Using real options for an eco-friendly design of water distribution systems

João Marques, Maria Cunha and Dragan A. Savić

ABSTRACT

This paper presents a real options approach to handling uncertainties associated with the long-term planning of water distribution system development. 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 optimise 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.

Key words | carbon emissions, optimisation, real options, simulated annealing, uncertainty, water distribution networks

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INTRODUCTION

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

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

In this paper, we propose an approach that both handles environmental impacts, and tries to find appropriate flexible solutions for the design and operation of water distribution systems. McConnell (2007) defined system flexibility as 'the ability for a system to actively transform, or facilitate a future transformation, to better anticipate or respond to changing internal or external conditions'. These problems are challenging and very difficult to solve. The real options (ROs) approach could be very useful in this field. Black & Scholes (1973) and Merton (1973) are the works that define and solve the financial option valuing problem. Inspired by them, Myers (1977) introduced ROs. This approach permits flexible planning, thus allowing decision makers to adjust investment according to new future information. ROs have already been utilised for: designing maritime security systems (Buurman *et al.* 2009); finding the optimal capacity for hydropower projects (Bockman *et al.* 2008); dam project investments (Michailidis & Mattas 2007); constructing a parking garage (De Neufville *et al.* 2006); and designing satellite

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fleets (Hassan *et al.* 2005). However, there are very few papers where ROs concepts are applied to water infrastructure: Woodward *et al.* (2011) used ROs for flood risk management and Zhang & Babovic (2012) used ROs for decision support in the design and management of a flexible water resources framework through innovative technologies. We propose a ROs approach to define the design of water distribution networks under different possible future conditions and taking carbon emissions into account.

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

In the last decade, objectives focused on environmental issues have started to feature in water distribution networks optimisation works. The key work by Filion *et al.* (2004) has been followed by a vast body of literature. Some works analysed and compared the carbon emissions with different pipe material installation (e.g. Dandy *et al.* (2006) and Shilana (2011)) in a single objective framework.

Wu *et al.* (2008) were the first work to introduce the goal of minimising GHG into the multiobjective optimal design of water networks. The works of Wu *et al.* (2010, 2011, 2013) report some developments and comparisons based on the multiobjective approach.

Herstein *et al.* (2009) take the idea of concentrating different environmental impacts in a single measure and present an index-based method to evaluate the environmental impacts of water distribution systems. This environmental index aims to aggregate multiple environmental measures calculated by an economic input–output life-cycle assessment model. However, some criticism of this methodology has emerged (Herstein & Filion 2011). Herstein *et al.* (2010) and Herstein *et al.* (2011) include different optimisation models to minimise this index.

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

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

A simulated annealing heuristic has been used to solve the optimisation model. The problem addressed in our work is large, non-linear and complex and involves discrete decision variables; therefore modern heuristics (simulated annealing, genetic algorithms, particle swarm optimisation and so on) are suitable for its resolution. A literature review shows that simulated annealing has been used in various fields and good performances were observed. It has been successfully implemented in areas such as aquifer management (Cunha 1999), water treatment plants (Afonso & Cunha 2007), wastewater systems (Zeferino *et al.* 2012), rail network planning (Costa *et al.* 2013) and water distribution design (Cunha & Sousa 2001; Reca *et al.* 2007, 2008).

Simulated annealing is an iterative process based on the Monte Carlo method and inspired by an analogy made between the annealing process as a metal cools into a minimum energy crystalline structure and a search for a global minimum solution in an optimisation problem. The simulated annealing approach used is based on Cunha & Sousa (1999, 2001), where a more detailed analysis of the parameterisation of this method and its application to the optimisation of water distribution networks can be found. In brief, the basic idea of simulated annealing rests on the analogy made between the temperature reduction of physical systems and the minimisation problem. The simulated annealing temperature is used in the Metropolis criterion (Metropolis *et al.* 1953) to accept uphill moves in terms of cost. The temperature starts at a high value so that a high proportion of attempted changes can be accepted. As the iterative process progresses, the temperature is reduced according to an annealing schedule, defined in our work by a geometric progression with a cooling factor of 0.90. A minimum number of iterations are required to reduce the temperature. In each temperature reduction, the proportion of accepted moves goes down until, finally, no uphill moves (in cost) are accepted. If the simulated annealing has been performed slowly enough the final solution could be the global minimum.

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

CARBON EMISSIONS OF WATER DISTRIBUTION SYSTEMS

To incorporate carbon emission costs in the design and operation of the water networks, it is necessary to quantify emissions from the very beginning of the extraction of the materials that are used until their final disposal. Water distribution infrastructure is built from and maintained with a range of materials. The most common are the steel and cast iron used in pipes, accessories and pumps; reinforced concrete in civil construction works like tanks, manholes and anchorages; plastic in pipes and accessories; aggregates in pipeline backfill and asphalt for repaving. The carbon emissions of these materials can only be evaluated if the whole life cycle is involved, which includes the extraction of the raw material, transport, manufacturing, assembling, installation, dismantling, demolition and/or decomposition. The embodied energy is determined by the sum of the energy sources (fuels, materials, human resources and so on) that are used for product manufacturing and its use. The embodied energy tries to compute the sum of the total energy expended during all the life cycle of the product. Hammond & Jones (2008) present the embodied energy for the life cycle of some materials. Table 1 shows the embodied energy of the most common materials used in water distribution infrastructure.

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

To determine the embodied energy of pipe construction in the traditional way, the quantity of energy per metre of pipe is considered. The weight of the materials used to settle 1 m of pipe must, therefore be determined. Given

Table 1 | Embodied energy of some materials used in water infrastructure

	Embodied energy	
Material	**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

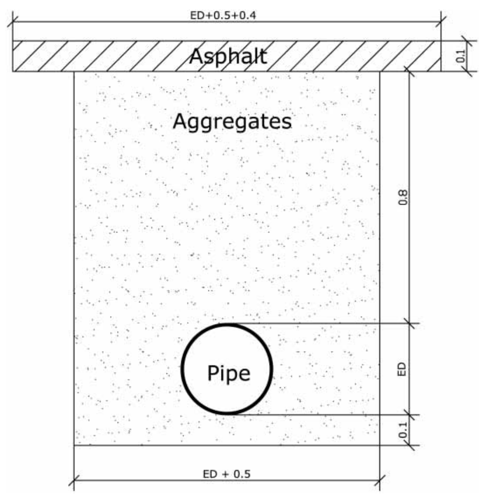

Figure 1 | Scheme to compute quantities of materials (dimensions in metres).

the scheme in Figure 1, we can calculate the volume of aggregates and asphalt needed for the settlement of each metre of pipe. The quantity of materials per metre is a function of the pipe's external diameter (ED), since the excavation and repaving volumes increase the higher the pipe diameter ED. We assume ductile iron pipes and Equation (1) is used to compute the embodied energy of the material:

$$EE_{\text{pipe}_{D_c}} = WD_c \times EE_{\text{iron}} \quad (1)$$

where $EE_{\text{pipe}_{D_c}}$ is the embodied energy of the pipe with commercial diameter D_c (kWh/m); WD_c is the weight of the commercial diameter D_c (kg/m); and EE_{iron} is the embodied energy of the ductile iron for pipes (kWh/kg).

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

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

where $EE_{\text{aggr}_{D_c}}$ is the embodied energy of aggregates to backfill a pipe with diameter D_c (kWh/m); ED_{D_c} is the external diameter of the pipe with diameter D_c (m); W_{aggr} is the weight of aggregates, equal to 2,240 kg/m^3; and EE_{aggr} is the embodied energy of the material (kWh/kg).

Finally, the last material is asphalt; 0.2 m is assumed for the extra paving of each side of the trench. The embodied energy is computed by Equation (3):

$$EE_{\text{asphalt}_{D_c}} = \{((0.5 + ED_{D_c}) + 0.2 + 0.2) \times 0.1 \times 1\} \times EE_{\text{asphalt}} \times EE_{\text{asphalt}} \quad (3)$$

where $EE_{\text{asphalt}_{D_c}}$ is the embodied energy of asphalt (kWh/m); W_{asphalt} is the weight of the asphalt, equal to 2,300 kg/m^3; and $EE_{\text{asphalt}D_c}$ is the embodied energy of asphalt (kWh/kg).

To determine the total embodied energy (Equation (4)) per metre of installed pipe, Equations (1)–(3) are added together:

$$EE_{\text{total}D_c} = EE_{\text{pipes}_{D_c}} + EE_{\text{aggr}D_c} + EE_{\text{asphalt}_{D_c}} \quad (4)$$

where $EE_{\text{total}_{D_c}}$ is the total embodied energy of pipe installation (kWh/m).

Now the embodied energy can be computed for the different commercial diameters, considering the contribution of the ductile iron pipes, aggregates to backfill the pipe and asphalt for repaving. The carbon emissions related to the total embodied energy can be computed through Equation (5):

$$CE_{\text{pipe}_{D_c}} = EE_{\text{total}D_c} \times CET \quad (5)$$

where $CE_{\text{pipe}_{D_c}}$ is the carbon emissions of installing pipes with commercial diameter D_c (tonCO_2/m); and CET is the total carbon emissions from energy generation (tonCO_2/kWh).

Carbon emissions are computed assuming a value of $CET = 0.637 \times 10^{-3}$ tonCO_2/kWh of energy produced by non-renewable resources and obtained by a fuel mix of 58% coal, 20% natural gas, 13% oil, 5% diesel and 4% of other resources. This is a mean value of the carbon emissions of electricity generation sector by non-renewable resources between 2005 and 2010 in Portugal (ERSE 2012).

This work also considered the carbon emissions related to the installation of new tanks in the network. New tanks are assumed to be cylindrical and have the same transversal area of 500 m^2. For simplification, the walls and the slabs of the tanks are assumed to have the same thickness (see Figure 2).

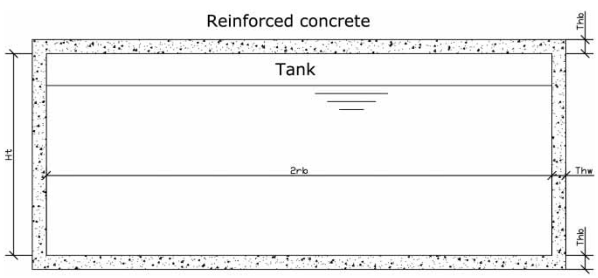

Figure 2 | Scheme for computing the concrete used in tank construction.

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

$$EET_{\text{concrete}_t} = \left[\begin{array}{l} \left\{ \pi \times (r_b + Th_w)^2 \times Th_b \right\} \times 2 \\ + \pi \times Ht_t \left\{ (r_b + Th_w)^2 - r_b^2 \right\} \end{array} \right] \times W_{\text{concrete}} \times EE_{\text{concrete}} \quad (6)$$

where EET_{concrete_t} is the embodied energy of concrete of the tank t (kWh); r_b is the radius of the slab of the tank, 12.62 m; Th_w is the thickness of the walls of the tank, 0.35 m; Th_b is the thickness of the slabs of the tank, 0.35 m; Ht_t is the height of the tank (m); W_{concrete} is the weight of concrete, 2,500 kg/m^3; and EE_{concrete} is the embodied energy of concrete (kWh/kg).

The embodied energy of reinforcing steel bars for the concrete of the tanks is also considered. For this study, the quantity of steel is taken to be a percentage of the cubic metres of concrete used in civil construction works, so the embodied energy of this material is given by Equation (7):

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

where EET_{steel_t} is the embodied energy of steel bars to build the tank t (kWh); Q_{steel} is the quantity of steel per cubic metre of concrete, 100 kg/m^3; and EET_{steel} is the embodied energy of steel bars (kWh/kg).

Summing the values given by Equations (6) and (7), the carbon emissions derived from constructing the tanks are determined through Equation (8):

$$CETK_t = (EET_{\text{concrete}_t} + EET_{\text{steel}_t}) \times CET \quad (8)$$

where $CETK_t$ is the carbon emissions of the tank t (tonCO_2).

In addition to the above, significant carbon emissions arise from generating the electric energy consumed during the water infrastructure operation. Large amounts of energy are consumed resulting in important carbon emissions that should be measured by Equation (9):

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

where CE_{op} is the carbon emissions from energy used in the operation of the network (tonCO_2); and EC is the energy consumption of the network during the operation (kWh).

Equation (9) computes carbon emissions generated by network operation. This work does not take into account carbon emissions related to other network elements that are negligible when compared with pipe and tank construction.

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

OPTIMISATION MODEL

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

The approach we describe uses ROs to handle different possible scenarios that can occur during the life cycle of the infrastructure. According to Wang *et al.* (2004), the ROs approach has two stages: option identification and option analysis. Option identification consists of trying to find all possible scenarios for the lifetime horizon. The option analysis stage can use an optimisation model to find possible solutions. This formulation enables decision makers to include additional possible situations simultaneously and to develop different decision plans throughout the life cycle.

The objective function, *OF*, includes the minimisation of the costs and carbon emissions resulting from implementing and operating the network. The objective function is presented in Equation (10):

$$OF = Min\, C_{\text{initial}} + \sum_{s=1}^{N_S}\sum_{t=2}^{N_{TI}}\left(C_{\text{future}_{t,s}}\cdot\prod_{nt=1}^{t}\text{Prob}_{nt,s}\right) + \left[CE_{\text{initial}} + \sum_{s=1}^{N_S}\sum_{t=2}^{N_{TI}}\left(CE_{\text{future}_{t,s}}\cdot\prod_{nt=1}^{t}\text{prob}_{nt,s}\right)\right]\cdot CEC \quad (10)$$

where C_{initial} is the cost of the initial solution to be implemented in year zero; N_S is the number of scenarios; N_{TI} is the number of time intervals into which the life cycle is subdivided; $C_{\text{future}_{t,s}}$ is the future design costs for time t in scenario s; $\text{Prob}_{nt,s}$ is the probability of future design in time nt in scenario s; CE_{initial} is the carbon emissions of the initial solution to be applied in year zero; $CE_{\text{future}_{t,s}}$ is the carbon emissions for time t in scenario s; and CEC is the carbon emissions cost.

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

$$C_{\text{initial}} = \left(\begin{array}{c}\sum_{i=1}^{N_{PI}}(C_{\text{pipe}_i}(D_{i,1})L_i)+\sum_{t=1}^{N_T}CT_t+\sum_{i=1}^{N_{PI}}(C_{\text{reab}_i}(D_{i,1})L_i)+\sum_{j=1}^{N_{PU}}(CE_{\text{p}_{s_{j,1}}})\\ \left(\sum_{d=1}^{N_{DC}}\left(Ce_d\cdot\sum_{j=1}^{N_{PU}}\frac{\gamma\cdot QP_{j,d,1}}{\eta_j}\cdot\Delta t_d\right)\cdot 365\cdot\frac{(1+IR)^{NY_1}-1}{IR\cdot(1+IR)^{NY_1}}\right)\end{array}\right) \quad (11)$$

where N_{PI} is the number of pipes in the network; $C_{\text{pipe}_i}(D_{i,1})$is the unit cost of pipe i as function of the diameter $D_{i,1}$ adopted; $D_{i,1}$ is the diameter of pipe i installed in time interval $T=1$; L_i is the length of pipe i; N_T is the number of new tanks in the network; CT_t is the cost of tank t; $C_{\text{reab}_i}(D_{i,1})$ is the unit cost to rehabilitate existing pipe i as a function of diameter $D_{i,1}$; N_{PU} is the number of pumps in the network; $CE_{\text{ps},_{j,1}}$ is the equipment cost of pump j for time interval $T=1$; N_{DC} is the number of demand conditions considered for the design; Ce_d is the cost of energy for demand condition d; γ is the specific weight of water; $QP_{j,d,1}$ is the discharge of pump j for demand condition d; and time interval $T=1$; $HP_{j,d,1}$ is the head of pump j for demand condition d and time interval $T=1$; η_j is the efficiency of pump j; Δt_d is the time in hours for demand condition d; IR is the annual interest rate for updating the costs; and NY_t is the number of years under the same conditions considered for time interval $T=1$.

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

$$CE_{\text{p}_s} = 700473.4Q^{0.7}H_m^{0.4} \quad (12)$$

where CE_{p_s} is the cost of the pump; Q is the flow of pump (m^3/s); and H_m is the head of pump (m).

The other term of the objective function is given by the weighted sum of the future costs. The future cost is computed by Equation (13):

$$C_{\text{future}_{t,s}} = \left(\begin{array}{c}\sum_{i=1}^{N_{PI}}(C_{\text{pipe}_i}(D_{i,t,s})L_i)\cdot\frac{1}{(1+IR)^{Y_t}}+\sum_{j=1}^{N_{PU}}(CE_{\text{ps}_{j,t,s}})\cdot\frac{1}{(1+IR)^{Y_t}}\\ +\left(\sum_{d=1}^{N_{DC}}\left(Ce_d\cdot\sum_{j=1}^{N_{PU}}\frac{\gamma\cdot QP_{j,d,t,s}\cdot HP_{j,d,t,s}}{\eta_j}\cdot\Delta t_d\right)\right.\\ \left.\cdot 365\cdot\frac{(1+IR)^{NY_t}-1}{IR\cdot(1+IR)^{NY_t}}\right)\cdot\frac{1}{(1+IR)^{Y_t}}\end{array}\right) \quad (13)$$

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

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

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

$$CE_{\text{initial}} = \left(\begin{array}{l} \sum_{i=1}^{N_{PI}} (CE_{\text{pipe}}(D_{i,1})L_i) + \sum_{t=1}^{N_T} CETK_t \\ + \sum_{d=1}^{N_{DC}} \left(CET \cdot \sum_{j=1}^{N_{PU}} \frac{\gamma \cdot QP_{j,d,1} \cdot HP_{j,d,1}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot NY_1 \end{array} \right) \quad (14)$$

$$CE_{\text{future}_{t,s}} = \left(\begin{array}{l} \sum_{i=1}^{N_{PI}} (CE_{\text{pipe}}(D_{i,t,s})L_i) \\ + \left(\sum_{d=1}^{N_{DC}} \left(CET \cdot \sum_{j=1}^{N_{PU}} \frac{\gamma \cdot QP_{j,d,t,s} \cdot HP_{j,d,t,s}}{\eta_j} \cdot \Delta t_d \right) \cdot 365 \cdot NY_t \right) \end{array} \right) \quad (15)$$

Equation (14) computes the total carbon emissions for the first operation period and Equation (15) computes the carbon emissions for the different future scenarios weighted by their probability of occurrence. The initial carbon emissions are calculated by adding together the carbon emissions related to the pipe installation, tank construction and energy consumption. The carbon emissions in the future scenarios are computed using a similar procedure. These emissions are multiplied by the carbon emission cost for each tonCO_2 (CEC). It should be noted that the carbon emissions costs are not updated. A zero discount rate should be used for carbon emissions (Wu *et al.* 2010). This complies with the recommendation of the Intergovernmental Panel on Climate Change (IPCC). High carbon emissions degrade air quality and thus it seems prudent and ethical to think about future generations and assign the same importance (or value) to the carbon emissions of today as well as those in future. A zero discount rate implies the same weight for current and future costs.

The objective function proposed in (Equation (10)) aims at minimising the initial and the future costs (Equations (11) and (13)) and initial and future carbon emissions (Equations (14) and (15)). The constraints of the model are those commonly used in the optimal design of water distribution networks and can be consulted in the work of Cunha & Sousa (2001).

Some decisions have to be taken now, but others can be delayed until new information is available. The ROs framework enables water infrastructure to be designed with some decisions postponed to a future date.

CASE STUDY

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

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

This work considers a number of expansion areas. For $T = 2$, the authorities are planning to build a new industrial area (NIA) and a new public services area (NPA) with some facilities near the river, so in this time interval the network may be extended to those two areas. For $T = 3$, it is predicted that a new residential area (NRA) may be developed close to the industries and public services, because of the labour required by the new industries and the public services facilities. However, if these areas are not built the area near the river may see a decline in population and the water consumption could fall to 75%. The areas in question are shown in Figure 3.

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

The network has two tanks operating with water levels between the elevations of 65.53 and 77.22 m and each with a capacity of 1,136 m^3, but according to the original

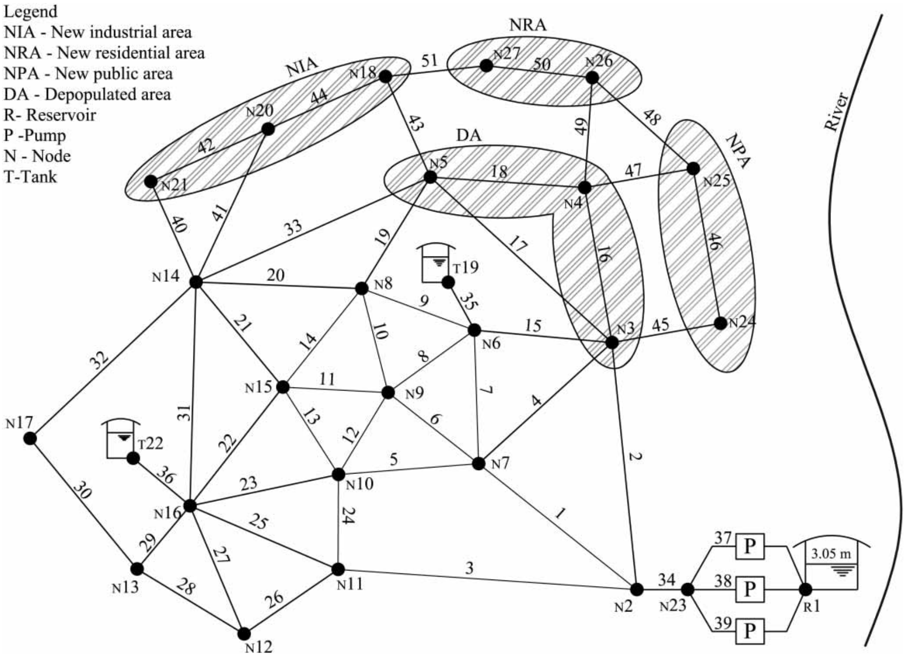

Figure 3 | Scheme of the network (inspired from Walski *et al*. 1987).

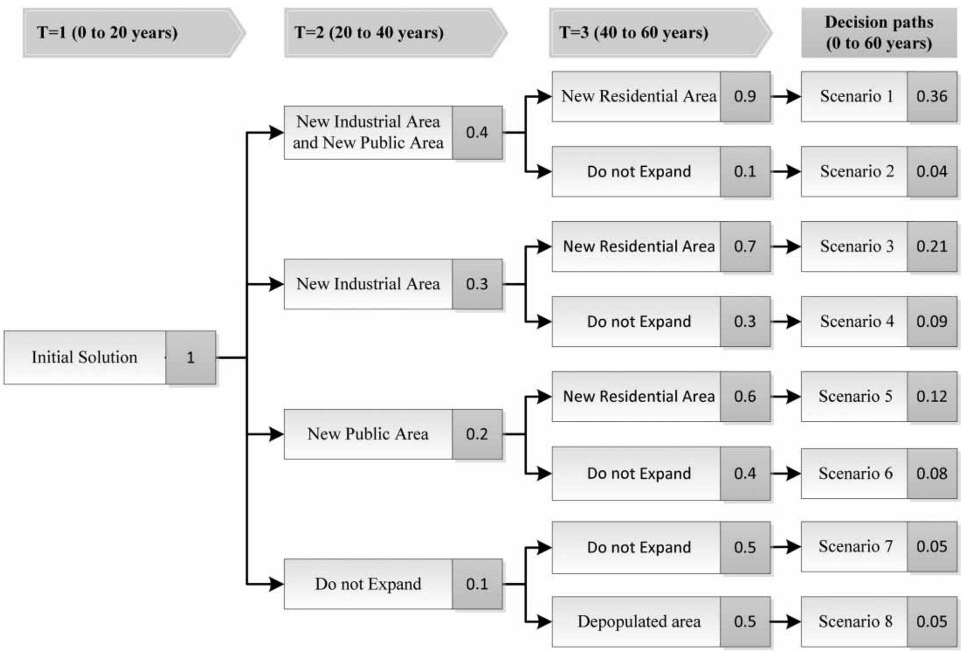

Figure 4 | Decision tree and probabilities of occurrence for the life cycle.

case study the company wants to operate the tanks between 68.58 and 76.20 m. The volume between 65.53 and 68.58 m is used for emergency needs and amounts to a volume of 284 m^3 in each tank. A minimum pressure of 28.14 m is required at all nodes for average daily flow conditions, and the instantaneous peak flow is given as the average nodal

Table 2 | Characteristics of the pipes

Pipe	Initial node	Final node	Length (m)	Existing diameter	Area
1	2	7	3,657.60	406.4	Urban
2	2	3	3,657.60	304.8	Residential
3	2	11	3,657.60	304.8	Urban
4	7	3	2,743.20	304.8	Residential
5	7	10	1,828.80	304.8	Urban
6	7	9	1,828.80	254.0	Urban
7	7	6	1,828.80	304.8	Urban
8	6	9	1,828.80	254.0	Urban
9	6	8	1,828.80	304.8	Urban
10	8	9	1,828.80	254.0	Urban
11	9	15	1,828.80	254.0	Urban
12	9	10	1,828.80	254.0	Urban
13	10	15	1,828.80	304.8	Urban
14	8	15	1,828.80	254.0	Urban
15	3	6	1,828.80	254.0	Residential
16	3	4	1,828.80	254.0	Residential
17	3	5	2,743.20	254.0	Residential
18	4	5	1,828.80	254.0	Residential
19	5	8	1,828.80	254.0	Residential
20	8	14	1,828.80	254.0	Residential
21	14	15	1,828.80	203.2	Residential
22	15	16	1,828.80	203.2	Residential
23	10	16	1,828.80	203.2	Residential
24	10	11	1,828.80	203.2	Urban
25	11	16	1,828.80	254.0	Residential
26	11	12	1,828.80	203.2	Residential
27	12	16	2,743.20		New
28	12	13	1,828.80	203.2	Residential
29	13	16	1,828.80	254.0	Residential
30	13	17	1,828.80	203.2	Residential
31	14	16	1,828.80	203.2	Residential
32	14	17	3,657.60	203.2	Residential
33	5	14	3,657.60	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	1,828.80		New

(*continued*)

Table 2 | continued

Pipe	Initial node	Final node	Length (m)	Existing diameter	Area
41	14	20	1,828.80		New
42	20	21	1,828.80		New
43	5	18	1,828.80		New
44	18	20	1,828.80		New
45	3	24	1,828.80		New
46	24	25	1,828.80		New
47	4	25	1,828.80		New
48	25	26	1,828.80		New
49	4	26	1,828.80		New
50	26	27	1,828.80		New
51	27	18	1,828.80		New

demand multiplied by 1.8. The system is also subject to three different firefighting conditions, each lasting 2 h. The minimum nodal pressures under firefighting conditions are 14.07 m. The firefighting conditions are: 157.73 L/s at node 9; 94.64 L/s at nodes 18, 20, 21; and 63.09 L/s at nodes 12 and 16. These fire flows should be met simultaneously with a daily peak flow 1.3 times the average flow. All the pressure requirements should be assured when one pump is out of service and the tanks are at the minimum levels after a normal operating day.

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			

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

Table 4 | Variation of demand during 24 h operation

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

Table 5 | Diameters and unit cost

	Unit cost				
	Installation of pipes		Cleaning and lining existing pipes		
Pipe diameter (mm)	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	

The average daily water demand for nodes is presented in Table 3 along with the elevation of the nodes and tanks.

Demand varies during an operating day. Table 4 shows the demand variation in 24 h. For example, between 0 and 3 h the demand is 70% of the average daily demand.

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

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

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

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

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

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

Table 7 | Tank cost

Volume (m^3)	Cost × 10^3 ($)
227.3	115
454.6	145
1,136.5	325
2,273.0	425
4,546.0	600

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

RESULTS

The approach described here uses ROs to minimise the life cycle costs of water distribution systems, taking uncertainty into consideration. When a long time horizon is considered, the future is unknown. The water demand will certainly vary considerably. New urban developments can be built and others can become depopulated. The ROs approach can handle these uncertainties and give decision makers good design solutions for flexible water networks. This work uses a decision tree with eight possible different scenarios that may occur over the 60-years life cycle. However, it is only necessary to decide the configuration of the network for the first time period of 20 years. The solution of this period should not only work well in the first stage, but also take into account future (uncertain) needs. This is a robust solution that will be adapted in the subsequent time intervals as circumstances evolve.

The hydraulic simulator EPANET (Rossman2000) has been used in the optimisation process whenever hydraulic constraints have to be verified. Figure 5 gives the solution achieved by the approach described. The results are represented in a life cycle tree that has the same shape as the decision-making alternatives exposed in Figure 4.

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

It can be concluded from the results that the life cycle cost depends on the decisions that are taken in the time intervals. However, the first time interval of 0–20 years accounts for most of the investment costs. In this time interval, the network will be reinforced with some new parallel pipes, new tanks and the cleaning and lining of existing pipes. The total cost takes the carbon emissions arising from the installation of pipes and tanks and from energy consumption into account. The solution for scenario 1 is schematised in Figure 6.

For scenario 1, the water distribution network will be expanded in the second time interval to cope with the NIA and the NPA. Furthermore, the network will be expanded for the NRA in the last time interval. Figure 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. However, 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 scenario 1. The ROs solution can handle uncertainties according to the life tree and adapt the solution to new requirements.

The ROs solution for the first time interval has to be implemented at year zero. To show that considering carbon emissions in the optimisation model has an impact on the final solution, a comparison is made of the first time interval

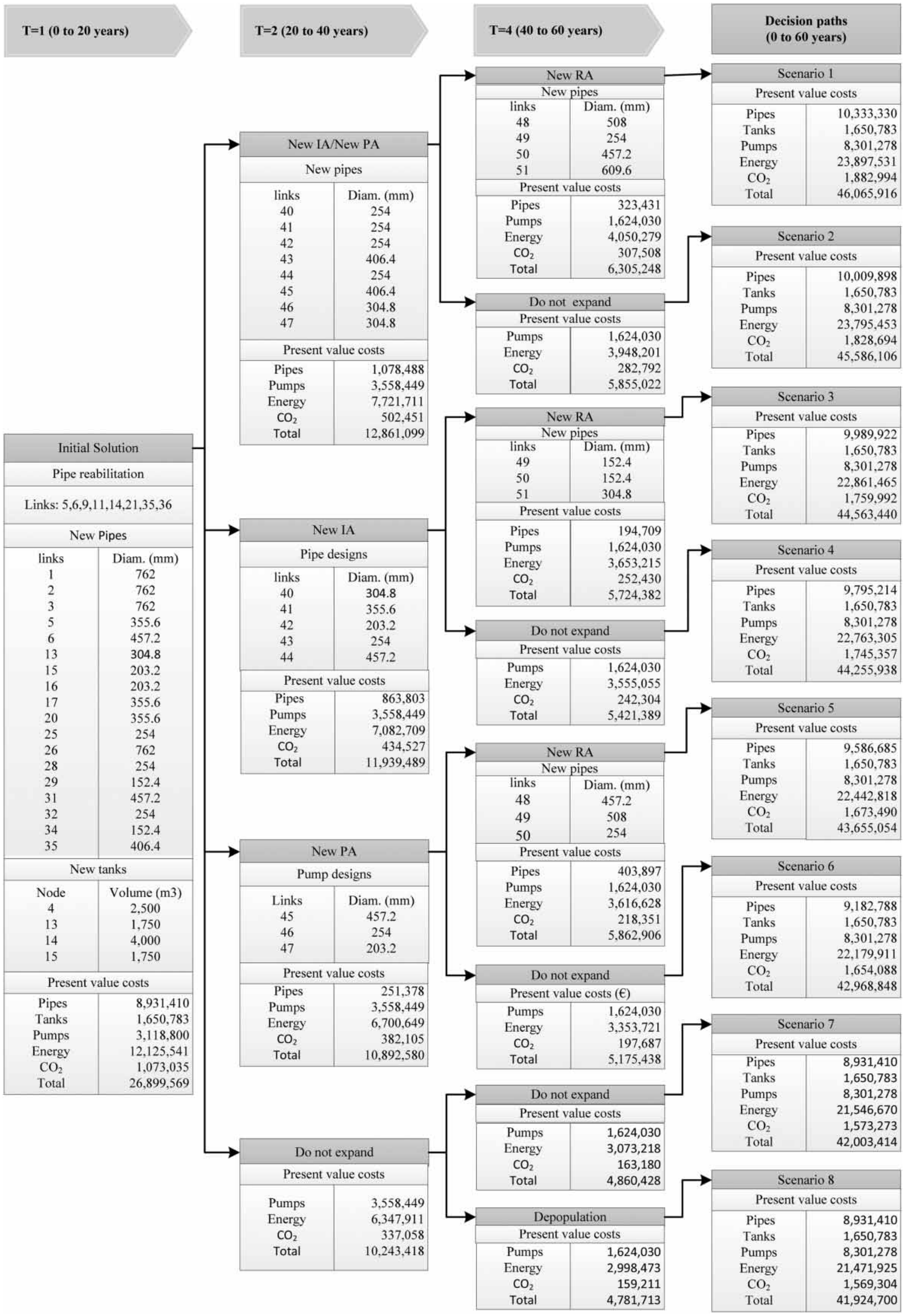

Figure 5 | Decision tree design of Anytown network.

Table 8 | Embodied energy and carbon emissions arising from installing commercial diameters

Diameters (mm)	Ductile iron pipes (kWh/m)	Aggregates (kWh/m)	Asphalt (kWh/m)	Embodied energy (kWh/m)	Total emissions (tonCO_2/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	1,119.33	0.71
304.8	705.15	60.26	509.87	1,275.27	0.81
355.6	776.37	65.52	531.37	1,373.26	0.87
406.4	890.32	70.86	552.87	1,514.05	0.96
457.2	1,004.37	76.27	574.37	1,655.01	1.05
508.0	1,118.33	81.75	595.87	1,795.95	1.14
609.6	1,346.24	92.95	638.86	2,078.05	1.32
762.0	1,688.10	110.30	703.36	2,501.77	1.59

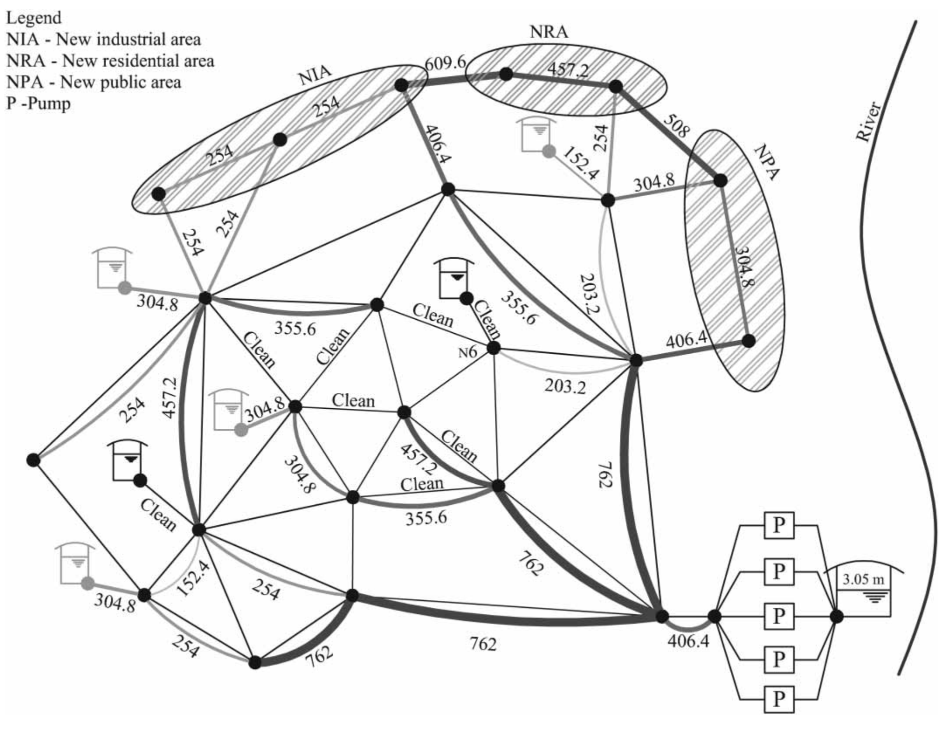

Figure 6 | Scheme of the network for the last time interval of scenario 1.

solution with and without carbon emissions costs. If the carbon emission costs are taken as zero, different results are obtained. Table 9 shows some comparisons regarding costs.

If carbon emission costs are taken into account, the total cost is high, but it can be seen that the difference is practically accounted for by the carbon emission costs. However, other conclusions can also be drawn. Most of the carbon emissions are derived from the energy consumed by the pumps. If carbon costs are not included, the optimisation model will find solutions that have high energy costs with some reduction in pipe and tank costs. Table 9 shows that if the total cost of the pipes, tanks, pumps and energy are kept practically the same, the consideration of carbon emissions implies allocating the costs in a different way,

Table 9 | Comparison of solutions with and without carbon emission costs

Costs	With CO_2 costs	Without CO_2 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_2	1,073,035	0
Total	26,899,569	25,846,820

i.e., by increasing the cost of the pipes and tank and decreasing the energy cost. Larger diameter pipes allow the energy expenditure to be cut, with a consequent reduction in the total carbon emissions.

CONCLUSIONS

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

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

The results indicate that the ROs approach is able to identify good solutions for flexible networks. The simultaneous optimisation of the network and carbon emission costs achieves solutions that take into account the environmental impacts of the networks. The solution presented provides flexibility to the network and automatically minimises the carbon emissions. The solution was obtained using the life cycle decision tree. It can also be concluded that if carbon emission costs are considered it is possible to find solutions with practically the same investment costs but with lower carbon emissions. This is achieved by higher investment cost and lower spending on energy. Further improvements can still be achieved by considering better carbon emission estimations and comparing the results for real networks.

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