

1 USING REAL OPTIONS IN THE OPTIMAL DESIGN OF WATER 2 DISTRIBUTION NETWORKS

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10 ABSTRACT

11
12 Water supply systems have to satisfy water needs in terms of quantity and quality. The
13 constant changes in urban areas require the regular adaptation of the water supply
14 infrastructure to meet new realities. However, decisions to design and operate water networks
15 have to be made under uncertainty. Flexibility is thus the key to more robust and confident
16 decisions. An approach called Real Options (ROs) can be used here. This approach makes it
17 possible to use adaptive strategies during the decision making process. Some decisions can be
18 delayed until future conditions become known. Water distribution systems are very costly and
19 complex infrastructures; once built, their operating structure cannot be changed significantly.
20 This work presents an innovative ROs approach to define an objective function to cope with
21 some future scenarios considered in a specific case study. The objective of the model
22 proposed is to find a minimum cost solution for the first period of a planning horizon, while
23 considering various possible future conditions that the network could have to cope with. The
24 results of this work show that building flexibility into the decision strategy enables an
25 adaptive approach to be taken that can avoid future lack of network capacity. In the case
26 study, an adaptive design of the network incurs an extra initial cost, but this cost can easily be
27 lower than the cost of reinforcing the network in a longer planning horizon. The real value of
28 ROs is their ability to adapt systems to different future possible scenarios.

29
30 **Keywords:** water distribution networks, real options, simulated annealing, flexible design,
31 uncertainty.

33 1 INTRODUCTION

34
35 Water distribution systems are costly and complex infrastructures which are meant to
36 distribute water over a long planning horizon without interruption. Once built, networks
37 cannot significantly change their operating conditions to adapt to new circumstances and the
38 capacity and level of service cannot be increased easily. During the planning horizon, the pipe
39 capacity declines as the roughness increases and the incidence of pipe burst also rises. Once

40 laid, pipes cannot be reinforced without making large investments. Therefore, it is very
41 important in water system planning to try to predict the future operating conditions. However,
42 if the worst case scenario design is adopted the network could become oversized, with the
43 result that resources are wasted and the water quality declines due to the lower velocity and
44 higher water residence times. Moreover, cities are continually changing and the water supply
45 systems have to be adapted for these changes. Sometimes a new urban or industrial area is
46 built and the network has to be reinforced to accommodate the increased demand. But the
47 opposite can also occur in areas whose population declines and the demand therefore falls.
48 There are many sources of uncertainty in the future: technology, industry, economics,
49 regulations and politics are some of them. It is very difficult to make correct forecasts under
50 these uncertainties. Urban infrastructure planning is an immense and complex task. According
51 to Haimes (1998) the great challenge for the scientific community of the third millennium will
52 be to develop tools and technologies to support and maintain infrastructure. Several methods
53 for effective planning in the area of water systems have appeared in the literature. To cope
54 with future uncertainty, a flexible plan is required. In this context an approach called Real
55 Options (ROs), originating in financial theory, could make an important contribution. Myers
56 (1977) was the first to introduce the term Real Options (ROs), soon after the works of Black
57 and Scholes (1973) and Merton (1973) which proposed a solution to the financial option
58 valuing problem. Since then a large number of studies have been published where the
59 concepts of ROs have been used in several fields. The ROs concept is analogous to financial
60 options but ROs refer to physical assets such as buildings and infrastructure rather than
61 financial instruments like stocks and shares.

62

63 Wang and Neufville (2004) divide ROs into two categories, ROs “on” systems and ROs “in”
64 systems. ROs “on” systems focus on the external factors of a system and benefit from the use
65 of financial valuation tools. On the other hand, ROs “in” systems incorporate flexibility into
66 the structural design of a system and it is harder to value flexibility. This is the ROs category
67 used to design water distribution networks.

68

69 The ROs approach facilitates adaptive strategies as it enables the value of flexibility to be
70 included in the decision making process. Opportunities are provided for decision makers to
71 modify and update investments when knowledge of future states is gained enabling them to
72 identify the most appropriate long term intervention strategies. This gives a totally different
73 perspective to a decision strategy, because there is no need for decisions to be inflexible and
74 there is no specific date on which to take them.

75

76 A number of studies have developed ROs approaches to solve a variety of problems. Roberts
77 and Weitzman (1981) analyse the nature of sequential investments during a time horizon. In
78 industry He and Pindyck (1992) solve investment decisions with flexible production
79 capacities. In petroleum exploration, Paddock et al. (1988) use ROs to evaluate the investment
80 in an offshore platform. In electric power systems, Tannous (1996) compares flexible and

81 rigid electrical systems. Other uses of ROs approaches include Nembhard and Akton (2010),
82 who systemized applications of ROs to design and develop engineering problems and
83 Neufville et al. (2006), reported the use of ROs in car parking problems. In the water industry,
84 an ROs technique appears in the work of Woodward et al. (2011) to define maritime coastal
85 defences to reduce the risk of flooding. In the area of water systems expansion, Suttinon and
86 Nasu (2010) present an ROs based approach where the demand increases. The work of
87 Buurman, et al, (2009) and the work of Zhang and Babovic, (2011) apply ROs to the
88 development of a maritime domain protection system. Zhang and Babovic (2012) also use an
89 ROs approach to evaluate different water technologies into water supply systems under
90 uncertainty. There is a vast body of literature reporting the use of ROs but, until now, it has
91 only been possible to find the work of Huang et al. (2010) that describes the application of
92 ROs to design of water distribution networks. The methodology used presents a flexible
93 design tool based on decision scenario trees that reflect uncertainty associated with future
94 demand for water. The authors use a genetic algorithm optimization model to find a flexible
95 design to a simple case study.

96
97 This work presents an innovative and different approach where uncertainty is not only
98 associated with future demand for water, but also, it considers new expansion scenarios for
99 the network. These scenarios are organized through a decision tree. The investment and the
100 corresponding design of the network have to cope with the first period, but they have to work
101 well throughout the planning horizon. This work uses a minimum cost objective function and
102 various scenarios are considered to predict different alternative future conditions. The
103 objective function also includes a regret term used to approximate the cost of the ROs solution
104 that must work well for all scenarios, with the cost of each scenario considered individually.
105 Therefore, before running the model it is necessary to find the optimal solution for each
106 scenario. The method proposed here to solve the optimization problem is a simulated
107 annealing heuristic based on Aarts and Korst (1989). The work of Cunha and Sousa (1999)
108 shows the capabilities of this method to find optimal solutions in water distribution network
109 problems. This method was also used in aquifer management (Cunha, 1999); water treatment
110 plants ((Afonso and Cunha, 2007); wastewater systems ((Zeferino, et al. 2012) and rail
111 planning networks ((Costa, et al. 2013). The case study presented in section 3 explains how
112 the ROs approach can be used and the benefits of using a flexible design.

113
114 The remainder of this study is organized as follows: in the next section a case study is
115 presented to explain the method. A decision model is built and the results are shown. Then
116 some comparisons are drawn with traditional approaches. Finally, the conclusions are
117 systemized.

118

119 **2 CASE STUDY**

120

121 In this section, an ROs approach is used in a simple case study. This is a water distribution
122 network inspired in (Taher & Labadie, 1996). The layout of the network and characteristics of
123 the pipes and nodes can be consulted in this work.

124

125 This is a simple new network with 10 nodes and 11 pipes supplied from a single reservoir
126 with a free water surface elevation of 304.8 m. The pump is used to increase pressure at the
127 remote end nodes of the network. The efficiency of the pump is 80% and the daily
128 consumption is 12 hours at demand condition (1) and the other 12 hours at demand condition
129 (2). Demand condition (3) considers the instantaneous peak discharge and a fire flow in node
130 10. These demand conditions can be consulted in (Taher & Labadie, 1996). The energy costs
131 are € 0.18 /kWh and should be evaluated for a 60-year period by a discount rate of 4% year.
132 This rate was fixed based on the work of Wu et al. (2010). The design of the network
133 considers the 11 different commercial diameters presented in table 1.

134

135 **Table 1:** Diameter, unit costs, Hazen-Williams coefficients

136

137 A network planning horizon of 60 years was taken for this case study, which was split into 4
138 periods. This subdivision considers periods of different lengths. It is supposed that in the first
139 period (T=1), no modifications will be needed and that conditions will remain the same for
140 the first 20 years. In this first step of the decision-making process, 10 pipes and the head of
141 the pumping station have to be designed for three different operating conditions. Periods T=2
142 and T=3, are short periods of 10 years each. The regional planning strategy assumes that the
143 land use of some areas of the city is reviewed. Therefore, for T=2 the authorities are planning
144 to license a new industrial area (NIA) if enough companies show an interest and so the
145 network will be expanded in this period. For T=3, it is expected that a new residential area
146 (NRA) might grow close to the industries, due to labour required for NIA, so the possible
147 expansion of the network to the new residential area is considered. It is assumed that the
148 pumps have to be changed every 20 years, so the pumps will have to be replaced in T=2 and
149 T=4. In the last period, T=4, the demand should be predicted. However the time horizon is
150 large and it is very difficult to accurately predict how demand will vary during the last 20
151 years of planning. For the last period it is assumed that the demand might increase between 0
152 and 20%, equally in all nodes in the network. The two different paths' scenarios that are
153 possible in the last period are the 20% increase in demand and demand remaining constant.
154 The potential expansion areas are shown by dashed pipe links in Fig. 1 and the characteristics
155 of the new nodes and pipes are presented respectively in tables 2 and 3.

156

157 **Figure 1:** Water distribution network inspired from Taher & Labadie (1996) with possible
158 expansion areas

159

160 **Table 2:** Characteristics of the new nodes

161

162 **Table 3:** Characteristics of the new pipes

163

164 As the planning horizon progresses and the pipes get older the wall roughness increases. The
165 planning horizon for this case study is 60 years and the fall in pipe capacity should not be
166 neglected for any future decision that has to be made. Based on the DWSD (2004) report, the
167 Hazen-Williams coefficients of ductile iron pipes decreased at a fixed rate of 2.5 per decade.
168 Of course this rate depends on many factors and is also time dependent. But to simplify
169 matters, a fixed rate was assumed for the entire planning horizon. The demand will also vary.
170 It was assumed that for the first 40 years' operation the demand would increase at a constant
171 rate of 10% per decade. For the last period, the demand could stabilize or increase by no more
172 than 20%, as was supposed before. The main virtue of real options approach remains on the
173 possibility to make midcourse corrections as new information comes. Thus, these assumptions
174 can be adapted if required to new future realities.

175

176 Assuming a subdivided planning horizon, different conditions and possible expansions, a
177 decision tree for all possible paths of the process and respective probabilities is shown in Fig.
178 2. This is a simple case study and the decision model can be easily solved. In real systems the
179 complexity can increase and the computation effort too. One of the possibilities to obtain
180 solutions in admissible time horizons is to use parallel computing.

181

182 **Figure 2:** Decision tree for the planning horizon

183

184 There are 8 different paths that can be tracked during the planning horizon of the network. In
185 the first period ($T=1$) an initial design for the network is determined, in $T=2$ the pumps have
186 to be replaced and an NIA may or may not need to be supplied. An NRA might be built in
187 $T=3$. In the last period $T=4$, the pumps have to be replaced and the demand for the last 20
188 years of the planning horizon is designated. Finally, the probabilities of the different scenarios
189 are assigned to each path. These probabilities can be obtained by different methods, taking
190 into account the urban planning and other plans for future developments and land use.
191 Aggregating all the information, the probabilities can be given by experts. For this case study
192 the probabilities considered for the different paths are shown in Fig. 2. In $T=1$, the probability
193 of occurrence is 1; it is the only possibility. For $T=2$, it is accepted that there is a 75% chance
194 that an NIA will be built. The probability that an NIA is not built is the other 25%. In $T=3$
195 it will be decided if the NRA will be extended or not. If the NIA has been installed then it is
196 more probable that the NRA will be built because of the labour needed for the industries, so
197 the probability of constructing the NRA is higher in the upper paths of the decision tree. In the
198 last period, $T=4$, the demand has to be assigned. If the NIA or/and the NRA are built the
199 probability of an increment in demand is higher. To conclude, the probability of the scenarios
200 is calculated by multiplying the probabilities of all nodes on the path of that scenario, and they
201 are shown in the last branches of the tree in Fig. 2.

202

203 2.1 DECISION MODEL

204

205 The decision model presented here is based on the ROs approach and aims to define an
 206 objective function to cope with all the different planning horizon paths that are considered in
 207 the case study. The objective function and the corresponding constraints of the model will
 208 determine a solution to implement in the first period, $T=1$, but taking into account all the
 209 possible future conditions that the network could cope with. The proposed objective function
 210 OF is given by Eq. 1:

211

$$OF = Min (Ci + Cf + R) \quad (1)$$

212 Where: Ci - cost of the initial solution to be implemented in year zero (€); Cf – cost of the
 213 future conditions (€) and R – regret term (€).

214

215 The objective function of Eq. 1 is written so that the solution for the first period, $T=1$, can be
 216 determined taking into account the different paths of decisions that have to be made during
 217 the planning horizon. The objective function seeks to minimize not only the initial cost but
 218 also the probable future costs of the system. To take into account the differences between the
 219 costs of the general solution and the optimum costs for each scenario considered individually,
 220 a regret term is used in the objective function. The cost of the solution to implement is given
 221 by the sum of three terms. The term Ci computes the cost of the network for the first period
 222 $t=1$ of planning and is given by Eq. 2:

$$Ci = \left(\sum_{i=1}^{NPI} (Cpipe_i(D_{i,1})L_i) + \sum_{j=1}^{NPU} (Cps_{j,1}) + \left(\sum_{d=1}^{NDC} \left(Ce_d \cdot \sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,d,1} \cdot HP_{j,d,1}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot \frac{(1 + IR)^{NY_1} - 1}{IR \cdot (1 + IR)^{NY_1}} \right) \right) \quad (2)$$

223 Where: NPI - number of pipes in the network; $Cpipe_i(D_{i,1})$ - unit cost of pipe i as function of
 224 diameter $D_{i,1}$ adopted (€/m); $D_{i,1}$ - diameter of pipe i installed in period $t=1$ (mm); L_i - length
 225 of pipe i (m); NPU - number of pumps in the network; $Cps_{j,1}$ – pumping station costs of pump
 226 j in the period $t=1$ (€); NDC - number of demand conditions considered for the design; Ce_d -
 227 cost of energy in demand condition d (€); γ - specific weight of water (KN/m³); $QP_{j,d,1}$ -
 228 discharge of pump j in demand condition d and for period $t=1$ (m³/s); $HP_{j,d,1}$ - head of the
 229 pump j in the demand condition d and for period $t=1$ (m); η_j - efficiency of pump j ; Δt_d -
 230 duration of demand condition d (h); IR - annual interest rate for updating the costs and NY_1 –
 231 number of years with the same conditions considered in the period $t=1$.

232

233 The initial cost is given by the sum of the cost of the pipes and the cost of the pumps and the
 234 energy cost. These costs are computed assuming $NY_1=20$ which is the number of years of the
 235 first period. The other term of the objective function represents the future costs of all the

236 decision nodes designs (Eq. 3) weighted by the respective probability of each decision node
 237 that is presented in Fig. 2:

$$Cf = \sum_{s=1}^{NS} \sum_{t=2}^{NTI} \left(Cfuture_{t,s} \cdot \prod_{nt=2}^t prob_{nt,s} \right) \quad (3)$$

238 Where: NS - number of scenarios; NTI - number of time intervals; $Cfuture_{t,s}$ – cost of the
 239 future path of designs in scenario s for period t (€) and $prob_{nt,s}$ - probability of the scenario s
 240 in period nt

241

242 Adding up all possible future costs conditions, starting from $T=2$, multiplied by the
 243 probability of occurrence of such costs, we get a weighted mean of the future costs for the
 244 network. The term $Cfuture_{t,s}$ is computed in Eq. 4, for all periods beginning in $T=2$ (the costs
 245 for the first period are already calculated in the $Cinitial$ term) and it is given by the sum of
 246 three terms:

247

$$Cfuture_{t,s} = \left(\sum_{i=1}^{NPI} (Cpipe_i(D_{i,t,s})L_i) \cdot \frac{1}{(1+IR)^{Y_t}} + \sum_{j=1}^{NPU} (Cps_{j,t,s}) \cdot \frac{1}{(1+IR)^{Y_t}} + \left(\sum_{d=1}^{NDC} \left(Ce_d \cdot \sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,d,t,s} \cdot HP_{j,d,t,s}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot \frac{(1+IR)^{NY_t} - 1}{IR \cdot (1+IR)^{NY_t}} \right) \cdot \frac{1}{(1+IR)^{Y_t}} \right) \quad (4)$$

248 Where: $Cpipe_i(D_{i,t,s})$ - unit cost of pipe i as function of diameter $D_{i,t,s}$ (€); $D_{i,t,s}$ - diameter of
 249 pipe i installed in period t for scenario s (mm); Y_t - year when costs will be incurred for period
 250 t ; $Cps_{j,t,s}$ – pumping station costs of pump j in period t for scenario s (€); $QP_{j,d,t,s}$ - discharge of
 251 pump j in demand condition d for period t and scenario s (m³/s) and $HP_{j,d,t,s}$ - head of pump j
 252 in demand condition d for period t and for scenario s (m)

253

254 The first term of Eq. 4 computes the current value of the cost of the pipes to be installed in the
 255 different periods and scenarios, the second term computes the current value of the cost of the
 256 pumps for the different periods and for the different scenarios and finally the last term
 257 computes the current value of the cost of energy for each period and for each scenario. To
 258 compute the current value of the costs of energy, first it is necessary to sum and discount the
 259 costs during the NY_t number of years of each the time interval. Then it is required to update
 260 these costs by Y_t years to year zero of the planning horizon. The pumping station costs are a
 261 function of the pump discharge and of the pump head.

262

263 So far, the first two terms of the objective function of Eq. 1 have been detailed. The sum of
 264 these two costs is intended to represent the full planning horizon cost of the network,
 265 considering future uncertainty. The decision variables are the pipe diameters and the head of
 266 the pump for each demand condition and for each time interval. The other term of the

267 objective function is given in Eq. 5 and computes the regret between the cost of the solution
268 to implement and the optimal cost for each scenario:

$$R = \sum_{s=1}^{NS} \left\{ \left[\left(C_{initial} + \sum_{t=2}^{NTI} C_{future_{t,s}} \right) - C_{optimal_s} \right]^2 \cdot \prod_{t=1}^{NTI} prob_{t,s} \right\} \cdot Nf \quad (5)$$

269 Where: NS - number of scenarios; $C_{optimal_s}$ – optimal cost design for scenario s (€) and Nf -
270 normalization factor.

271

272 The term given by Eq. 5 aims to find solutions whose costs are as close as possible to all the
273 individual optimal costs, with all the constraints being verified and performing well for all the
274 scenarios. But the scenarios do not have the same probability of occurrence, so the weight of
275 the situations more likely to occur should be higher. Therefore, these differences are
276 multiplied by the probability of occurrence of each path scenario. The regret term is used to
277 introduce the idea of making decisions without perfect information. This means that the
278 design solution to be implemented can be sub-optimal and the regret term is included to
279 represent the risk of such decision. The squared term allows balancing that difference across
280 scenarios. The normalization factor Nf is a value used to avoid that the optimization process
281 became high dependent from the regret term. If this term is much higher than the other terms
282 of the objective function, then the progress of the optimization is ruled by the modifications of
283 the regret term. Therefore, it is used a factor playing the role of a normalization to avoid this
284 situation. The value of the normalization factor is problem dependent and was defined
285 according to a kind of sensitivity analysis considering this particular case study.

286

287 2.2 OPTIMAL SOLUTION FOR EACH SCENARIO

288

289 The regret term shown in the objective function of Eq. 5, is based on the minimum cost
290 solution for each scenario. Consequently, the model shown in Eq. 6 is used to find these
291 solutions:

$$\text{Min} \sum_{t=1}^{NTI} \left(\sum_{i=1}^{NPI} (C_{pipe_i}(D_{i,t})L_i) \cdot \frac{1}{(1+IR)^{Y_t}} + \sum_{j=1}^{NPU} (C_{ps_{j,t}}) \cdot \frac{1}{(1+IR)^{Y_t}} + \left(\sum_{d=1}^{NDC} \left(C_{e_d} \cdot \sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,d,t} \cdot HP_{j,d,t}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot \frac{(1+IR)^{NY_t} - 1}{IR \cdot (1+IR)^{NY_t}} \right) \cdot \frac{1}{(1+IR)^{Y_t}} \right) \quad (6)$$

292 The objective function is the sum of 4 periods of the current value of the costs of pipes,
293 pumps and energy. The first term computes the present value of the pipe costs for the year
294 zero. The second term computes the pumping stations' costs. Over the planning horizon the
295 pumps have to be replaced every 20 years, so this cost has to be updated for the first operation
296 year. Finally, the last term computes the cost of energy consumed by the pumps. The energy

297 costs must be updated for each period of the planning horizon and then to the year zero.
 298 Adding up these costs for all 4 periods, we get the cost of pipes, pumps and energy for the
 299 whole planning horizon of the water distribution network.

300

301 The model includes a set of constraints. Eq. (7) is used to verify the nodal continuity
 302 equations; Eq. (8) is used to compute the head loss of the pipes; Eq. (9) is used to limit the
 303 pressure of the nodes and Eq. (10) is used to guarantee a minimum diameter for the pipes.
 304 Furthermore, the optimization model use a candidate diameter for each pipe based on a set of
 305 commercial diameters, Eq. (11) and the assignment of only one commercial diameter for each
 306 pipe, Eq. (12).

$$307 \quad \sum_{i=1}^{NPI} I_{n,t} Q_{i,d,t,s} = QC_{n,s} \quad \forall n \in NN; \forall d \in NDC; \forall t \in NTI; \forall s \in NS \quad (7)$$

$$308 \quad \Delta H_{i,d,t,s} = K_i Q_{i,d,t,s}^{\alpha} \quad \forall n \in NN; \forall d \in NDC; \forall t \in NTI; \forall s \in NS \quad (8)$$

$$309 \quad PMAX_{n,d,t,s} \geq P_{n,d,t,s} \geq PMIN_{n,d,t,s} \quad \forall n \in NN; \forall d \in NDC; \forall t \in NTI; \forall s \in NS \quad (9)$$

$$310 \quad D_i \geq Dmin_i \quad \forall i \in NPI \quad (10)$$

$$311 \quad D_i = \sum_{d=1}^{ND} YD_{d,i} \cdot Dcom_{d,i} \quad \forall i \in NPI \quad (11)$$

$$312 \quad \sum_{d=1}^{ND} YD_{d,i} = 1 \quad \forall i \in NPI \quad (12)$$

313

314 Where: $I_{n,i}$ - incidence matrix of the network; $Q_{i,d,t,s}$ – flow on the pipe i in demand condition d
 315 for period t and scenario s (m^3/s); $QC_{n,d,t,s}$ - consumption in node n in demand condition d
 316 for period t and scenario s (m^3/s); NN - number of nodes; $\Delta H_{i,s}$ - head loss in pipe i in demand
 317 condition d for period t and scenario s ; K_i, α - coefficients that depends of the physic
 318 characteristics of the pipe i ; $PMAX_{n,d,t,s}$ - maximum pressure in node n in demand condition d
 319 for period t and scenario s (m^3/s); $P_{n,d,t,s}$ - pressure in node n in demand condition d for period
 320 t and scenario s (m); $PMIN_{n,d,t,s}$ - minimum pressure in node n in demand condition d for
 321 period t and scenario s (m); D_i - diameter of pipe i ; $Dmin_i$ - minimum diameter for the pipe i ;
 322 $YD_{d,i}$ - binary variable to represent the use of the diameter d in pipe I ; $Dcom_{d,i}$ - commercial
 323 diameter d assigned to pipe I and ND - number of commercial diameters.

324

325 Mainly, this study comprises three main elements. The ROs are used to shape the
 326 optimization model of Eq. 1. The simulated annealing is used to solve the optimization model
 327 and the EPANET (Rossman, 2000) is used to simulate the hydraulics and return the results to
 328 verify the constraints of the model. The interaction between the optimizer and the hydraulic
 329 simulator is shown in Fig. 3.

330

331 **Figure 3:** Main program diagram

332

333 The program start by input data, then simulated annealing process starts by choosing an initial
334 solution generated randomly in the solution space. To it, is associated a value of the objective
335 function. The current solution is initialized by considering it equal to initial solution. The
336 candidate solution is selected in the neighborhood of the current solution and is given by a
337 random change of current solution. After generation the hydraulic constraints are verified
338 through EPANET and the candidate solution can be accepted or not according to Metropolis
339 criterion (Metropolis, et al. 1953). If it is accepted, this solution will be used as the starting
340 point for the next iteration. If not, the current solution will play this role. After a number of
341 generations, the cooling process is performed and the temperature parameter decreases. The
342 process progresses until a stop criterion is achieved. In the end the results are presented.

343

344 The design of the network has to satisfy minimum pressure constraints for 3 different demand
345 conditions and for 4 different subintervals of the planning horizon. The solution thus has to
346 verify 12 different hydraulic conditions for each scenario. Table 4 shows the solutions cost of
347 each scenario.

348

349 **Table 4:** Network cost for the different scenarios

350

351 Table 4 presents the cost subdivided into the cost of pipes, cost of PS and energy cost. All of
352 these costs are updated for the year zero. These solutions are used to evaluate the regret term
353 of the objective function of Eq. 1. Each of these solutions takes about 190 seconds to be
354 achieved by the optimization method.

355

356 It is possible to draw some conclusions from Table 4. The pipe costs are the greatest
357 percentage of the total costs. Another conclusion is that a decision about the increase of the
358 demand has an impact on the pipe cost in the last period. This can be seen by comparing the
359 construction costs in Table 4 of scenario 1 that considers a demand increase in the last period
360 and scenario 2 were there is no demand increase. It can be seen that if demand does not
361 increase in the last period the cost of the pipes will be lower. This happens because, if there is
362 a substantial increase in the demand, the size of the pipes has to be larger and therefore the
363 cost will be higher.

364

365 **3 RESULTS AND DISCUSSIONS**

366

367 The model was solved for the case study and the results are presented in Fig. 4.

368

369 **Figure 4:** Solution for Real Options approach

370

371 Decisions have to be made for each node of the decision tree. Fig. 4 presents, for each node, a
372 table with the results of the design, beginning with the diameters in millimetres of the pipes to
373 install in the network. Then the pump heads are presented for each of the three operating
374 conditions considered in the case study and the costs are shown in the last lines, subdivided
375 into the cost of the pipes, the pumps and energy. Finally the last branches of the decision tree
376 present the total cost of the pipes, pumps and energy, updated for the year zero. These figures
377 represent, for each scenario, the total amounts of investment and operating cost that will be
378 expended if that scenario occurs. These future costs of the global solution can be compared
379 with the optimal costs of each scenario. Fig. 4 shows this comparison and enables some
380 conclusions to be achieved. First, the cost of the global solution is higher than the optimal cost
381 of each scenario. In fact considering uncertainty in the process will increase the cost. If the
382 future is well defined, the solution can be designed only for those conditions and not provide
383 the flexibility to accommodate future alterations; the pipes and pumps can be designed to a
384 specific capacity that will reduce the cost of investments.

385

386 **Figure 5:** Cost comparison

387

388 Scenario 1 is the most likely to occur, $prob_1=0.54$, and it can be seen in Fig. 5 that the cost is
389 very similar to the cost of the ROs solution for scenario 1. This proximity is due to the regret
390 term used in the objective function in Eq. 1. The difference between the cost of the global
391 solution and the optimal cost for each scenario is minimized by the regret term, but this
392 difference is weighed with the probability of each scenario, and the scenarios with high
393 probabilities will further penalize the objective function.

394

395 Finally, the expected cost of the solution is computed. The ROs approach considers different
396 scenarios with different probabilities. By adding together all the future weighted costs
397 presented in each node of the decision tree in Fig. 4 it is possible to achieve to the present
398 value of ROs solution, which is € 5,442,569. This is the expected cost for the case study
399 considered for this work and is the sum of the initial solution cost, $C_{initial} = € 4,287,509$ that
400 has to be implemented now plus the weighted costs of all the future options,

401
$$\sum_{s=1}^{NS} \sum_{t=2}^{NTI} \left(C_{future,t,s} \cdot \prod_{nt=2}^t prob_{nt,s} \right) = € 1,155,060.$$
 The decision makers can use this cost as the

402 reference for the entire planning horizon operation of the system.

403

404 To understand the difference that using ROs will make in the flexible design of water
405 distribution networks, a comparison between the ROs approach and a traditional design is
406 made. The comparison presented covers the first 30 years of operation. The comparisons are
407 presented in Fig. 6.

408

409 **Figure 6:** Comparison between ROs and Traditional design

410

411 Fig. 5 presents, for each node, a table with the results of the design, beginning with the
412 diameters in millimetres of the pipes to be installed in the network. Then the pump heads are
413 presented for each of the three operating conditions considered in the case study and the costs
414 are shown in the last lines, subdivided into the cost of the pipes, the pumps and energy. These
415 results are presented in two columns: ROs design and a traditional design.

416

417 The RO solution given in Fig. 6 is designed for the first period $T=1$, but consider 2 possible
418 future scenarios: for $T=2$ a NIA either is installed with a probability of 75%, or it is not
419 installed with a probability of 25%. Another design option for the first period $T=1$ is a
420 solution planned only to function in the first 20 years of operation. This is the traditional
421 design for this case study and does not take future uncertainty into account. Analyzing the
422 solutions for the first time interval allows us to reach some conclusions. The ROs solution
423 adopts larger pipe diameters than the traditional design, if only the first period is considered.
424 The cost of the ROs solution is 12% higher than the cost of the traditional design solution.
425 This cost increment is the initial price to pay to have a flexible solution that will perform well
426 for the first 30 years of operation. The pump heads are higher for the traditional design
427 solution due to the smaller diameters of the pipes next to the pumping station. Using larger
428 diameters permits a reduction in head losses and, therefore, less energy is used to pump the
429 water.

430

431 As has been shown, the ROs solution has a higher cost for the first period. However, the
432 comparison has to cover the whole 30-year life and it was ascertained that the minimum
433 pressures could not be satisfied in $T=2$ where the traditional design solution is adopted in the
434 first period. Therefore, this solution has to be reinforced to satisfy the minimum pressure
435 constraints. To compare the solutions, it was considered that the reinforcements can be made
436 by using parallel pipes. The optimization problem assumes that these parallel pipes can be
437 used for all the existing pipe links and considers that the unit pipe cost is the same as that
438 given in Table 1.

439

440 To compare the designs the weighted cost of solutions for the 30-year planning horizon is
441 used. The initial cost (Eq. 2) is added to the future weighted cost (Eq. 3) to obtain the value of
442 € 4,288,757 to the ROs design and the value of € 4,359,026 to the design that implies
443 reinforcements of the network. This shows that the cost of the ROs design is 2% lower than in
444 an inflexible design.

445

446 If it is compared to the costs of the traditional design with the ROs design for the 60-year
447 planning horizon and if the decision path of scenario 1 (Fig.2) is considered, a traditional
448 design implies expenditure of more than 270,000 € of actualized costs. This solution includes
449 the installation of 11 new parallel pipes. In fact, the ROs solution makes it possible to save on
450 resources if an extended planning horizon analysis is performed.

451

452 From these comparisons it is also possible to conclude that the length of the planning horizon
453 is very important for the initial design. However, the longer the planning horizon the more
454 uncertainties arise and the design should be adjusted between different possible future
455 scenarios. The ROs approach makes an important contribution because it can handle future
456 uncertainty. But design flexibility has a cost. In this comparison, the ROs solution is 12%
457 more costly than the traditional solution designed only for the first period. However, if a 30-
458 year operation planning horizon is considered the ROs solution costs less than a solution that
459 ignores different future possible scenarios. This is a proactive way to arrive at a minimum
460 cost design solution for an extended planning horizon.

461

462 **4 CONCLUSIONS**

463

464 This work describes an innovative ROs approach used for a decision making process under
465 uncertainty, in the field of water supply networks' design. The optimization model presented
466 in this paper tries to minimize costs over the whole planning horizon. Based on trying to delay
467 some decisions for the future, ROs enables total investment to be reduced. But this delay
468 comes at a cost. The initial solution has to be flexible enough to accommodate all the future
469 conditions, and some pipes have to be oversized.

470

471 The design of a specific case study was used to explain the approach. Different options were
472 considered for the infrastructure and the planning horizon was subdivided into periods with
473 the aim of making midcourse corrections or additional investments. The results were
474 presented by a decision tree, with the value for the different decision variables as well as the
475 total amounts of investment and operating cost that will be expended. The future costs of the
476 ROs solutions were compared with the optimal costs of each scenario.

477

478 A comparison between the ROs approach and a traditional design was made. Results show
479 that the ROs solution makes it possible to save on resources if an extended and uncertain
480 planning horizon analysis is performed.

481

482 The ROs philosophy tries to find opportunities to incorporate flexibility into decision making
483 so as to mitigate the potential impact of future uncertainties, which in turn creates
484 opportunities for adaptation. For the case study, an adaptable network design for a 60-year
485 planning horizon had an extra initial cost, since a flexible solution is more costly than a
486 solution that does not take the future into account. However, the latter solutions will not have
487 sufficient robustness to accommodate the future scenarios, and therefore some pipes in the
488 network will need to be reinforced, for example by installing new parallel pipes. These
489 reinforcements will of course increase the overall cost of the system over its entire planning

490 horizon. The real value of ROs is their ability to adapt the solution to different future possible
491 decisions.

492

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499

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Table 1: Diameter, unit costs, Hazen-Williams coefficients

Diameters (mm)	Unit costs (€/m)	Hazen-Williams Coefficients
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100	87	125
125	97	125
150	102	125
200	120	125
250	147	125
300	157	125
350	187	125
400	215	125
450	247	125
500	277	125
600	371	125

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Table 2: Characteristics of the new nodes

Node	Ground elevation (m)	Nodal consumption (l/s)			Minimum pressure (m)		
		(1)	(2)	(3)	(1)	(2)	(3)
11	298.56	18.927	13.249	18.927	35.0	35.0	14.0
12	289.56	31.545	22.082	31.545	35.0	35.0	14.0
13	243.84	18.927	13.249	18.927	35.0	35.0	14.0
14	243.84	12.618	8.833	12.618	35.0	35.0	14.0

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Table 3: Characteristics of the new pipes

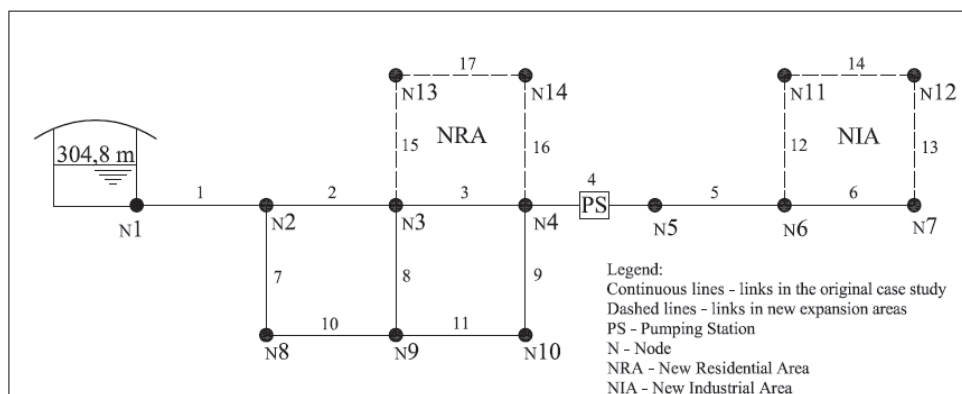
Pipe	Initial Node	Final Node	Length (m)
12	6	11	1609.344
13	7	12	1609.344
14	11	12	1609.344
15	3	13	1609.344
16	4	14	1609.344
17	13	14	1609.344

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Table 4: Network cost for the different scenarios

	Scenarios							
	1	2	3	4	5	6	7	8
Construction cost (€)	3,992,269	3,682,766	3,794,636	3,512,817	3,242,176	3,215,033	2,937,053	2,975,677
Cost of energy (€)	1,190,024	1,156,966	1,163,855	1,137,703	756,193	717,879	779,515	733,601
Cost of the pumps (€)	389,067	382,747	387,690	383,855	318,121	312,560	322,491	315,145
Total costs (€)	5,571,360	5,222,478	5,346,181	5,034,376	4,316,491	4,245,471	4,039,059	4,024,423

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Figure 1: Water distribution network inspired from Taher & Labadie (1996) with possible expansion areas

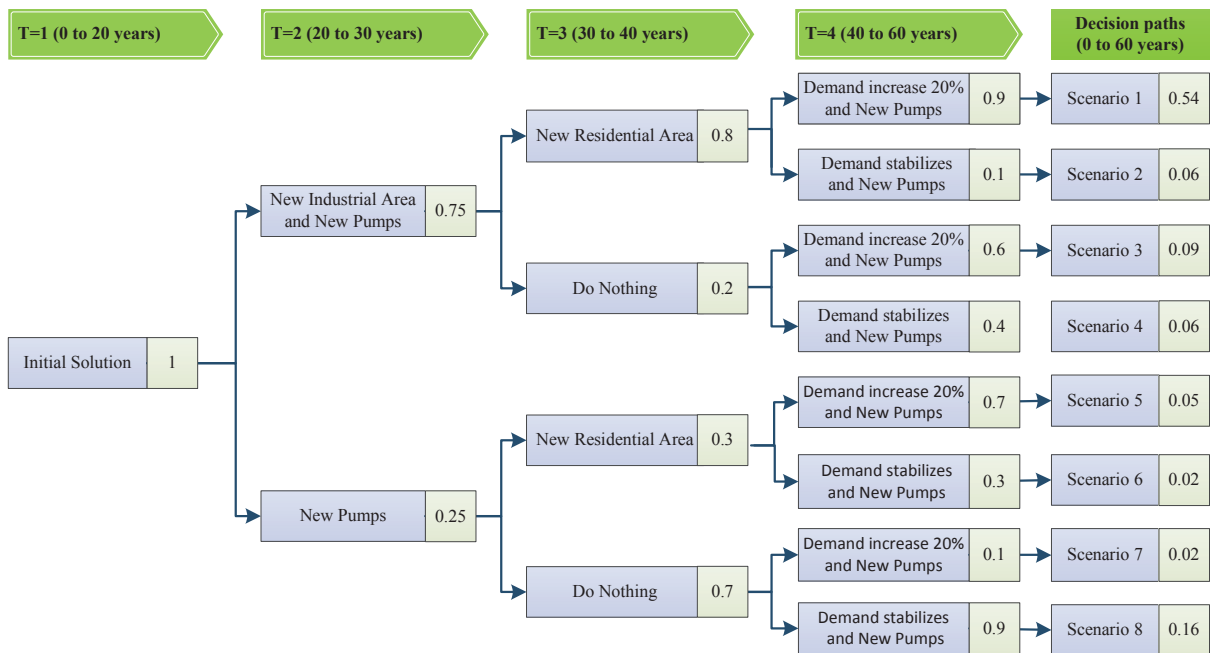
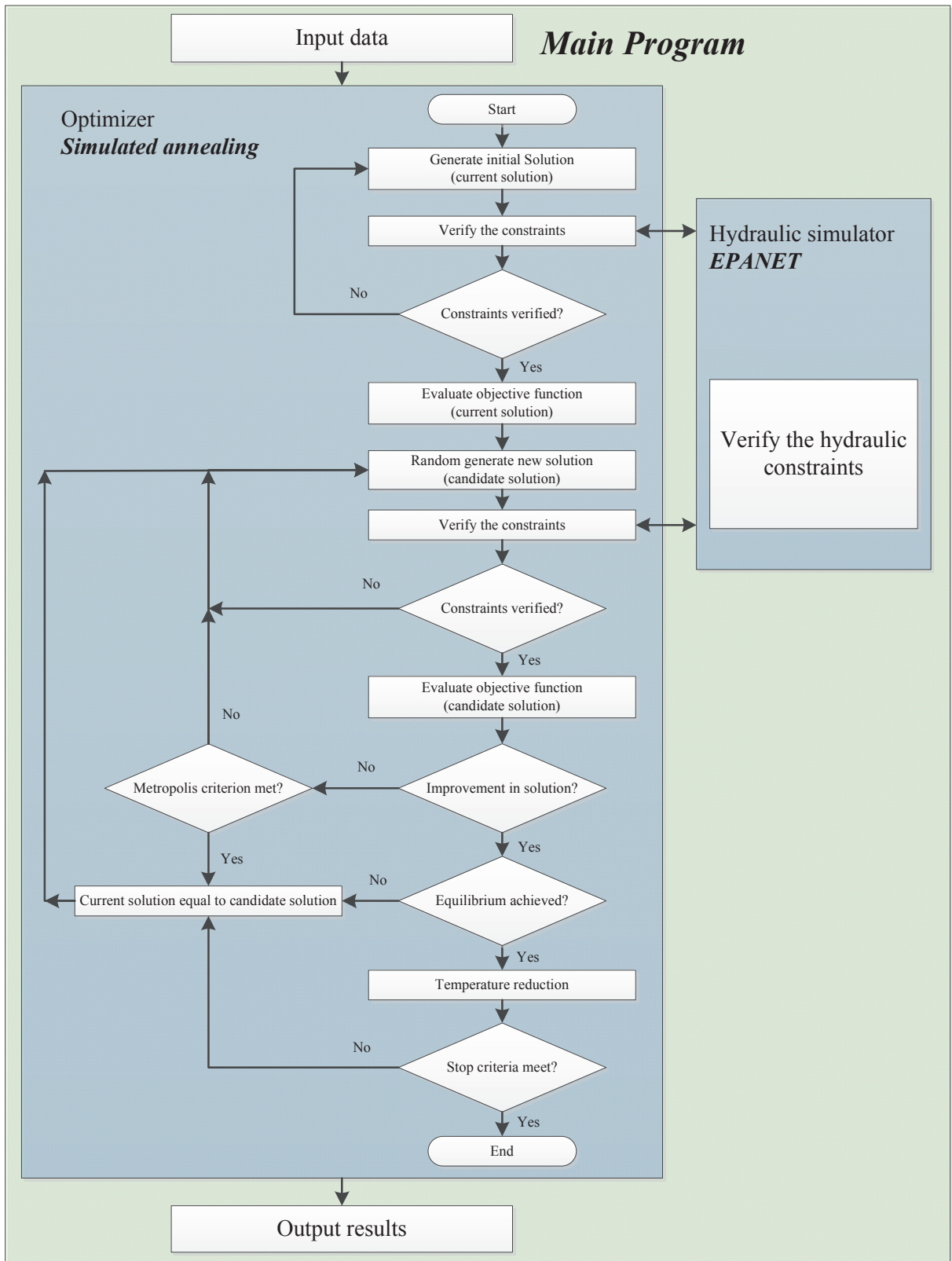


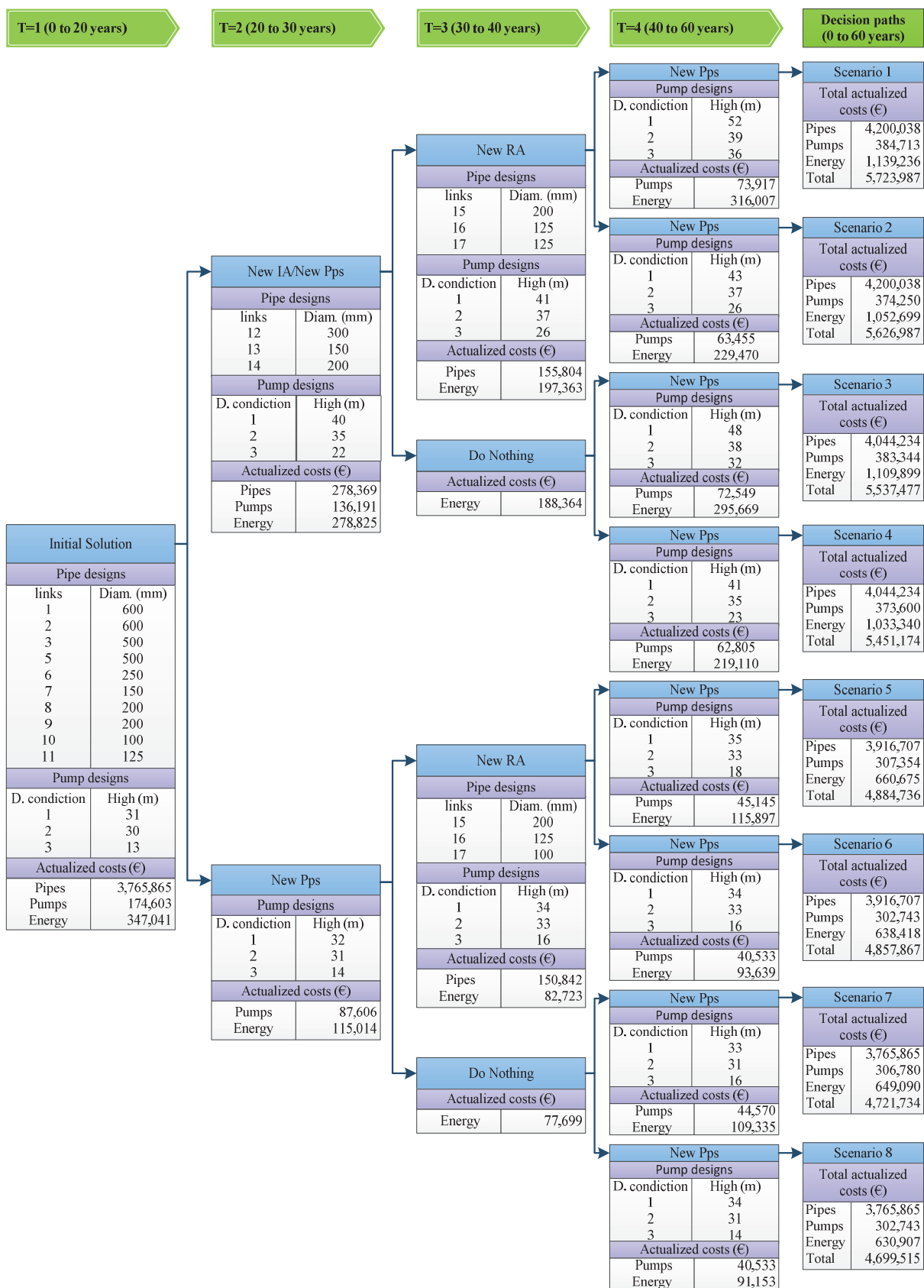
Figure 2: Decision tree for the planning horizon

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Figure 3: Main program diagram



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Figure 4: Solution for Real Options approach

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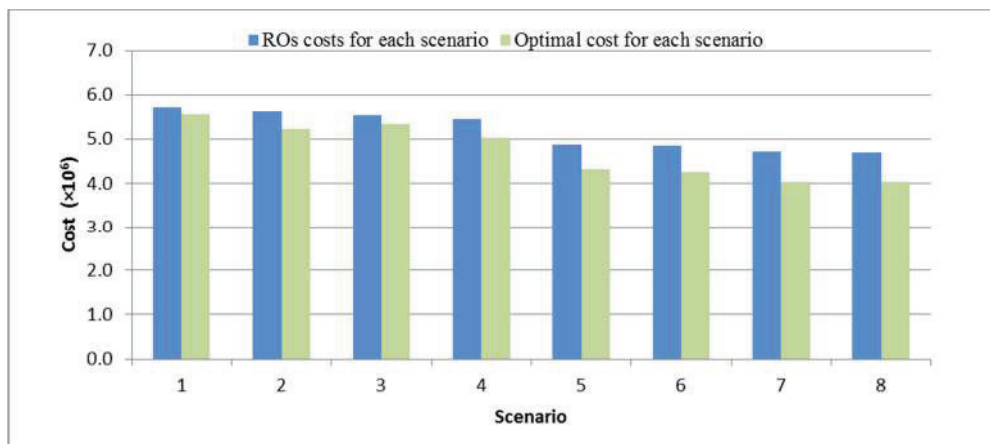


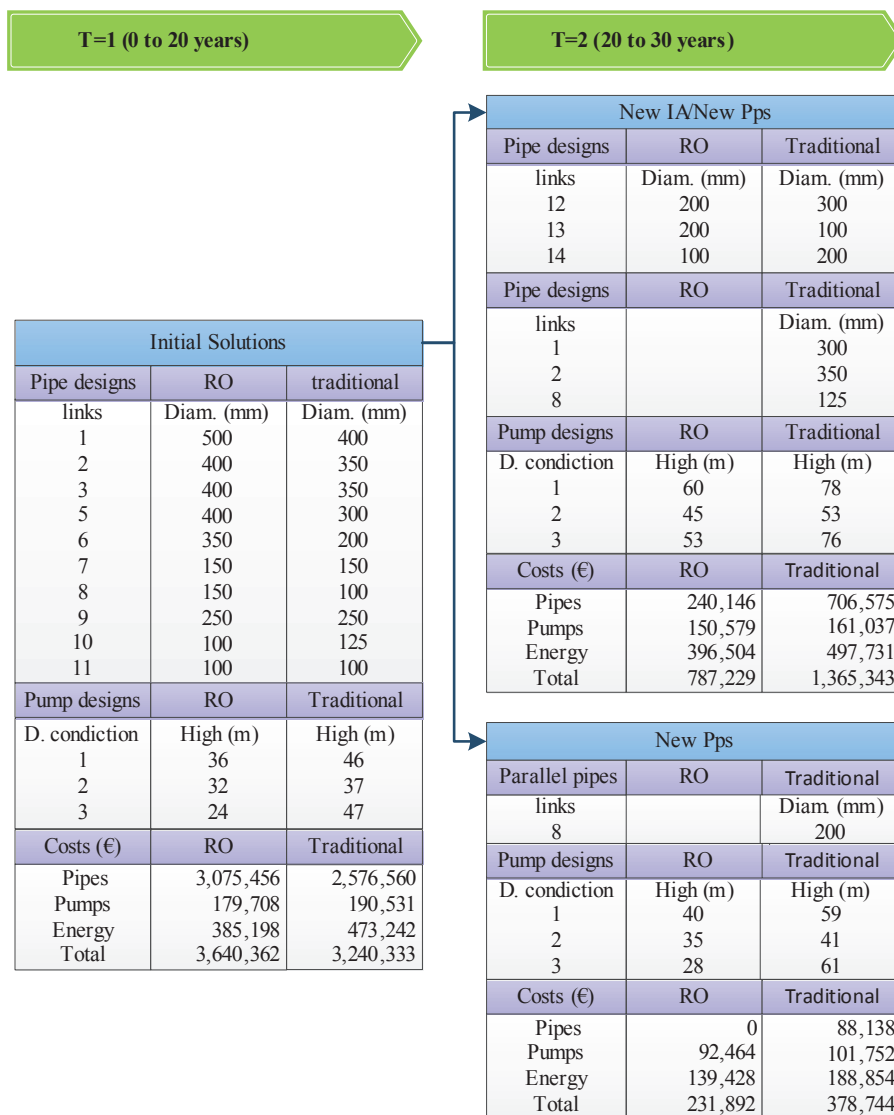
Figure 5: Cost comparison

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Figure 6: Comparison between ROs and traditional design