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Dealing with Uncertainty through Real Options for the Multi-Objective Design of Water Distribution Networks

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Abstract

Water supply systems are very important for societies. If these systems are to function properly uncertainty must be handled. Flexibility is essential when operating systems for long-term planning horizons where uncertainty is high. This work proposes a multi-objective framework based on Real Options with three objectives. A Pareto front of solutions is traced whilst satisfying the constraints of the model. The hydraulic constraints are checked using EPANET hydraulic simulator. The model is solved by means of a multi-objective simulated annealing algorithm and the results are presented through a visualization tool and by showing some water network designs for specific solutions.

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Keywords: Water distribution network; uncertainty; real options; simulated annealing; multi-objective optimization; carbon emissions.

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1. Introduction

Water distribution networks are a very important part of a country's infrastructure, and aim at delivering good quality water in the appropriate quantity and without interruptions. Nowadays consumers in developed countries have higher requirements regarding the level of service of water distribution networks (WDNs) and are less tolerant of failure. Thus, water companies are subject to high performance and quality standards. The functioning of these systems under normal and abnormal operating conditions can be improved if uncertainty is proactively taken into account

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during the planning process. This work presents a decision aid tool for the optimal design and operation of WDNs for a long planning horizon, using multi-stage design and multiple objectives to account for uncertainty.

The optimization of the design and operation of WDNs has been viewed as a single-objective, least-cost optimization problem with pipe diameters being the primary decision variables. One of the first attempts was proposed by [1] and some developments were implemented by [2], [3]. These studies focus mostly on cost minimization formulations. A number of researchers have noted that the optimal design of WDNs is a multi-objective problem since it involves compromises between conflicting objectives such as cost, reliability and environmental issues. Some limitations of single-objective optimization approaches are described in [4], which uses a multi-objective based genetic algorithm to avoid these difficulties. The works of [5], [6] include multi-objective approaches to the optimization of WDNs. Multi-objective problems lead to a set of solutions which are tradeoffs between the objectives. That is to say, they are equally good (Pareto optimal solutions) and defined as non-inferior or non-dominated solutions. None of the objectives of any of them can be improved without degrading some other objective.

This study aims at including environmental issues in the multi-objective model for the design and operation of water networks. The carbon emissions caused by the construction and operation of water networks must therefore be quantified. The literature contains a number of studies that include these issues: [7] compare the environmental impact of different pipe materials: [8] compare the minimum cost design with the sustainable environmental design and [9] presents an index-based method to assess the environmental impact of water supply systems. The process we used to compute the carbon emissions is based on the work of [10]. The carbon emissions were calculated based on the whole life cycle, including the extraction of the raw materials, transport, manufacture, assembly, installation, disassembly, demolition and/or decomposition. The carbon emissions from the energy used during the network's operation, mainly by pumping stations, are also computed.

This work describes a novel multi-objective model for the optimization of WDNs considering three different objectives, as well as a multi-phased design scheme through the use of Real Options (ROs). ROs were proposed by [11] and originally come from financial theory. A number of studies have been published where the concepts of ROs have been used in several fields, such as by [12] in industrial processes, [13] in car parking problems, [14] in maritime costal defenses and [15] in a water supply system problem. The ROs approach proposed here aims to handle future uncertainty associated with new expansion scenarios for the network. A multi-phased design enables the decision makers to actively manage the configuration of the network and adapt it without jeopardizing previous investments. A decision tree to reflect the different intervention strategies that might be deployed during the planning horizon is implemented. The optimal design of WDNs considering ROs in a single objective approach to minimize costs was implemented in by the authors in [16].

A multi-objective method based on simulated annealing is used to solve the model. Simulated annealing was proposed by [17] and it can solve large, nonlinear, complex problems. A literature review shows that simulated annealing has been used in WDNs for single objective optimization models and shown good performances [18], [19] and [20]. The multi-objective optimization tool used in this work is based on [10]. The results are plotted using the AeroVis visualization tool [21]. The rest of this communication is organized as follows: the next section sets out the case study and presents the future scenarios options; the multi-objective decision model, established according to an ROs approach, is presented in section 3, and then the results are set out. Finally, the conclusions are in section 5.

2. Case study

A simple case study is used to demonstrate the applicability of our approach. The WDN presented in Fig. 1 is described in [16]. It is a small network supplied by three reservoirs with fixed levels and a pumping station at link 1 downstream of reservoir 1.

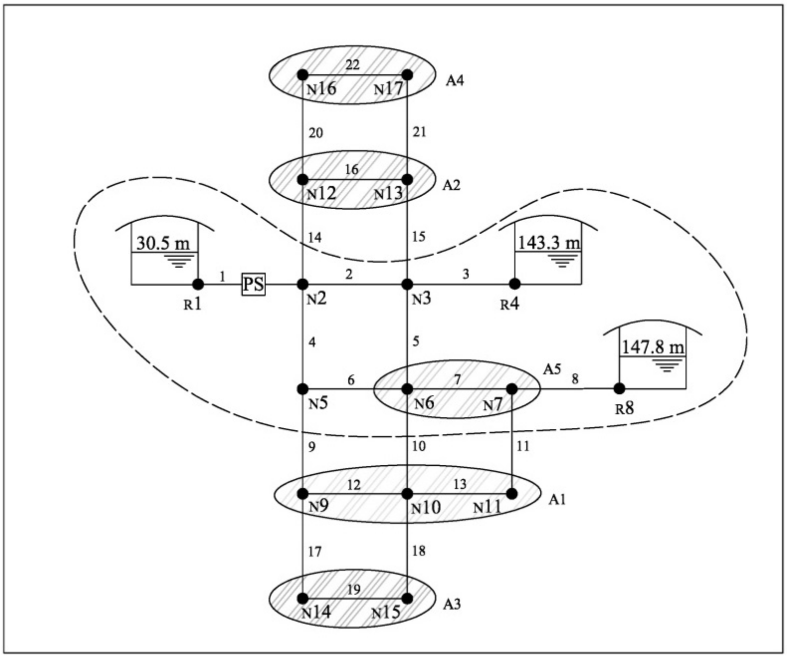


Fig.1. Water distribution network in [16]

In Fig. 1, the layout of the network that has to be designed in the first stage is enclosed by the dashed line, including pipes 1 to 8. However, this case study also considers the possibility of expanding the network to four more areas A1, A2, A3 and A4, enclosed by ellipses. Furthermore, we consider another area, A5, where it is possible that the population declines. The characteristics of the nodes, which include two different minimum pressures values, and the characteristics of the pipes can be found in [16]. The optimal design of the water network considers 8 possible commercial diameters presented in Table 1, giving the unit cost, Hazen-Williams coefficient and the carbon emissions for each diameter. These carbon emission values are computed using a procedure proposed by [10].

Table 1. Diameter, unit costs, carbon emissions and Hazen-Williams coefficients

Diameters (mm)	Unit costs ($/m)	Hazen-Williams Coefficients	Carbon emissions (TonCO$_2$/m)
152.4	49.541	100	0.48
203.2	63.32	100	0.59
254	94.816	100	0.71
304.8	132.874	100	0.81
355.6	170.932	100	0.87
406.4	194.882	100	0.96
457.2	225.066	100	1.05

The proposed ROs approach can contemplate several possible expansion areas for the network, depending on future conditions. Some parts of the water network could be expanded while others may see a decrease in water consumption. The dynamics of urban growth during the life-time horizon has impacts on the water distribution network and must therefore be taken into account at the planning stage.

The planning horizon for this case study is 60 years and it is divided into three periods of 20 years, when different options can be taken. The decision tree in Fig. 2 shows the possible future conditions for the network:

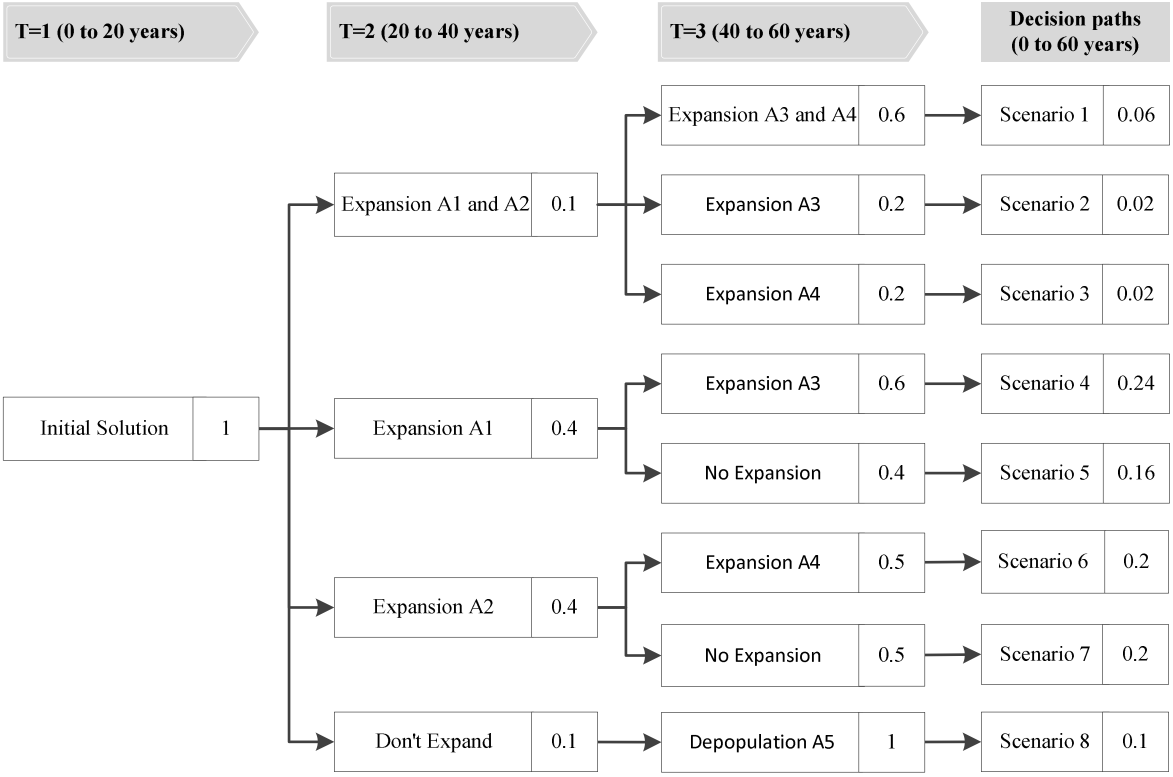


Fig. 2. Decision tree for the planning horizon and probabilities of occurrence

The decision tree is built based on various options that can be taken in the future. In the first period, T=1, the network design is required for pipes 1 to 8. In T=2, four different options are available: expansion to A1 and A2 (pipes 9 to 16); expansion to A1 (pipes 9 to 13); expansion to A2 (pipes 14 to 16), and no expansion. For the last period, T=3, some other expansion options are possible, viz., expansion to A3 and A4 (pipes 17 to 22), expansion to A3 (pipes 17 to 19), expansion to A4 (pipes 20 to 22) and no expansion. A decline in population in area A5 (nodes 6 and 7) is also considered, where the consumption could decrease by 30%. The decision tree is built assuming the most probable future conditions for the case study. The probabilities of each choice node are shown in the squares. In real world case studies, these probabilities can be given by expert judgment. The probabilities of scenarios are shown in the last branches of the decision tree. These values are calculated by multiplying the probabilities of all nodes on the decision path for that scenario.

3. Multi-objective optimization problem

The multi-objective design problem of water distribution networks in this work is formulated with three different objectives. This model aims to determine the tradeoffs between a set of solutions and the objective functions are represented in expressions 1, 2 and 3:

$$O1 = Min\ (Ci + Cf) \tag{1}$$

$$O2 = Min\ (HPD) \tag{2}$$

$$O3 = Min\ \left(tonCO_2\right) \tag{3}$$

where Ci = cost of the initial solution to be implemented for the first period (\$); Cf = future cost (\$); HPD = hydraulic pressure deficit (m); $tonCO_2$ is the emitted CO_2 in metric tons.

The cost minimization in expression (1) is the first objective to be detailed. The objective function is given by the sum of the initial cost Ci with the future cost Cf of all the scenarios considered in the decision tree in Fig. 2. The initial cost is given by the design and operation of the network for the first period T=1 and the future cost is arrived at by summing all possible chance node costs, starting from the second period T=2. These values are computed for each chance node by multiplying the cost of each design option by the probability of taking that option.

The second objective function given in expression (2) aims at minimizing the total pressure deficits considering all possible chance nodes that can be taken during the planning horizon. These pressure deficits are computed by summing the pressures insufficiencies, for all nodes. The value of the total pressure deficits can be taken as a measure of network performance since small pressure deficit values correspond to good behavior of the water network and high values correspond to networks with poor hydraulic behavior. The process used to compute these pressure deficits and the threshold pressure values are both given in [10]. The purpose is to obtain higher minimum pressures and thus have fewer pressure violations for scenarios with a high probability of occurrence. This procedure should therefore provide better performance for more probable future scenarios of the WDN. A demand driven the hydraulic simulator is used, because the pressure deficits allowed are not severe.

In expression (3), the objective comprises the minimization of carbon emissions arising from the construction and operation of the WDN. The carbon emissions are computed based on the pipe installation emissions given in Table 3 and the emissions from the electricity used by pumping stations. The process used to compute these carbon emissions is explained in [10]. Finally, the model also includes some constraints: nodal continuity equations; pipe head loss equations; minimum pipe diameter for each pipe; use of a set of commercial diameters, and assigning only one commercial diameter for each pipe [10].

The model aims to determine the design and operation decision variables not only for the first period but also for all the future options that can be taken according to the decision tree. The network design for the first period is the one required now. Subsequent decisions will be made according to future outcomes. The optimization model proposed here was linked to the EPANET hydraulic simulator [22] to verify the hydraulic constraints. The multi-objective simulated annealing method described in [10] is used to solve the optimization model. The results are shown in the next section.

4. Results

Single objective optimization methods set out to find a unique optimal solution (global optimum). But multi-objective approaches establish a series of efficient solutions, known as Pareto optimal solutions. The multi-objective simulated annealing method we propose uses a domination concept to find them. The results are plotted in Fig. 3, which gives an overall view of the Pareto front (600 solution values shown). This representation results from a visualization tool proposed by [21].

The solutions in Fig. 3 are shown from different angles to facilitate the visualization of the Pareto front surface. The trade-offs between the solutions can be explored in greater detail using the Fig. 4 plots, which show 2D representations of two objectives a time. The solutions that define the Pareto front between each of the pairs for two objectives are indicated by emphasizing the color of cones of the non-dominated solutions. Fig. 4 enables us to draw some conclusions. Fig. 4(a) shows that increasing the costs permits the hydraulic pressure deficits to be lowered, and Fig. 4(b) shows that low carbon emissions are achieved by the low cost solutions. In fact, lower carbon emissions result from using smaller quantities of materials in constructing the network and from reducing energy consumption during operation, thereby reducing the total cost. Fig. 4(c) shows that the hydraulic pressure deficits are reduced by increasing both the carbon emissions and the costs.

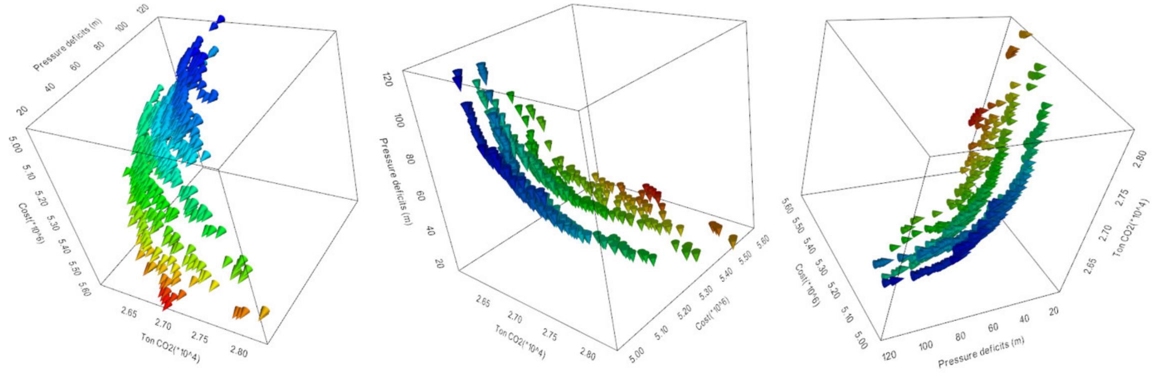
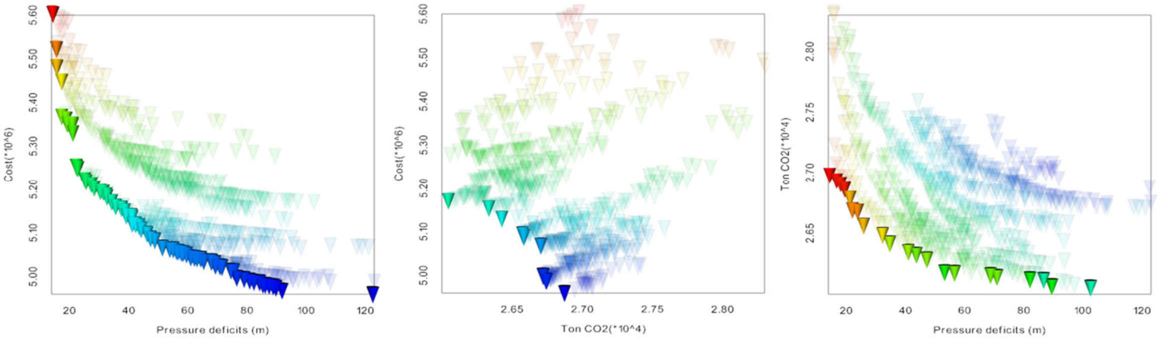


Fig. 3. Different views of the Pareto front



(a) (b) (c)

Fig. 4. Two objective Pareto front view angles: Cost vs. Pressure deficits (a); Cost vs. Ton CO_2 (b); Ton CO_2 vs. Pressure deficits (c).

The results presented in Fig. 3 and 4 just give the values for the three objective functions, for each solution. Each of these solutions can be detailed according to the water distribution design for the different possible scenarios. The designs of three different water distribution solutions are given in Fig. 5, for all the three stages and considering scenario 1 of the decision tree. In scenario 1, all the possible expansion areas are installed.

The water network designs given in Fig. 5 for the three stages of scenario 1 are the lowest cost solution (a), the lowest pressure deficit solution (b) and the lowest carbon emissions solution (c). These solutions were selected in the Pareto front (Fig. 3), taking into account the lowest cost solution (Costs *O1:* \$4,957,916; Pressure deficits *O2:* 123 m; Carbon emissions *O3*: 26,874 TonCO_2), the lowest hydraulic pressure deficit solution (Costs *O1*: \$5,600,568; Pressure deficits *O2*: 15 m; Carbon emissions *O3*: 26,976 TonCO_2) and lowest carbon emissions solution (Costs *O1*: \$5,168,771; Pressure deficits *O2*: 103 m; Carbon emissions *O3*: 26,046 TonCO_2). It is possible to pinpoint some conclusions from Fig. 5. In terms of pipe diameter, solution 5(a) uses the smallest pipe diameters. This is the solution that offers the lowest cost identified. Conversely, the solution with large pipe diameters, also the most costly, has the lowest pressure deficits 5(b). Finally the solution with low carbon emissions is low cost but has high hydraulic pressure deficits 5(c). In fact, to reduce the pressure deficits it is necessary to increase the pipe diameters and/or increase the pumping station head, which will increase both the total cost and the carbon emissions. However, there is a compromise between increasing the hydraulic capacity of pipes either through high initial investment or by increasing the head of the pumps and spending more on energy.

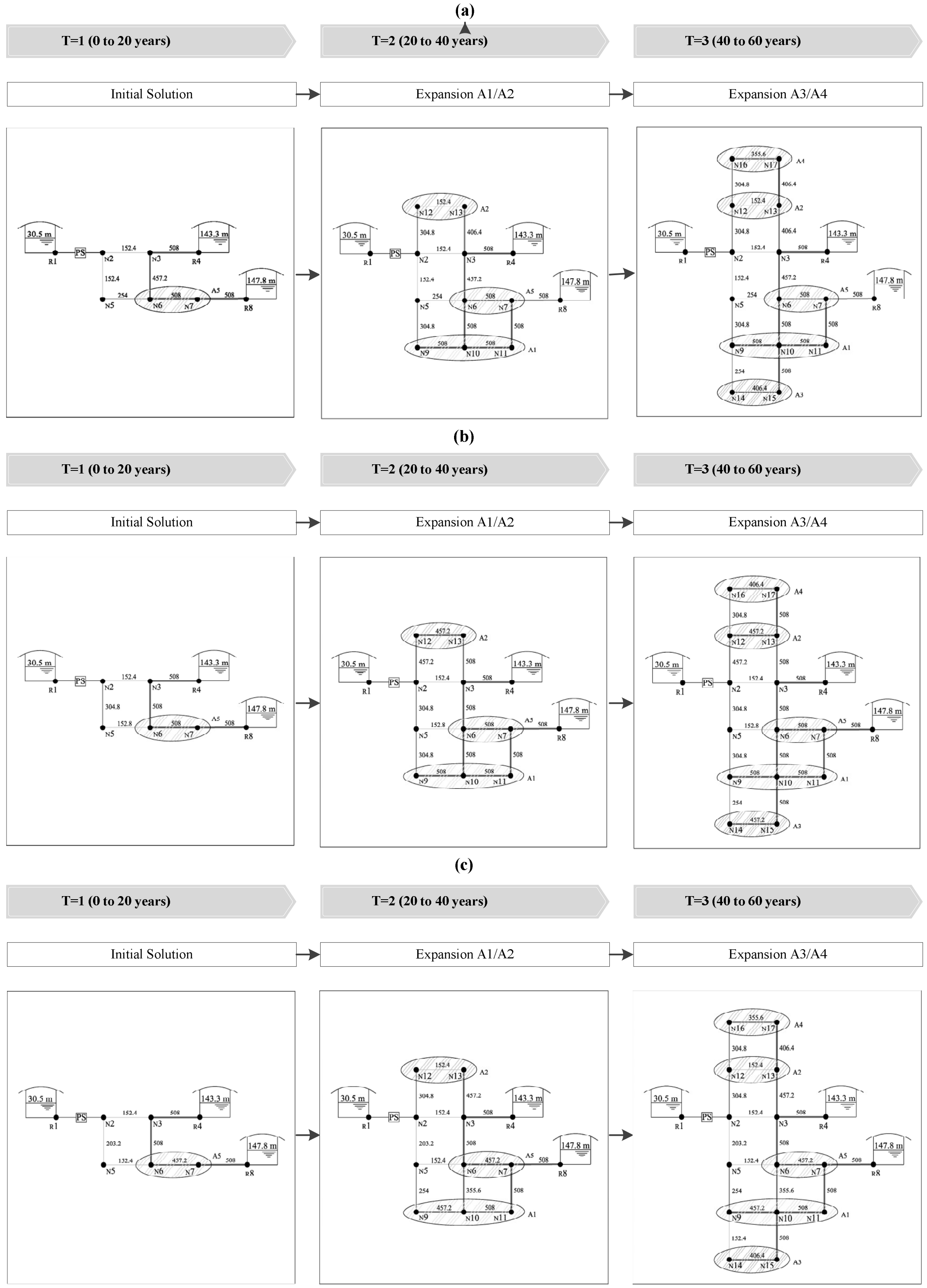


Fig. 5. Water network design for scenario 1: lowest cost solution (a); lowest pressure deficit solution (b) lowest carbon emissions solution (c)

5. Conclusions

This work uses a ROs multi-objective and multi-stage optimization approach for the design and operation of water distribution networks. The proposed optimization model is intended to minimize the design and operation costs, the hydraulic pressure deficits and the total carbon emissions. The approach was applied to a case study and the results were presented by means of an appropriate visualization tool. A set of solutions were obtained to shape the Pareto front with different values of the three objectives. The ROs approach allows uncertainty to be included in the decision process by splitting up the planning horizon, thereby enabling midcourse adjustments or further investment to be made. These adjustments are defined in a decision tree where different scenarios with specific probabilities of occurrence are stated. Three particular network design solutions are detailed so that the trade-off between the objectives and the particular practical results can be compared. From a decision-making point of view, tools of this kind will help decision makers to understand the impact of giving more importance to one objective rather than another. The ROs approach is intended to give a certain amount of flexibility to decision making.

Acknowledgements

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