in civil construction works, so the embodied energy of  
216 this material is given by Eq. 7:

$$EET_{steel_t} = \left[ \pi \times (r_b + Th_w)^2 \times Th_b \times 2 + \pi \times Ht_t \left\{ (r_b + Th_w)^2 - r_b^2 \right\} \right] \times Q_{steel} \times EE_{steel} \quad (7)$$

217

218 Where:

219  $EET_{steel_t}$  - embodied energy of steel bars to build the tank  $t$  (KWh);

220  $Q_{steel}$  - quantity of steel per cubic meter of concrete, 100 (kg/m<sup>3</sup>);

221  $EE_{steel}$  - embodied energy of steel bars (KWh/kg).

222

223 Summing the values given by Eq. 6 and 7, the carbon emissions derived from  
224 constructing the tanks are determined through Eq. 8:

$$CETK_t = (EET_{concrete_t} + EET_{steel_t}) \times CET \quad (8)$$

225

226 Where:

227  $CETK_t$  - carbon emissions of the tank  $t$  (tonCO<sub>2</sub>).

228

229 In addition to the above, significant carbon emissions also arise from generating  
230 the electric energy consumed during the water infrastructure operation. Large amounts  
231 of energy are consumed resulting in important carbon emissions that should be  
232 measured by Eq. 9:

$$CE_{op} = EC \times CET \quad (9)$$

233

234           Where:  
235                      $CE_{op}$  - carbon emissions from energy used in the operation of the  
236                     network ( $tonCO_2$ );  
237                      $EC$  - energy consumption of the network during the operation ( $KWh$ ).

238  
239           Eq. 9 computes carbon emissions generated by network operation. This work  
240           does not take into account carbon emissions related to other network elements that are  
241           negligible when compared with pipe and tank construction.

242           By adding together the individual contributions of pipes, tanks and energy  
243           consumption we can determine the cost in terms of total carbon emissions of the water  
244           network life cycle. This cost is included in the optimization model presented in the next  
245           section.

### 246   **3 Optimization model**

247           Many scenarios are possible over the life cycle of a water distribution  
248           infrastructure. The future operating conditions of the water networks are uncertain.  
249           However, decisions have to be made and there are some constraints that further increase  
250           the complexity of the problem. The optimization of a water distribution network is very  
251           complex because the objective is to find a good solution within an enormous solution  
252           space. Furthermore, the decision variables are normally discrete, which makes it even  
253           harder to find optimum solutions.

254           The approach we describe uses ROs to handle different possible scenarios that  
255           can occur during the life cycle of the infrastructure. According to Wang *et al.* (2004),

256 the ROs approach has two stages: option identification and option analysis. Option  
 257 identification consists of trying to find all possible scenarios for the lifetime horizon.  
 258 The option analysis stage can use an optimization model to find possible solutions. This  
 259 formulation enables decision makers to include additional possible situations  
 260 simultaneously and to develop different decision plans throughout the life cycle.

261 The objective function,  $OF$ , includes the minimization of the costs and carbon  
 262 emissions resulting from implementing and operating the network. The objective  
 263 function is presented in expression 10:

$$OF = Min \ C_{initial} + \sum_{s=1}^{NS} \sum_{t=2}^{NTI} \left( C_{future_{t,s}} \cdot \prod_{nt=1}^t prob_{nt,s} \right) + \left[ CE_{initial} + \sum_{s=1}^{NS} \sum_{t=2}^{NTI} \left( CE_{future_{t,s}} \cdot \prod_{nt=1}^t prob_{nt,s} \right) \right] \cdot CEC \quad (10)$$

264 Where:

265  $C_{initial}$  - cost of the initial solution to be implemented in year zero;

266  $NS$  - number of scenarios;

267  $NTI$  - number of time intervals into which the life cycle is subdivided;

268  $C_{future_{t,s}}$  - future design costs for time  $t$  in scenario  $s$ ;

269  $Prob_{nt,s}$  - probability of future design in time  $nt$  in scenario  $s$ ;

270  $CE_{initial}$  - carbon emissions of the initial solution to be applied in year  
 271 zero;

272  $CE_{future_{t,s}}$  - carbon emissions for time  $t$  in scenario  $s$ ;

273  $CEC$  - carbon emissions cost.

274 The objective function given by Eq. 10 has to find the first stage solution,  $T=1$ ,  
 275 and future decisions to implement. The objective function is given by the sum of  
 276 different terms. The initial solution cost is given by Eq. 11:

$$C_{initial} = \left( \sum_{i=1}^{NPI} (C_{pipe_i}(D_{i,l})L_i) + \sum_{t=1}^{NT} CT_t + \sum_{i=1}^{NPI} (C_{reab_i}(D_{i,l})L_i) + \sum_{j=1}^{NPU} (CEps_{j,l}) \right) + \left( \sum_{d=1}^{NDC} \left( Ce_d \cdot \sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,d,l} \cdot HP_{j,d,l}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot \frac{(1+IR)^{NY_i} - 1}{IR \cdot (1+IR)^{NY_i}} \right) \quad (11)$$

277 Where:

278  $NPI$  - number of pipes in the network;

279  $C_{pipe_i}(D_{i,l})$  - unit cost of pipe  $i$  as function of the diameter  $D_{i,l}$  adopted;

280  $D_{i,l}$  - diameter of pipe  $i$  installed in time interval  $T=l$ ;

281  $L_i$  - length of pipe  $i$ ;

282  $NT$  - number of new tanks in the network;

283  $CT_t$  - cost of tank  $t$ ;

284  $C_{reab_i}(D_{i,l})$  - unit cost to rehabilitate existing pipe  $i$  as a function of  
285 diameter  $D_{i,l}$ ;

286  $NPU$  - number of pumps in the network;

287  $CEps_{j,l}$  - equipment cost of pump  $j$  for time interval  $T=l$ ;

288  $NDC$  - number of demand conditions considered for the design;

289  $Ce_d$  - cost of energy for demand condition  $d$ ;

290  $\gamma$  - specific weight of water;

291  $QP_{j,d,l}$  - discharge of pump  $j$  for demand condition  $d$  and time interval  
292  $T=l$ ;

293  $HP_{j,d,l}$  - head of pump  $j$  for demand condition  $d$  and time interval  $T=l$ ;

294  $\eta_j$  - efficiency of pump  $j$ ;

295  $\Delta t_d$  - time in hours for demand condition  $d$ ;

296  $IR$  - annual interest rate for updating the costs;

297  $NY_t$  - number of years under the same conditions considered for time  
 298 interval  $T=I$ .

299 The term  $C_{initial}$  (Eq. 11) computes the network cost for the first stage. This  
 300 term is given by the sum of the cost of pipes, the cost of the tanks, the rehabilitation cost  
 301 of the existing pipes, the cost of new pumps and the present value energy cost. The  
 302 pump cost is given by Eq. 12:

$$CEps = 700473.4Q^{0.7}H_m^{0.4} \quad (12)$$

303 Where:

304  $CEps$  - cost of the pump;

305  $Q$  - flow of pump ( $m^3/s$ );

306  $H_m$  - head of pump ( $m$ ).

307 The other term of the objective function is given by the weighted sum of the  
 308 future costs. The future cost is computed by Eq. 13:

$$C_{future_{t,s}} = \left( \sum_{i=1}^{NPI} (C_{pipe_i}(D_{i,t,s})L_i) \cdot \frac{1}{(1+IR)^{Y_i}} + \sum_{j=1}^{NPU} (CEps_{j,t,s}) \cdot \frac{1}{(1+IR)^{Y_i}} + \left( \sum_{d=1}^{NDC} \left( C_{e_d} \cdot \sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,d,t,s} \cdot HP_{j,d,t,s} \cdot \Delta t_d}{\eta_j} \right) \cdot 365 \cdot \frac{(1+IR)^{NY_i} - 1}{IR \cdot (1+IR)^{NY_i}} \right) \cdot \frac{1}{(1+IR)^{Y_i}} \right) \quad (13)$$

309 The future cost is computed for all time intervals beginning at  $T=2$  (the cost is  
 310 already computed for the first time interval) and is given as the sum of three terms. The  
 311 first term computes the present value cost of the pipes to be laid in the different time  
 312 intervals and scenarios, the second term computes the present value equipment cost of

314 the pumps for the different time intervals and for the different scenarios, and finally the  
 315 third term computes the present value of energy cost for each scenario.

316 The sum of the initial and the future costs give the network cost for the entire  
 317 time horizon, considering future uncertainty. Looking at events on statistically  
 318 independent decision nodes, the probabilities for the different scenarios can be  
 319 computed by the product of the probabilities of the decision nodes in each path for all  
 320 the time periods.

321 Finally, a term to compute the environmental impacts of the water supply system  
 322 is also added. This term is computed as the sum of two terms multiplied by the carbon  
 323 emission cost, *CEC*. These terms are introduced in Eqs 14 and 15.

$$CE_{initial} = \left( \sum_{i=1}^{NPI} (CE_{pipe}(D_{i,1})L_i) + \sum_{t=1}^{NT} CETK_t + \sum_{d=1}^{NDC} \left( CET \cdot \sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,d,1} \cdot HP_{j,d,1}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot NY_1 \right) \quad (14)$$

$$CE_{future_{t,s}} = \left( \sum_{i=1}^{NPI} (CE_{pipe}(D_{i,t,s})L_i) + \sum_{d=1}^{NDC} \left( CET \cdot \sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,d,t,s} \cdot HP_{j,d,t,s}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot NY_t \right) \quad (15)$$

324 Eq. (14) computes the total carbon emissions for the first operation period and Eq.  
 325 (15) computes the carbon emissions for the different future scenarios weighted by their  
 326 probability of occurrence. The initial carbon emissions are calculated by adding together  
 327 the carbon emissions related to the pipe installation, tank construction and energy  
 328 consumption. The carbon emissions in the future scenarios are computed using a similar  
 329 procedure. These emissions are multiplied by the unit carbon emission cost *CEC*. It

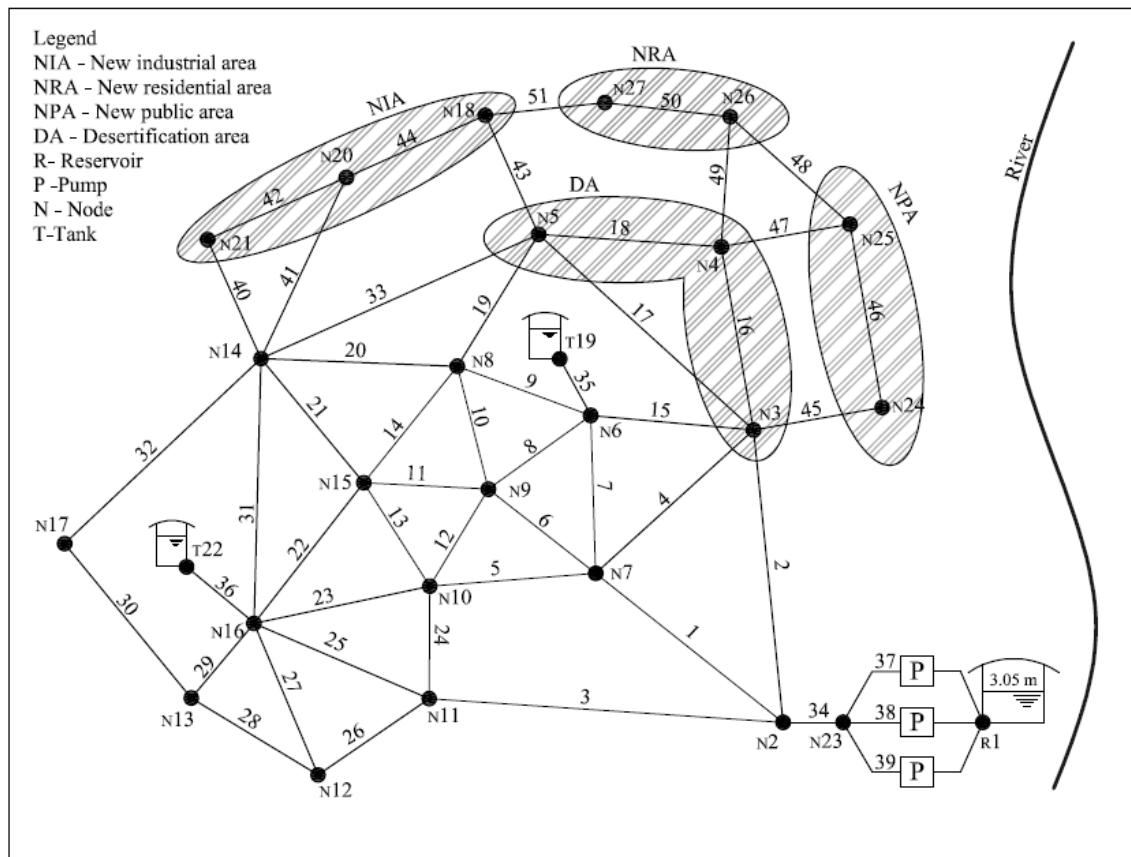


330 should be noted that the carbon emissions costs are not updated. A zero discount rate  
331 should be used for carbon emissions (Wu *et al.* 2010). This is complies with the  
332 recommendation of the Intergovernmental Panel on Climate Change (IPCC). High  
333 carbon emissions degrade air quality and thus it seems prudent and ethical to think  
334 about future generations and assign the same importance (or value) to the carbon  
335 emissions of today as well as those in future. A zero discount rate implies the same  
336 weight for current and future costs.

337         The objective function represents the network cost for the entire time horizon.  
338 Some decisions have to be taken now, but others can be delayed until such time as  
339 future uncertainties are determined. The ROs framework enables water infrastructure to  
340 be designed with some decisions postponed to a future date.

#### 341 **4 case study**

342 A well-known water network was used to demonstrate the application of the ROs  
343 approach. The case study was based on a hypothetical network inspired by Walski *et al.*  
344 (1987). The network aims to represent an old town, small in size, Fig. 3.



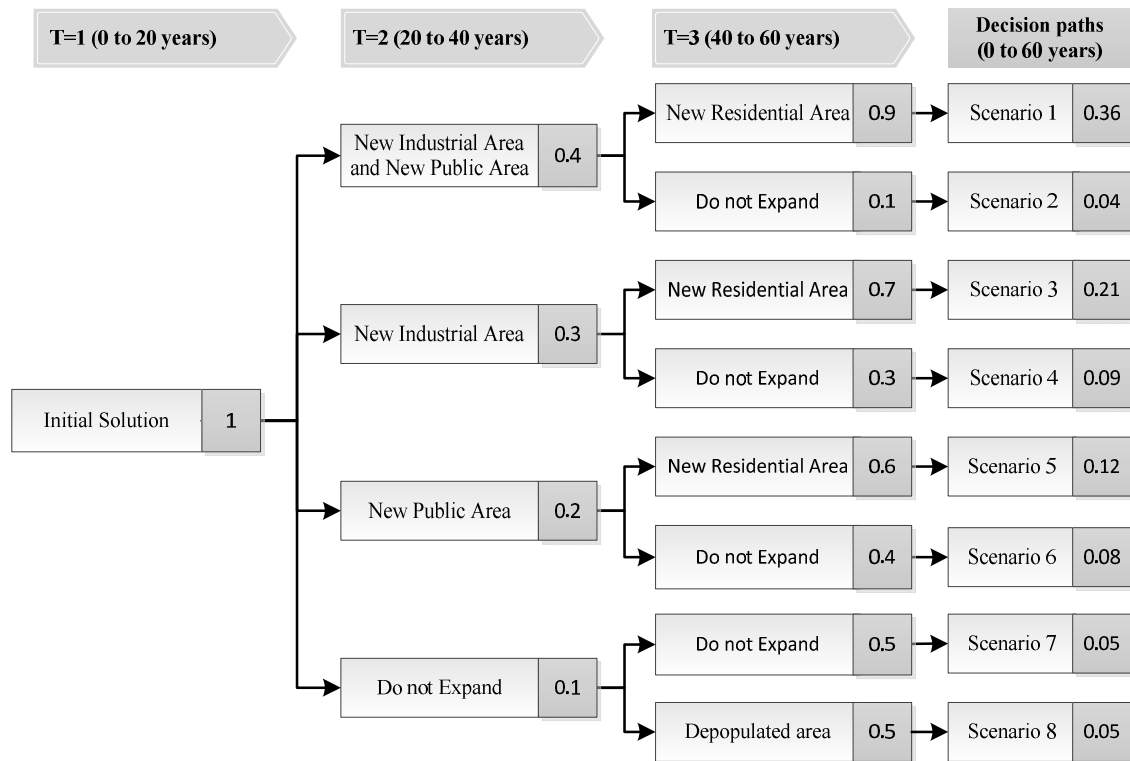
345

346 **Figure 3:** Scheme of the network (inspired from Walski *et al.* 1987)

347 Fig. 3 shows a water distribution network planned for the next 60 years.  
 348 However, this planning horizon is subdivided into 3 time intervals of 20 years. In the  
 349 first 20 years of operation, some decisions have to be made. The water company is held  
 350 to need to improve the network capacity to satisfy future demand during the first 20-  
 351 year time interval. However, 8 different possible future scenarios could be considered,  
 352 as shown in Fig 4.

353 This work considers a number of expansion areas. For T=2 the authorities are  
 354 planning to build a new industrial area (NIA) and a new public services area (NPA)  
 355 with some facilities near the river, so in this time interval the network may be extended  
 356 to those two areas. For T=3 it is predicted that a new residential area (NRA) may be  
 357 developed close to the industries and public services, because of the labour required by

358 the new industries and the public services facilities. However, if these areas are not built  
 359 the area near the river may see a decline in population and the water consumption could  
 360 fall to 75%. The areas in question are shown in Fig. 3.



361

362 **Figure 4:** Decision tree and probabilities of occurrence for the life cycle

363 Finally, the probabilities for each path of the different scenarios should be  
 364 indicated. The probabilities for the different paths of the systems for the case study are  
 365 shown in Fig. 4. The probabilities of the scenarios are computed by the product for all  
 366 the time periods of the decision node probabilities in each path.

367 The network has two tanks operating with water levels between the elevations of  
 368 65.53 m and 77.22 m and each with a capacity of 1,136 m<sup>3</sup>, but according to the original  
 369 case study the company wants to operate the tanks between 68.58 and 76.20 m. The  
 370 volume between 65.53 m and 68.58 m is used for emergency needs and amounts to a  
 371 volume of 284 m<sup>3</sup> in each tank. A minimum pressure of 28.14 m is required at all nodes

372 for average daily flow conditions, and the instantaneous peak flow is given as the  
 373 average nodal demand multiplied by 1.8. The system is also subject to three different  
 374 firefighting conditions, each lasting two hours. The minimum nodal pressures under  
 375 firefighting conditions are 14.07 m. The firefighting conditions are: 157.73 L/s at node  
 376 9; 94.64 L/s at nodes 18, 20, 21; and 63.09 L/s at nodes 12 and 16. These fire flows  
 377 should be met simultaneously with a daily peak flow 1.3 times the average flow. All the  
 378 pressure requirements should be assured when one pump is out of service and the tanks  
 379 are at the minimum levels after a normal operating day.

380 This problem is solved by considering the design and operation of the network  
 381 simultaneously. The city has grown up around an old centre located to the southeast of  
 382 link 14. Excavations in this area cost more than in other areas. There is an adjacent  
 383 residential area with some industries near node 16. The reinforcement possibilities are  
 384 to duplicate existing pipes, clean and line existing pipes, install new pumps and build  
 385 new tanks. The city is supplied from a water treatment plant and three identical pumps  
 386 connected in parallel. Pumps have to be replaced every 20 years, but according to the  
 387 original case study, there are already pumps in the first time interval and there is no cost  
 388 associated with installation. The possibility of installing 2 additional pumps in parallel  
 389 is considered if additional capacity is required. The water treatment plant is maintained  
 390 at a fixed level of 3.048 m. The characteristics of the links are given in table 2.

391 **Table 2:** Characteristics of the pipes

Pipe	Initial node	Final node	Lenght (m)	Existing diameter	Area
1	2	7	3657.60	406.4	Urban
2	2	3	3657.60	304.8	Residential
3	2	11	3657.60	304.8	Urban
4	7	3	2743.20	304.8	Residential
5	7	10	1828.80	304.8	Urban
6	7	9	1828.80	254.0	Urban
7	7	6	1828.80	304.8	Urban

8	6	9	1828.80	254.0	Urban
9	6	8	1828.80	304.8	Urban
10	8	9	1828.80	254.0	Urban
11	9	15	1828.80	254.0	Urban
12	9	10	1828.80	254.0	Urban
13	10	15	1828.80	304.8	Urban
14	8	15	1828.80	254.0	Urban
15	3	6	1828.80	254.0	Residential
16	3	4	1828.80	254.0	Residential
17	3	5	2743.20	254.0	Residential
18	4	5	1828.80	254.0	Residential
19	5	8	1828.80	254.0	Residential
20	8	14	1828.80	254.0	Residential
21	14	15	1828.80	203.2	Residential
22	15	16	1828.80	203.2	Residential
23	10	16	1828.80	203.2	Residential
24	10	11	1828.80	203.2	Urban
25	11	16	1828.80	254.0	Residential
26	11	12	1828.80	203.2	Residential
27	12	16	2743.20		New
28	12	13	1828.80	203.2	Residential
29	13	16	1828.80	254.0	Residential
30	13	17	1828.80	203.2	Residential
31	14	16	1828.80	203.2	Residential
32	14	17	3657.60	203.2	Residential
33	5	14	3657.60	203.2	Residential
34	2	23	30.48	762.0	Urban
35	6	19	30.48	304.8	Urban
36	16	22	30.48	304.8	Residential
37	1	23	Pump		
38	1	23	Pump		
39	1	23	Pump		
40	14	21	1828.80		New
41	14	20	1828.80		New
42	20	21	1828.80		New
43	5	18	1828.80		New
44	18	20	1828.80		New
45	3	24	1828.80		New
46	24	25	1828.80		New
47	4	25	1828.80		New
48	25	26	1828.80		New
49	4	26	1828.80		New
50	26	27	1828.80		New
51	27	18	1828.80		New

392 The average daily water demand for nodes is presented in table 3 as along with  
 393 the elevation of the nodes and tanks.

394 **Table 3:** Characteristics of the nodes

Node	Elevation (m)	Average day demand (l/s)	Node	Elevation (m)	Average day demand (l/s)
1	3.05	WTP	15	36.58	24.236
2	6.10	31.545	16	36.58	63.090
3	15.24	12.618	17	36.58	25.236
4	15.24	12.618	18	24.38	37.854
5	15.24	37.854	19	65.53	Tank
6	15.24	31.545	20	24.38	37.854
7	15.24	31.545	21	24.38	37.854
8	15.24	31.545	22	65.53	Tank
9	15.24	63.090	23	3.05	0.000
10	15.24	31.545	24	15.24	37.854
11	15.24	31.545	25	15.24	37.854
12	36.58	24.236	26	15.24	12.618
13	36.58	24.236	27	15.24	12.618
14	24.38	24.236			

395

396 Demand varies during an operating day. Table 4 shows the demand variation in  
 397 24 hours. For example, between 0 – 3 hours the demand is 70% of the average daily  
 398 demand.

399 **Table 4:** Variation of demand during 24 hours operation

Daily period	Demand
0 - 3h	0.7
3 - 6h	0.6
6 - 9h	1.2
9 - 12h	1.3
12 - 15h	1.2
15 - 18h	1.1
18 - 21h	1.0
21 - 24h	0.9

400

401 It is possible to duplicate or clean and line 35 pipes. There are also 13 new links  
 402 in the expansion areas. The commercial diameters and the unit cost of new pipes,  
 403 cleaning and lining, as function of the network area, are given in table 5.

404

405 **Table 5:** Diameters and unit cost

Pipe	Unit cost
------	-----------

diameter (mm)	Installation of pipes			Cleaning and lining existing pipes	
	Urban (\$/m)	Residential (\$/m)	New (\$/m)	Urban (\$/m)	Residential (\$/m)
152.4	85.958	46.588	41.995	55.774	39.370
203.2	91.207	64.961	58.399	55.774	39.370
254.0	111.877	82.349	73.819	55.774	39.370
304.8	135.827	106.299	95.801	55.774	42.651
355.6	164.698	131.890	118.766	59.711	46.588
406.4	191.929	159.121	143.045	64.961	50.853
457.2	217.192	187.664	168.963	70.866	56.102
508.0	251.969	219.160	197.178	77.100	66.273
609.6	358.268	280.512	252.625	98.753	
762.0	467.520	380.906	346.129	135.499	

406

407 If a pipe has been cleaned and lined, the Hazen-Williams coefficient is then  
 408  $C=125$ , and if there is a new pipe it is  $C=130$ . Over the life cycle, pipes age and wall  
 409 roughness increases. Based on the DWSD (2004) report, the Hazen-Williams  
 410 coefficients of ductile iron pipes decrease at a fixed rate of 2.5 per decade. Obviously  
 411 this rate depends on all kinds of different conditions and is also time dependent. But to  
 412 simplify the problem we have assumed a fixed rate for the life cycle.

413 The 24 hour operation of the network is subdivided into 1- hour time steps.  
 414 Three pumps have to supply the daily needs. This work considers the possibility of  
 415 installing two extra parallel pumps because of planned building of new areas. The  
 416 number of the pumps used in the 24 hours results in additional variables to solve in the  
 417 optimization problem, in each time interval and for each scenario. Table 6 gives five  
 418 points of the characteristic curves for each pump. These curves are to the same as in the  
 419 original case study.

420

421 **Table 6:** Function points of each pump

Flow (L/s)	Pump head (m)	Efficiency (%)
0	91.5	0
126.2	89.1	50
252.4	82.4	65
378.5	70.2	55
504.7	55.2	40

422

423 The energy costs are \$0.12 per KWh. The present value costs are computed  
424 using a discount rate of 4% over the life cycle. According to Wu *et al.* (2010) defining  
425 discount rates is a very complex issue and they normally vary from 2 to 10%. This work  
426 takes a 4% rate to emphasize the importance of the future costs in the decision-making  
427 process. There is also the possibility of installing new tanks at the nodes in the network.  
428 Tanks are connected to nodes by a short pipe 30.48 m long whose pipe varies. Tank cost  
429 is a function of the volume and is given in table 7. These data are to the same as in the  
430 original case study.

431

432

**Table 7: Tank cost**

Volume (m <sup>3</sup> )	Cost × 10 <sup>3</sup> (\$)
227.3	115
454.6	145
1136.5	325
2273.0	425
4546.0	600

433

434 Finally, it is held that the tank installation and rehabilitation of the existing pipes  
435 can only occur in the first time interval and has to perform well relative to all the  
436 possible future conditions given in Fig. 5. Based on Eq. 4, the embodied energy is  
437 calculated for different commercial diameters used in this work and is shown in table 8.

438



439 **Table 8:** Embodied energy and carbon emissions arising from installing commercial  
440 diameters

Diameters (mm)	Ductile iron pipes (KWh/m)	Aggregates (KWh/m)	Asphalt (KWh/m)	Embodied energy (KWh/m)	Total emissions (tonCO <sub>2</sub> /m)
152.4	269.88	44.91	445.38	760.17	0.48
203.2	406.20	49.95	466.87	923.03	0.59
254.0	575.89	55.07	488.37	1119.33	0.71
304.8	705.15	60.26	509.87	1275.27	0.81
355.6	776.37	65.52	531.37	1373.26	0.87
406.4	890.32	70.86	552.87	1514.05	0.96
457.2	1004.37	76.27	574.37	1655.01	1.05
508.0	1118.33	81.75	595.87	1795.95	1.14
609.6	1346.24	92.95	638.86	2078.05	1.32
762.0	1688.10	110.30	703.36	2501.77	1.59

441

442 Table 8 shows the embodied energy computed for the different commercial  
443 diameters, considering the contribution of the ductile iron pipes, aggregates for pipe  
444 bedding and asphalt for repaving works. The last column (right) of the table shows the  
445 carbon emissions of the total embodied energy. The optimization model described here  
446 is intended to minimize the installation cost of pipes, pumps and tanks, the energy cost  
447 and the carbon cost. The carbon emission costs are calculated assuming a carbon tax  
448 given by a value associated with each carbon tonne emitted. This study takes \$5 as  
449 reference value and defined according to European Union allowances market, but  
450 different values can be easily accommodated by the model.

## 451 **5 Results**

452 The approach described here uses ROs to minimize the life cycle costs of water  
453 distribution systems, taking uncertainty into consideration. When a long time horizon is  
454 considered, the future is unknown. The water demand will certainly vary considerably.  
455 New urban developments can be built and others can become depopulated. The ROs

456 approach can handle these uncertainties and give decision makers good design solutions  
457 for flexible water networks. This work uses a decision tree with 8 possible different  
458 scenarios that may occur over the 60-year life cycle. However, it is only necessary to  
459 decide the configuration of the network for the first time period of 20 years. The  
460 solution of this period should not only work well in the first stage, but also take into  
461 account future (uncertain) needs. This is a robust solution that will be adapted in the  
462 subsequent time intervals as circumstances evolve.

463 The model is solved using the hydraulic simulator EPANET (Rossman 2000) to verify  
464 the hydraulic constraints. The simulated annealing heuristic is the optimization method  
465 used. The problem addressed in our work is large, nonlinear and complex and involves  
466 discrete decision variables. Modern heuristics such as simulated annealing, genetic  
467 algorithms, particle swarm optimisation, and others, have proved to be effective in  
468 solving similar problems. A literature review shows that simulated annealing has been  
469 used in various fields with problems of similar mathematical characteristics and good  
470 performances were observed. Simulated annealing has been successfully implemented  
471 in several areas as such: aquifer management (Cunha, 1999); water treatment plants  
472 (Afonso and Cunha, 2007); wastewater systems (Zeferino *et al.*, 2012); rail planning  
473 networks (Costa *et al.*, 2013); water distribution design (Cunha and Sousa, 2001); (Reca  
474 *et al.*, 2007) and (Reca *et al.*, 2008).

475 Simulated annealing is an iterative process based on Monte Carlo method and  
476 inspired by an analogy made between the annealing process as a metal cools into a  
477 minimum energy crystalline structure and a search for a global minimum solution in an  
478 optimization problem. The simulated annealing approach used is based on Cunha and  
479 Sousa (1999) and Cunha and Sousa (2001). A more detailed analysis of the application

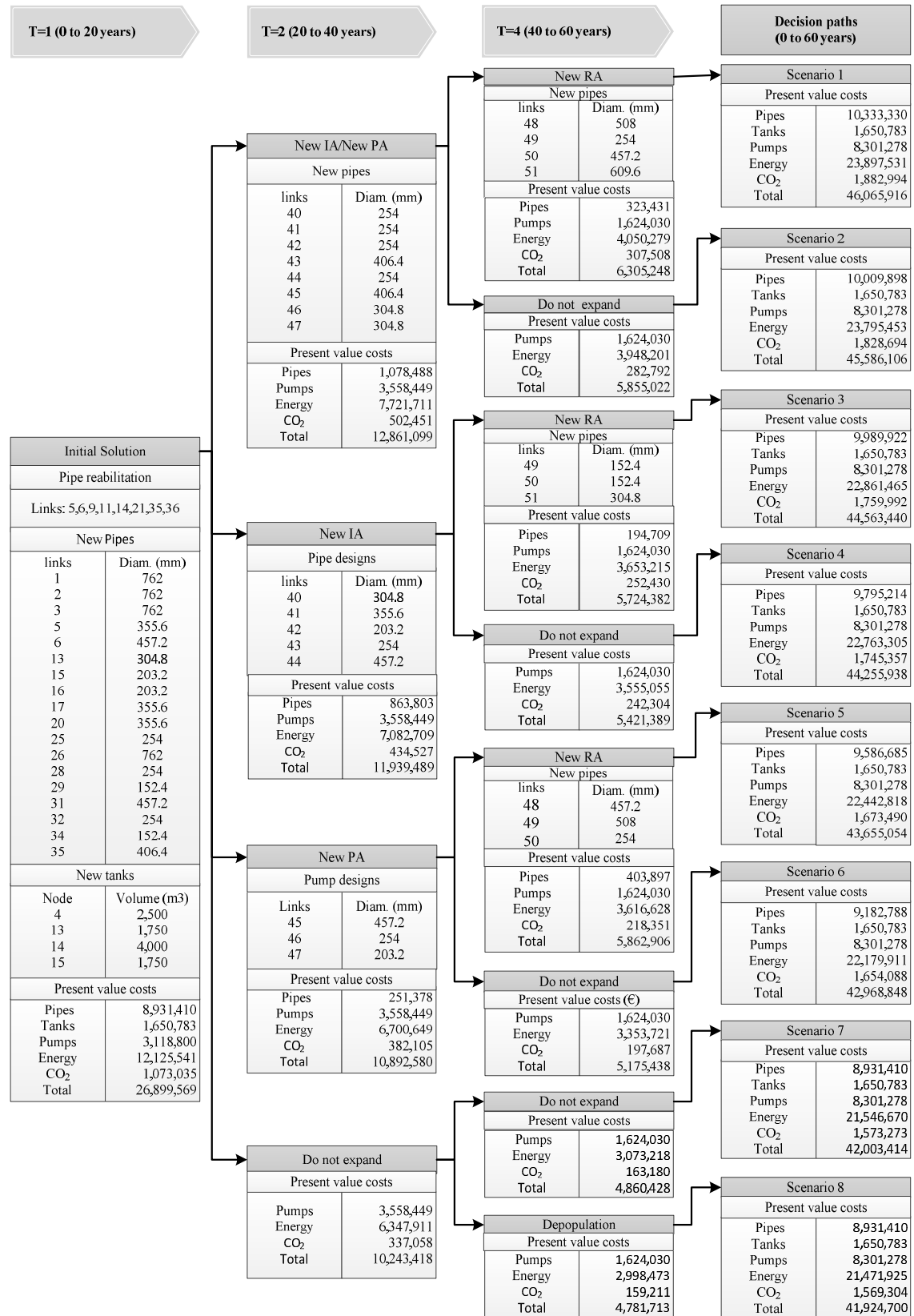
480 and parameterization of this method to the optimization of water distribution networks  
481 can be found in these papers. In brief, the basic idea of simulated annealing rests on the  
482 analogy made between the temperature reduction of physical systems and the  
483 minimization problem. The simulated annealing temperature is used in the Metropolis  
484 criterion (Metropolis et al. 1953) to accept uphill moves in terms of cost. The  
485 temperature starts at high value so that a high proportion of attempted changes are  
486 accepted. As the iterative process progresses, the temperature is reduced according to an  
487 annealing schedule defined in our work by a geometric progression with a cooling  
488 factor of 0.90. A minimum number of generations are required to reduce the  
489 temperature. In each reduction in temperature, the proportion of accepted moves goes  
490 down until, finally, no uphill moves (in cost) are accepted. If the simulated annealing  
491 has been performed slowly enough the final solution should be the global minimum.  
492 Fig. 5 gives the solution achieved by the approach described. The results are represented  
493 in a life cycle tree that has the same shape as the decision-making alternatives  
494 reproduced in Fig. 4.

495 Fig. 5 summarizes the design achieved for the case study. A table is presented  
496 for each node with the results of the design, starting by showing the pipe rehabilitation  
497 decisions, the new parallel pipes and the tank locations and capacities. The present  
498 value costs are subdivided into the cost of the pipes, tanks, pumps, energy, carbon  
499 emissions and total costs. The last branches of the decision tree represent the total life  
500 cycle cost for each of the scenarios.

501 It can be concluded from the results that the life cycle cost depends on the  
502 decisions that are taken in the time intervals. However, the first time interval of 0-20  
503 years accounts for most of investment costs. In this time interval the network will be

504 reinforced with some new parallel pipes, new tanks and the cleaning and lining of  
505 existing pipes. The total cost takes the carbon emissions arising from the installation of  
506 pipes and tanks and from energy consumption into account. The solution for scenario 1  
507 is schematized in figure 6.

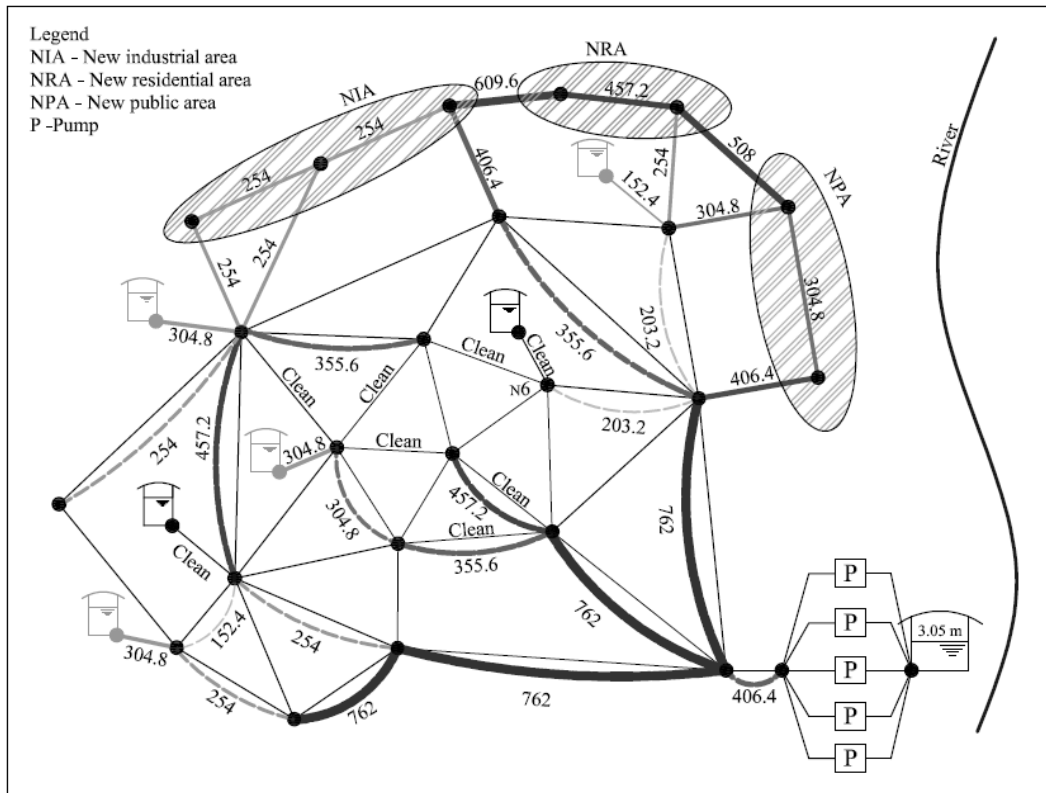
508



509

510 **Figure 5:** Decision tree design of Anytown network

511



512  
513

**Figure 6:** Scheme of the network for the last time interval of scenario 1

514  
515

For scenario 1 the water distribution network will be expanded in the second time interval to cope with the new industrial area and the new public area. Furthermore the network will be expanded for the new residential area in the last time interval. Fig. 6 shows the pipes that will be cleaned, the diameters of the new parallel pipes and the diameters of the pipes installed in the new areas. The location of the new tanks and the inclusion of two additional parallel pumps are also shown. These interventions will result in a total life cycle cost of \$46,975,016, including the carbon emissions cost of the construction and operation of the water distribution network. This is the most expensive solution. But if the life cycle does not follow the decision path of scenario 1 then other interventions will occur. In the case of scenario 8, the network does not need to expand to new areas, so the life cycle cost is approximately 10% lower than for

525

526 scenario 1. The ROs solution can handle uncertainties according to the life tree and  
527 adapt the solution to new requirements.

528 The ROs solution for the first time interval has to be implemented at year zero.  
529 To show that considering carbon emissions in the optimization model has an impact on  
530 the final solution, a comparison is made of the first time interval solution with and  
531 without carbon emissions costs. If the carbon emission costs are taken as zero, different  
532 results are obtained. Table 9 shows some comparisons regarding costs.

533 **Table 9:** Comparison of solutions with and without carbon emission costs

Costs	With CO <sub>2</sub> costs	Without CO <sub>2</sub> costs
Pipes	8,931,410	8,010,350
Tanks	1,650,783	1,324,100
Pumps	3,118,800	3,118,800
Energy	12,125,541	13,393,570
CO <sub>2</sub>	1,073,035	0
Total	26,899,569	25,846,820

534  
535 If carbon emission costs are taken into account the total cost is high, but it can be  
536 seen that the difference is practically accounted for by the carbon emission costs.  
537 However, other conclusions can also be drawn. Most of the carbon emissions are  
538 derived from the energy consumed by the pumps. If carbon costs are not included, the  
539 optimization model will find solutions that have high energy costs with some reduction  
540 in pipe and tank costs. Table 9 shows that if the total cost of the pipes, tanks, pumps and  
541 energy are kept practically the same, the consideration of carbon emissions implies  
542 allocating the costs in a different way, i.e. by decreasing the cost of the pipes and tank  
543 and increasing the energy cost. Larger diameter pipes allow the energy expenditure to  
544 be cut, with a consequent reduction in the total carbon emissions.

## 545 **6 Conclusions**

546           The scientific community has made efforts in recent years to find tools to  
547 optimize water network design and operation. Water distribution infrastructure has a  
548 high cost and is essential to people's well-being. This work has tried to find good  
549 solutions for water distribution networks that may operate under uncertain future  
550 scenarios, and considering the carbon emission costs generated by installation and  
551 operation works.

552           The application of the ROs approach has been examined in the search for a  
553 flexible, robust solution to a water distribution network design and operation problem  
554 that includes the carbon emission costs. The problem consisted of finding the minimum  
555 cost solution for a design whose variables included additional new pipes, cleaning and  
556 lining existing pipes, replacement of existing pipes, siting and sizing of new tanks and  
557 installing and operating pumps. The optimization algorithm was based on simulated  
558 annealing, a method that can be successfully applied to solve such problems.

559           The results indicate that the ROs approach is able to identify good solutions for  
560 flexible networks. The simultaneous optimization of the network and carbon emission  
561 costs achieves solutions that take into account the environmental impacts of the  
562 networks. The solution presented provides flexibility to the network and automatically  
563 minimizes the carbon emissions. The solution was obtained using the life cycle decision  
564 tree. It can be also concluded that if carbon emission costs are considered it is possible  
565 to find solutions with practically the same investment costs but with lower carbon  
566 emissions. This is achieved by higher investment cost and lower spending on energy.



567 Further improvements can still be achieved by considering better carbon emission  
568 estimations and comparing the results for real networks.

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