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Decision support for optimal design of water distribution networks: a real options approach

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Abstract

There is a growing concern about how the technical, managerial and financial capacity of drinking water systems can be sustained in the long run with future uncertainties. A water supply system is critical for the well-being of a community and it must provide water in sufficient quantity, of appropriate quality and without interruption. People have high expectations for the proper functioning of these systems but the future is uncertain and it is very difficult to conceive an infallible infrastructure. This work proposes a real options (ROs) approach that takes into account future uncertainty associated with water distribution networks. The ROs methodology extends traditional analysis to include flexible strategic implementation. This work describes a decision support methodology to design water networks that are adaptable over a long-term planning horizon. Representing design strategies as decision trees allows decision makers to easily adapt the system according to future circumstances. Results show that the ROs solution makes it possible to save on resources through an analysis based on an extended and uncertain planning horizon.

Keywords: Water distribution networks; real options, optimization, simulated annealing

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1. Introduction

The adaptation of an infrastructure is intrinsically related to the development of a community. Water supply systems have to be adjusted if there is an important change in demand. Urban infrastructure planning is an immense and complex task. According to (Haimes, 1998) the great challenge for the scientific community of the third millennium will be to develop tools and technologies to support and maintain infrastructures. Several methods for effective planning in the field of water systems have appeared in the literature. If flexible planning can be adopted, infrastructures will be capable of coping with future uncertainty. In this context an approach called real options (ROs), originating in financial theory, could make an important contribution. Myers (1977) was the first to introduce the term Real Options (ROs). Since then a large number of studies have been published where the concepts of ROs have been used in several fields.

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

A number of studies have developed ROs approaches to solve a variety of problems: Wang and Neufville (2004) divide ROs into two categories, ROs “on”systems and ROs “in” systems. ROs “on” systems focus on the external factors of a system and benefit from the use of financial valuation tools. In the other hand, ROs “in” systems incorporate flexibility into the structural design of a system and it is harder to value flexibility. This is the ROs category used to design water distribution networks; Nembhard and Aktan (2010), who systemized applications of ROs to design and develop engineering problems; Neufville et al. (2006), report the use of ROs in car parking problems and Gersonius et al. (2010) apply ROs analysis to the option planning process in urban drainage systems to incorporate flexibility to accommodate climate change while reducing future flood risk. In the water industry, an ROs technique appears in the work of Woodward et al. (2011) to define maritime coastal defences to reduce the risk of flooding. In the area of water systems expansion, Suttinon and Nasu (2010) present an ROs based approach where the demand increases. Zhang and Babovic (2012) also use an RO approach to evaluate different water technologies into water supply systems under uncertainty. Finally, the work of Huang et al. (2010) describes the application of ROs to design of water distribution networks. The methodology used presents a flexible design tool based on decision scenario trees that reflect uncertainty associated with future demand for water. The authors use a genetic algorithm optimization model to find a flexible design in a simple case study. This work presents a different approach where uncertainty is not only associated with future demand for water, but it also considers new expansion scenarios for the network. The different possible network configurations during the planning horizon provide an alternative approach to how flexibility can be taken into account in the process of finding the optimal design of water distribution systems.

Water distribution systems are costly and complex infrastructures which are meant to distribute water uninterruptedly over a long planning horizon. Once laid, pipes cannot be reinforced without making large investments. Lansey et al. (1992) presented the first attempt to solve the optimal maintenance scheduling of water distribution systems and more recently Creaco et al. (2013) formulated the problem according to a multi-objective approach without uncertainty. Therefore, it is very important in water system planning to try to predict the future operating conditions. However, cities are continually changing and the water supply networks have to be adapted to these changes. Sometimes a new urban or industrial area is built and the network has to be reinforced to accommodate the new conditions. But the opposite can also occur in areas whose population declines and the demand falls.

The benefits of flexible design relate to the facility to accommodate different future scenarios. But usually, flexibility implies extra cost at the initial stage of a water network design. A flexible design is the one that enables the designer, developer, or operator to actively manage or further develop the configuration of the system downstream, to adapt it to changes in the supply, demand, or economic environment. The ROs approach presented in this work uses a decision tree to reflect different scenarios that can occur during the planning horizon. The process uses an optimization model to find the optimal solution for the first period and for different future possible realities. The model uses a minimum cost objective function and various scenarios are considered to predict different alternative future conditions.

The new ROs approach presented in this work deals with future uncertainties and tries to minimize costs over the whole planning horizon. Decision planning based on trying to delay some decisions for the future, enables current investment to be reduced. But this delay entails some costs because the initial solution has to be flexible enough to accommodate all the future conditions, and this flexibility comes at a price.

The remainder of this study is organized as follows: in the next section the case study and the future scenarios are set out. This is followed by a decision model based on a ROs approach. Then the results are presented and some comparisons are drawn. Finally, the conclusions are systemized.

2. Case study

During the planning horizon, water supply systems have to be continually adapted to urban growth. Some areas can become urbanized or alternatively, other areas that can become depopulated. These changes have impacts on the hydraulic behavior of the networks and should be taken into account. In this section, a case study is presented with the objective of demonstrating how the ROs approach is employed. This is a water distribution network used in Walski et al. (1990) and presented in Fig. 1.

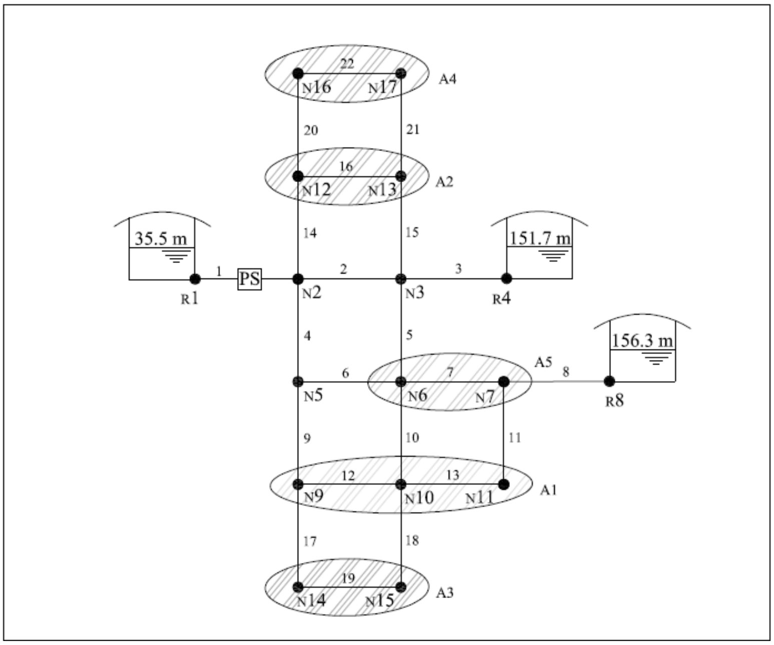

Fig. 1. Water distribution network, inspired from Walski et al (1990)

Three reservoirs, with a fixed level of water, supply the network. There is also a pump placed at link (1). The efficiency of the pump is 75% and the daily consumption is 20 hours at demand condition (1) and the other 4 hours at demand condition (2). The energy costs are 0.075$/KWh and should be evaluated for a 60-year period by a discount rate of 4% year. This rate was fixed based on the work of Wu et al. (2010). The characteristics of the nodes are presented in table 1 for demand conditions (1) and (2). The characteristics of the pipes are exhibited in table 2.

Table 1. Characteristics of the nodes

Node	Areas	Ground elevation (m)	Nodal consumption (l/s)		Minimum pressure (m)	
			(1)	(2)	(1)	(3)
1		36.48	Reservoir at the level of 35.48 m			
2		30.48	0	0	28.132	17.583
3		106.68	31.545	47.318	28.132	17.583
4		117.35	Reservoir at the level of 151.73 m			
5		106.68	31.545	47.318	28.132	17.583
6	A5	106.68	126.180	189.270	28.132	17.583
7	A5	106.68	63.090	94.635	28.132	17.583
8		121.92	Reservoir at the level of 156.30 m			
9	A1	106.68	31.545	47.318	28.132	17.583
10	A1	106.68	31.545	47.318	28.132	17.583
11	A1	106.68	31.545	47.318	28.132	17.583
12	A2	106.68	31.545	47.318	28.132	17.583
13	A2	106.68	31.545	47.318	28.132	17.583
14	A3	106.68	31.545	47.318	28.132	17.583
15	A3	106.68	31.545	47.318	28.132	17.583
16	A4	106.68	31.545	47.318	28.132	17.583
17	A4	106.68	31.545	47.318	28.132	17.583

Table 2. Characteristics of the pipes

Pipe	Initial Node	Final Node	Length (m)	Areas
1	1	2	Pump	
2	2	3	3218.688	
3	3	4	3218.688	
4	2	5	1609.344	
5	3	6	1609.344	
6	5	6	3218.688	
7	6	7	3218.688	
8	7	8	1609.344	
9	5	9	1609.344	A1
10	6	10	1609.344	A1
11	7	11	1609.344	A1
12	9	10	3218.688	A1
13	10	11	3218.688	A1
14	2	12	1609.344	A2
15	3	13	1609.344	A2
16	12	13	3218.688	A2
17	9	14	1609.344	A3
18	10	15	1609.344	A3
19	14	15	3218.688	A3
20	12	16	1609.344	A4
21	13	17	1609.344	A4
22	16	17	3218.688	A4

This is a new network that considers 8 different commercial diameters presented in table 3 to the pipe design.

Table 3. Diameter, unit costs, Hazen-Williams coefficients

Diameters (mm)	Unit costs ($/m)	Hazen-Williams Coefficients
152.4	49.541	100
203.2	63.32	100
254	94.816	100
304.8	132.874	100
355.6	170.932	100
406.4	194.882	100
457.2	225.066	100
508	262.795	100

A network planning horizon of 60 years was taken for this case study, which was split into 3 stages of 20 years each. Assuming a subdivided planning horizon, different conditions can occur in future time intervals. This case study adopts 8 possible scenarios that are schematized in a decision tree shown in Fig. 2.

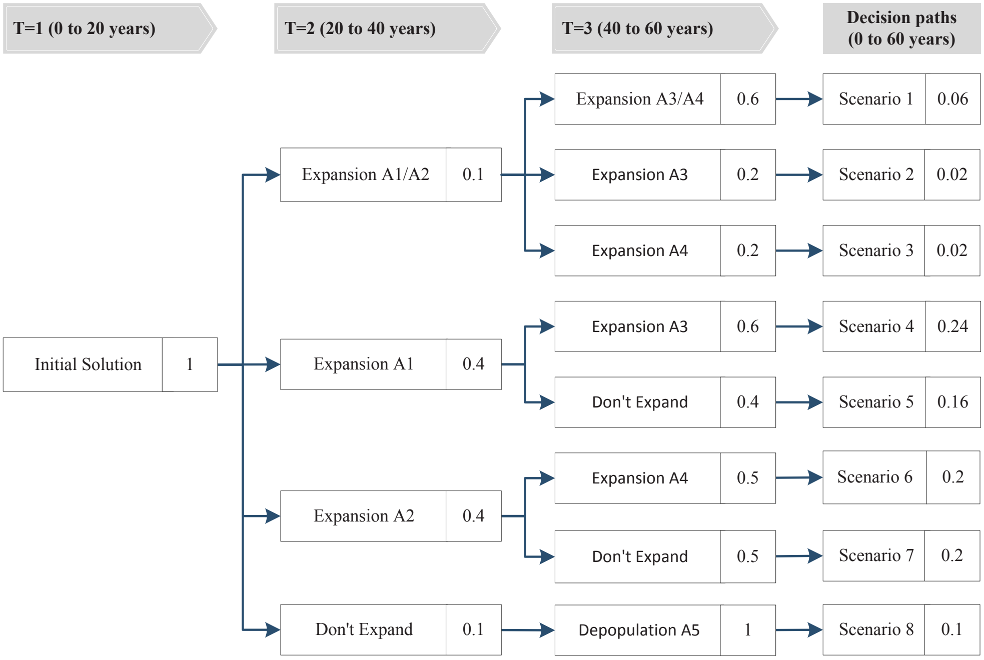

Fig. 2. Decision tree for the planning horizon and probabilities of occurrence

The different scenarios have different probabilities. For this case study the probabilities considered for the different paths are shown in the squares of Fig. 2. The probabilities of the scenarios are calculated by multiplying the probabilities of all nodes on the path of that scenario, and are shown in the last branches of the tree. In the first period (T=1) an initial design for the network is determined. For T=2, four different situations can occur, expansion to A1 and A2, expansion to A1, expansion to A2 and don’t expand. In the last period T=3, new expansion areas are possible A3 and A4, expansion to A3, expansion to A4 and don´t expand. It is also possible to have a depopulated area A5 where the consumption could decrease by 30%. These scenarios included in the decision tree of Fig. 2 are considered the most probable future conditions for the case study.

3. Decision model

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

$$OF = Min\ \left(Ci + Cf\right) \tag{1}$$

Where:

Ci	cost of the initial solution to be implemented in year zero ($)
Cf	cost of the future scenarios ($)

The objective function of Eq. 1 is written so that the solution for the first period, T=1, can be determined taking into account the different paths of decisions that have to be made during the planning horizon. The objective function seeks to minimize not only the initial cost but also the probable future costs of the system. The term *Ci* computes the cost of the network for the first period t=1 of planning and is given by Eq. 2

$$Ci = \left(\sum_{i=1}^{NPI}\left(Cpipe_i\right) + \sum_{j=1}^{NPU}\left(Cps_{j,1}\right) + \sum_{d=1}^{NDC}\left(Ce_d\right) \right) \tag{2}$$

Where:

NPI	number of pipes in the network
$Cpipes$	cost of pipe *i*
NPU	number of pumps in the network
$Cpsj$	pumping station costs of pump *j* in the period *t=1*
NDC	number of demand conditions considered for the design
Ced	updated cost of energy in demand condition *d*

The initial cost is given by the sum of the cost of pipes, the cost of pumps and the present value of energy cost. The other term of the objective function represents the future cost of all the decision node designs (Eq. 3) weighted by the respective probability of each decision node presented in Fig. 2.

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

Where:

NTI	number of periods into which the planning horizon is subdivided
NDN	number of decision nodes in each time interval
$Cfuture_{t,s}$	cost of the future designs in scenario *s* for period *t*
$Prob_{nt,s}$	probability of the scenario *s* in period *nt*

The cost of future scenarios are achieved summing all possible future costs, starting from T=2. These costs are computed multiplying the cost of each decision option by the probability of tanking that decision path. The value of the probability of the decision path is given by the product of all the nodal probabilities of that decision path. A weighted mean is obtained for the future possible costs for the network. The term *Cfuture* is computed in Eq. 4, for all periods beginning in T=2 (the costs for the first period are already calculated in the *Cinitial* term) and it is given by the sum of three terms.

$$Cfuture_s = \sum_{t=2}^{NTI} \left\{ \left(\sum_{i=1}^{NPI} \left(Cpipe_i \right) + \sum_{j=1}^{NPU} \left(Cps_{j,t,s} \right) + \sum_{d=1}^{NDC} \left(Ce_d \right) \right) \cdot \frac{1}{\left(1+IR\right)^{Y_t}} \right\} \tag{4}$$

Where:

IR	annual interest rate for cost updating
Yt	year when costs will be incurred for period t

The first term of Eq. 4 computes the cost of the pipes to be installed for different decision paths, the second term computes the costs to install pumps every 20 years and finally the last term computes the cost of energy. Thereafter, the present value costs are computed, considering the year when costs will be incurred.

The sum of the initial costs with future costs is intended to represent the full planning horizon of the network, considering future uncertainty. This model has to determine the decision variables not only for the first period but also for all the future decisions that have to be taken according to certain possible decision paths. The values of the decision variables that are achieved for the first period are effectively the ones that are needed to be adopted now. The constraints of the model are those normally used in the optimal design and operation of water distribution systems (Cunha and Sousa 2001). The optimization model is solved by a simulated annealing algorithm used by Cunha and Sousa (1999) and adapted for this work. The optimization model was linked to EPANET, Rossman (2000) hydraulic simulator to verify the hydraulic constraints. This design, achieved by considering some ROs, makes it possible to obtain flexible solutions that can accommodate various future realities that may occur.

4. Results

In this work, the uncertainty is modeled by a scenario tree method. The ROs approach was formulated as a multi-stage model that has the objective to design the network for the first time interval and help decision makers to find the best system development strategy with the aim of minimizing the costs. The results for the case study are presented in Fig. 3.

Decisions have to be made for each time interval of the decision tree. Fig. 3 presents, for each node, a table with the results of the design, beginning with the diameters of pipes in millimetres required in the network. Then the costs are shown, subdivided into cost of pipes, energy, pumps and total costs. Finally the last branches of the decision tree present the total cost for each scenario of the pipes, energy for pumps, updated for the year zero. These figures represent, for each scenario, the total amounts of investment and operating cost that will be expended if that scenario occurs. Only the first stage design decision has to be implemented now, and therefore, the future decisions will be made according to the evolution’s requirements.

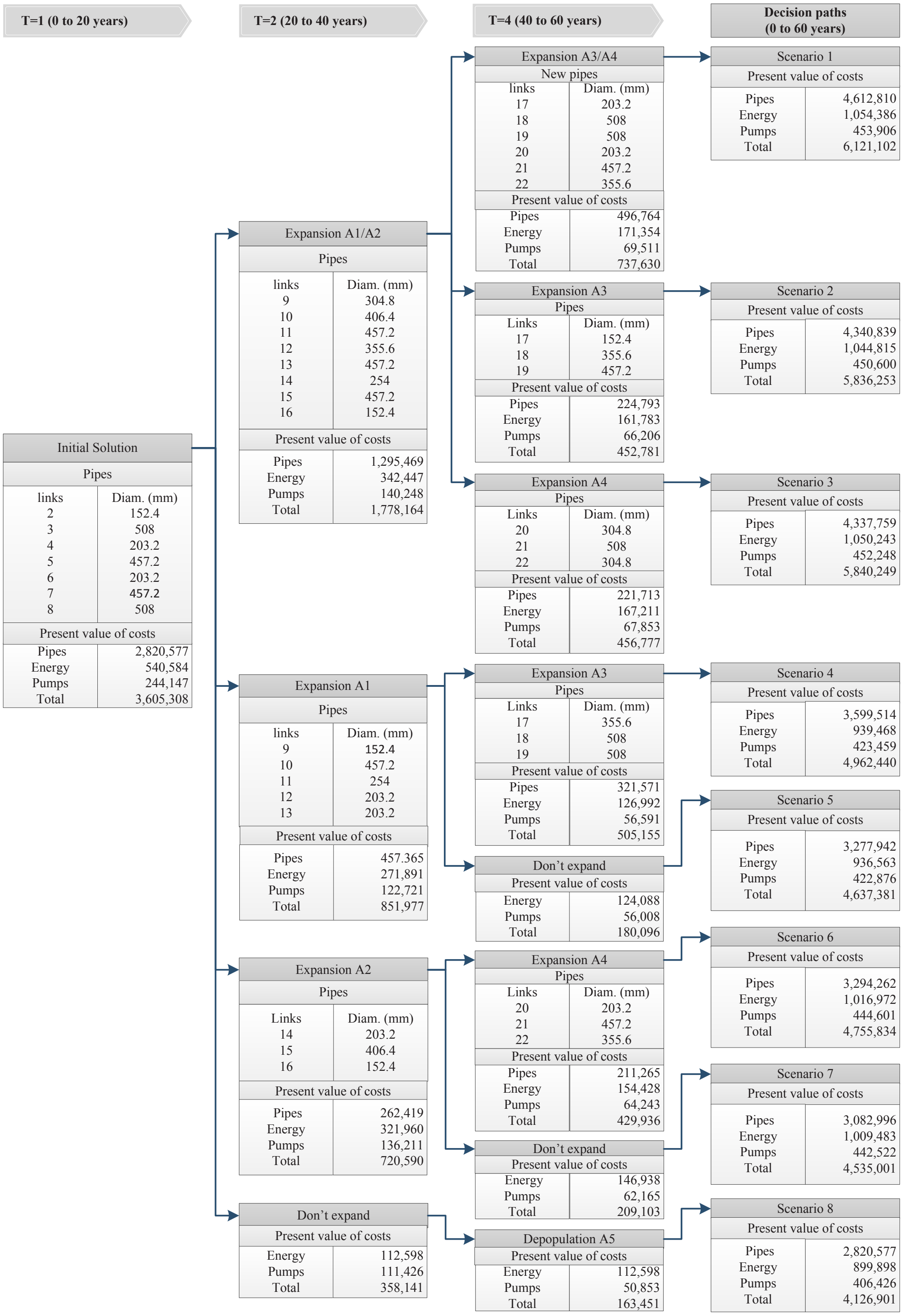

Fig. 3. Designs and costs for the case study according to the decision tree of the planning horizon

From Fig. 3 it is possible to understand the different future possible decisions that can be made. The design for the network is not only dependent on the hydraulic conditions of the present decision but also is dependent on the decision paths that can be followed. The decisions taken in prior stages have to accommodate the future possible conditions of the network. The ROs approach considers different scenarios with different probabilities. By adding together the initial cost with all the future weighted costs presented in each node of the decision tree in Fig. 3 it is possible to achieve to the present value of ROs solution, which is $4,804,620. The decision makers can use this cost as the reference for the entire planning horizon design and operation of the network.

The design achieved for each link has enough capacity to supply the network to future new areas that may be built. Pipes 2 to 8 (see Fig. 1) are designed in the first stage, but need to have enough capacity for different decision paths. However, a tradeoff exists to determine the minimum cost solution that can use the pumping station to increase the pressure in the network, but the energy costs also increase, or it is also possible to increase the diameter of the pipes to decrease the head losses, but an initial high investment is required. The optimization model used in this works as it is possible to find solutions for the different time horizon paths that can be followed in the future.

The solution for the first stage is flexible enough to accommodate all possible situations. However this flexibility comes at a cost. If a solution for the first stage is determined considering that the decision path followed will be scenario 8, the first stage costs are 23% lower than the ROs solution. This scenario is the less demanding case for the network. Fig 4 represents the design of the network with ROs (1) and considering scenario 8 (2).

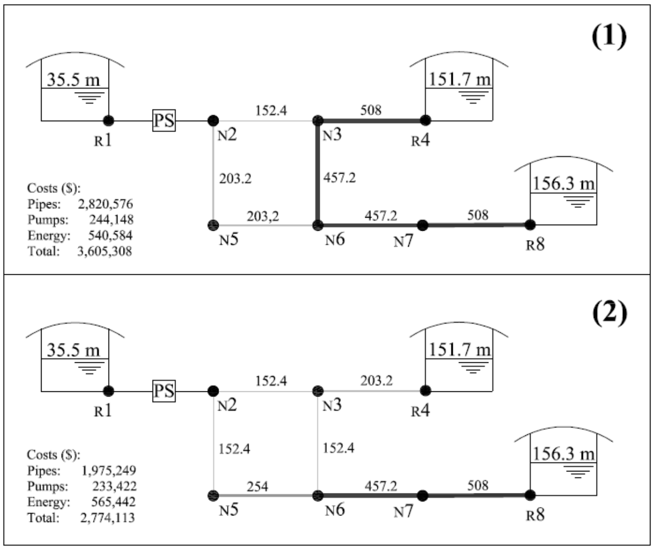

Figure 4: Solutions for first stage design (1) ROs design (2) tradition design for scenario 8

It can be seen from Fig. 4 that the optimal design achieved with ROs approach (1) adopts larger diameters for some links of the network than the traditional design for the future decision path of scenario 8 (2). Design (2) cost less, however it does not function well in more demanding conditions. If different scenarios occur and some of the links have to be reinforced that will increase the overall costs of the planning horizon. If solution (2) is adopted for the first stage and the decision path follows the most probable situation (scenario 4) the global cost will be 4% higher than the costs determined by ROs solution, due to reinforcements required on some links of the network. In the case of the design (1) the network has enough capacity to verify the minimum pressure requirements for all possible decision paths considered in the case study.

5. Conclusion

This work describes an ROs approach used for a decision making process under uncertainty, in the field of water supply networks design. The optimization model presented in this communication tries to minimize costs over the whole planning horizon. Based on trying to delay some decisions for the future, ROs enables total investment to be reduced. But this delay comes at a cost. The solution for the first stage has to be flexible enough to accommodate all future decision paths. The design of a specific case study was used to explain the approach. Different options were considered for the infrastructure and the planning horizon was subdivided into periods with the aim of making midcourse corrections or additional investments. The results were presented by a decision tree, with the value for the different decision variables as well as the total amounts of investment and operating cost that will be expended. In the case study, an adaptable network design for a 60-year planning horizon had an extra initial cost, since a flexible solution is more costly than a solution that does not take the future into account. However, the latter solutions will not have sufficient resilience to accommodate the future scenarios, and therefore some pipes in the network will need to be reinforced, for example by installing new parallel pipes. These reinforcements will of course increase the overall cost of the system over its entire planning horizon. The real value of ROs is their ability to adapt the solution to different future possible decisions.

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