Comparison of various phased approaches for the constrained minimum-cost design of water distribution networks

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Abstract

When the traditional approach is used for designing a water distribution system, reference to its final and complete configuration is made while the water demand is represented by the very final expected peak demand. This design approach (aimed at designing all the network at a time) is incompliant with its actual development, which instead takes place in steps. As a consequence, practitioners, in order to follow the network demand and layout growth in time, prefer to sub-divide the whole construction life into various time steps thus including the different phases of construction in the network design.

This work is aimed at analyzing and comparing three different phased approaches for constrained minimum-cost design of water distribution networks: the single-step design with demand feedback, the multi-step design without demand feedback and the multi-step design with demand feedback. The difference between the single-step design and the multi-step design lies in the fact that whereas the former entails optimizing a single construction step at a time, i.e. the current construction phase, the latter is based on the phasing of construction and then is aimed at optimizing the current construction phase and all the subsequent phases, included inside a certain temporal horizon, simultaneously. The demand feedback is here used as a pragmatic tool for updating the forecast at a generic time instant of the future demand growth: such an update is performed by setting the future demand growth equal to that really observed in the previous time step. Alternatively, the predicted demand growth rate at the generic time instant can be kept equal to the value assumed at the time instant when the generic node appears, without taking account of the

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demand variation really observed in time in the node (absence of demand feedback).

Applications to a real case study show that the multi-step design with the demand feedback is the most reliable because it make it possible to reduce the overall construction costs while attenuating the occurrence of pressure deficits in the various construction steps of the network.

Keywords: water distribution networks, design, optimization, phasing of construction, demand growth.

Introduction

Network design is one of the most investigated topics in the scientific literature of water distribution systems. Starting from the late seventies (Alperovitz and Shamir 1977), numerous single objective (Fujiwara et al. 1987; Savic and Walters 1997; Eusuff and Lansey 2003; Krapivka and Ostfeld 2009; Haghighi et al., 2011 to name a few) and multi-objective (Gessler and Walski 1985; Todini 2000; Prasad et al. 2003; Bentley Systems, 2006; Creaco and Franchini 2012 to name a few) algorithms have been proposed. Though being worthwhile contributions to the field, most of the proposed algorithms were developed laying on the restrictive assumptions that design is performed ‘statically’ and all the construction is done in a single phase such that there is no gradual growth/build-out in the system. These assumptions render the algorithms incompliant with the design methods usually adopted by practitioners who instead operate following the natural expansion of water networks. As a matter of fact, the single step design approach presents the following evident disadvantages:

- if applied to a short time step, it does not make possible to include considerations pertinent to the long time network growth in the design;
- if applied to a long time step, it could lead to the installation of exceedingly large pipes, oversized with respect to the network growth really occurring in the future, and then to exceedingly large investments at the beginning of the construction.

Recently, some studies (Basupi and Kapelan, 2012; 2013; Creaco et al., 2013; 2014) attempted to produce new multi-objective algorithms (cost minimization plus reliability maximization), aimed at conceiving network design dynamically and in phases, in a bid to follow the real expansion of urban centres. The algorithms proposed by Basupi and Kapelan (2012; 2013) and Creaco et al. (2013; 2014) make it possible to optimize all the construction steps inside a certain temporal horizon simultaneously while producing a Pareto front. In particular, Creaco et al. (2013) showed that resorting to phasing of construction in the context of network design yields some advantages, in that:

- it allows engineers to design the short term upgrades, which are supposed to guarantee a prefixed level of reliability, while keeping an idea of the long term network growth and expansion;
- for long time horizons, it turns out to be cost effective; in fact, by partially deferring construction, the community is able to put aside resources that can be more effectively allocated to alternative uses.

Basupi and Kapelan (2012; 2013) and Creaco et al. (2014) proposed algorithms able to consider the uncertainty in network demand growth inside the phasing of construction approach. With respect to the algorithm proposed by Basupi and Kapelan (2012; 2013), the algorithm of Creaco et al. (2014) has the advantage of being able to take account of the network layout growth in time, though the latter growth was dealt with deterministically. The main conclusion of the work of Creaco et al. (2014) was that considering uncertainty leads to the network being sized more conservatively, especially in the first steps, in order to render network construction more flexible to adapt itself to various conditions of demand growth over time.

Though the recent studies of Basupi and Kapelan (2012; 2013) and Creaco et al. (2013; 2014) have the undisputed merit of presenting a more realistic version of network design, based on phasing of construction, they limit themselves to planning the whole construction design at the beginning of the construction life and do not then consider the fact that in practical applications the construction design is indeed corrected at the end of each time step, in order to upgrade both the current and the projected network demands on the basis of the demand growth actually observed in the past.

The aim of the present work is then to analyze to which extent the network design based on phasing of construction is affected by repeating the design at the beginning of each phase while upgrading the forecasted future demand growth. This analysis is developed by comparing the results of performing simultaneously, at a certain time instant, the design of all the remaining construction phases with those produced by performing the design with reference to a single time step at once. In both cases, future demand growth is pragmatically estimated on the basis of the last observed values in the network already constructed.

In order to make the disquisition easier and closer to the practitioners' viewpoint, pressure surplus-constrained minimum-cost optimizations were performed rather than the multi-objective optimizations proposed by Basupi and Kapelan (2012; 2013) and Creaco et al. (2013; 2014) thus avoiding the collateral complexities related to the multi-objective approach and the choice of the solution to be selected in each design phase is avoided since just one solution is produced by the optimization algorithm. This allows to focus the phasing problem alone while reliability is indirectly represented by the pressure surplus constraint.

The remainder of the paper is organized as follows. In the next section, the methodology, i.e. the single-step design with demand feedback and the multi-step design without and with demand feedback, is described following a brief recall of the traditional single-step design. The subsequent section reports the applications to a real case study. Finally, conclusions are drawn.

Methodology

Traditional design approach

Figure 1 makes it easier to describe how the traditional design approach is carried out. At time $t = t_0$ the network is designed considering the configuration that it is expected to reach at the end of its life (t = T). Figure 2 shows a possible final configuration of the water network. The demand considered is the peak expected value for t = T. In the case of single objective design, such as that considered here, the cost is minimized under the minimum pressure head constraint at each demanding node, in order that a suitable service is guaranteed to the users at the end of the construction life.

This design approach (aimed at designing all the network at a time) is incompliant with its actual development, which takes place in steps such as those shown in Figure 3. Network design should be carried out taking account of these steps. To this end two different design modes (hereinafter described) can be adopted. In these modes, *the design is carried out by minimizing the present worth construction costs, under the minimum pressure constraint at each demanding node and at each construction step.*

In the following subsections, reference is made to a temporal axis subdivided into (regular or not) time steps whose ends are characterized by instants t_{i-1}, t_i, t_{i+1}, etc. (Figure 4).

Single step design applied to short time steps considering demand feedback

In this case, network design is carried out considering a single construction step at a time. At time t = t_0, the first construction step Δt_1 = t_1-t_0 (see Figure 4) is considered. The configuration of the network at the end of this interval is known (as an example, see Figure 3, time step 0-20, i.e. the first construction step). As far as network demand, its initial value at the n-th node $D_{n,init}$ is assumed to be known (at time $t_{n,init}$ – equal to t_0 in this case, with $t_{n,init}$ indicating the time instant when the n-th node appears for the first time in the network layout). For each node, a possible value is assumed for the future growth rate: $\alpha_{n,1}^{pr}$ (where pr, n and 1 indicate "*predicted*", the reference node and the first construction step). The n-th node then features the following demand value at the end of the first construction step:

$$D_{n,t_1} = D_{n,init} + \alpha_{n,1}^{pr}\left(t_1 - t_0\right) \tag{1}$$

Design is carried out on the basis of the layout (see as an example Figure 3, step 0-20) and of the demand values at the end of the first construction step. In particular, design concerns the definition of the diameters for the pipes interlinking the nodes which are present in the first construction step.

At time $t = t_1$, i.e. at the beginning of the second construction step with ends t_2 and t_1 (see Figure 4) *the part of the network relative to the first step has already been constructed* but insertion of pipes in parallel is allowed. The network configuration which will take form at the end of the second construction step (see Figure 3, time step 20-40), where new demanding nodes for which $t_{n,init}$ (i.e. the appearance time) is equal to t_1 are present, is known. Furthermore, at the end of the first construction step, it is possible to estimate the actual value of the demand growth rate in this time step. This demand growth is indicated with symbol $\alpha_{n,1}^{act}$ (where superscript *act* means "actual").

The demand at the *n*-th demanding node which is present since time t_0 (for which $t_{n,init} = t_0$) can be expressed as follows:

$$D_{n,t_2} = D_{n,init} + \alpha_{n,1}^{act}\left(t_1 - t_0\right) + \alpha_{n,2}^{pr}\left(t_2 - t_1\right). \quad (2)$$

The demand at the *n*-th demanding node present since time t_1 (for which $t_{n,init} = t_1$) can be written as:

$$D_{n,t_2} = D_{n,init} + \alpha_{n,2}^{pr}\left(t_2 - t_1\right), \quad (3)$$

where $D_{n,init}$ represents the demand at the *n*-th node in the second construction step, i.e. at time instant $t_{n,init} = t_1$ when it appears in the network.

As to the demand growth rate $\alpha_{n,2}^{pr}$, a reasonable, pragamtic way to assess it is to set it equal to the actual demand growth rate observed in the previous step, i.e. $\alpha_{n,2}^{pr} = \alpha_{n,1}^{act}$, when this information is available. This is possible for a node which has been present since time $t = t_0$ (eq. (2)). On the other hand, it is impossible for a node which appears at time $t = t_1$ (eq. (3)).

On the basis of the layout (see as an example Figure 3, construction step 20-40) and on the basis of the demand values at the end of the second construction step, the design can be carried out in the same way as for the first construction step. In this case, the design concerns the definition of the diameters for the pipes which have a newly born node at either end and for the pipes which have to be laid in parallel to the pipes laid in the first construction step.

The steps described above are repeated for each following construction step till time $t = T$, corresponding to full network development, is reached.

Summing up, the design is carried out for each step at a time by assuming the layout at the end of each step to be known and by characterizing the demand at the beginning t_i and at the end t_{i+1} of each step as follows:

1. demand at time t_i, at a node appearing at $t_i = t_{n,init}$, is equal to $D_{n,init}$;
2. the demand, for such a node, at time t_{i+1} is calculated as:

   $$D_{n,t_{i+1}} = D_{n,init} + \alpha_{n,i+1}^{pr}\left(t_{i+1} - t_i\right) \tag{4}$$

   where $\alpha_{n,i+1}^{pr}$ is the *first prediction* demand growth rate.
3. the demand at time t_i, in a node which has appeared earlier, is evaluated on the basis of the actual demand growth rate in the construction steps preceding t_i, starting from the appearance time of the node:

   $$D_{n,t_i} = D_{n,init} + \sum_{j=init+1}^{i} \alpha_{n,j}^{act}\left(t_j - t_{j-1}\right) \tag{5}$$

4. the demand, for such a node, at time t_{i+1} is calculated as:

   $$D_{n,t_{i+1}} = D_{n,t_i} + \alpha_{n,i+1}^{pr}\left(t_{i+1} - t_i\right) \tag{6}$$

   where the demand growth rate $\alpha_{n,i+1}^{pr}$ predicted for the construction step t_{i+1}-t_i is reasonably set equal to the actual demand growth rate in the preceding construction step, i.e.: $\alpha_{n,i+1}^{pr} = \alpha_{n,i}^{act}$.

The four steps summarized above attest to the fact that the procedure for demand evaluation takes advantage of the feedback from the actual demand growth in time.

The single step design is repeated at the beginning of each construction step with a vision focused on the current step. It has to be noted that only the first construction step following the appearance of the node requires a real prediction of the demand growth rate to be made. For the subsequent steps, the demand growth rate used for demand estimation is equal to that which has been actually observed in the construction step preceding the step under consideration. As a matter of fact, for each node, there is a *first prediction* growth rate, at the time instant when the node appears; later, there are *actually observed* demand growth rates.

Multi-phase design

In this case, the design is carried out considering all the steps together. In particular, in one single optimization process, the interventions which have to be performed in each step are defined, i.e. concerning the diameters of the pipes associated with the new sites and the diameters of the pipes which have to be laid in parallel to those laid in the previous steps. The design requires the following aspects to be known:

1. layout of the network in each step (see Figure 3), i.e. which nodes (and pipes) appear at each step;
2. demand $D_{n,init}$ of the n-th node when it appears for the first time (at time t_{init});
3. demand growth rate at the n-th node in all the steps following its appearance;

As to demand growth rate, two different methods for its assessment are hereinafter described: without feedback and with feedback.

Multi-step design without demand feedback

In this case the design is performed at time $t=t_0$ considering all the steps up to $t=T$. The demand growth rate in each node is thus estimated at time $t=t_0$ and assumed to be constant for all the subsequent steps. The design is carried out in light of this assumption, which makes it possible to evaluate the demand at the end of each step. The demand D_{n,t_i} at the n-th node (whose knowledge is necessary for the design) and at time t_i, when it appears at time instant $t_{n,init}$, can be expressed as:

$$D_{n,t_i} = D_{n,init} + \alpha_n^{pr} \sum_{j=init+1}^{i} \left(t_j - t_{j-1}\right) \qquad (7)$$

where α_n^{pr} represents the demand growth rate assumed at time t_0 for the n-th node and valid for all the time steps after its appearance.

Summing up, this approach requires only one design. Unlike the traditional approach, where reference is made to the final configuration of the network, this approach entails designing at time $t=t_0$ while keeping a vision of the temporal development of the network, that is of the various steps of network expansion. The prediction of the demand growth rate in each current and future node is made only once at time $t=t_0$. Summing up, in this case the method requires a single value of *first prediction* demand growth rate for each node.

Multi-step design with demand feedback

In this case the design is repeated at the beginning of each time step considering all the remaining steps up to $t=T$. In detail, at time $t = t_0$ the layouts of all the construction steps are assumed to be known (see, as an example, Figure 3). The demand at the n-th node and at the generic time $t= t_i$ can be estimated as:

$$D_{n,t_i} = D_{n,init} + \alpha_n^{pr} \sum_{j=init+1}^{i} \left(t_j - t_{j-1}\right) \qquad (8)$$

where α_n^{pr} represents the estimation of the demand growth rate for the n-th node, made at time $t = t_0$ and assumed to be valid for all the construction steps up to time $t = T$. The design which makes it possible to define the interventions relative to all the construction steps. It has to be noted that all stated above coincides with the multi step design without feedback described in the previous sub-section. Differences arise starting from time $t = t_1$. At time $t = t_1$, *the pipes designed for the first construction step are assumed to be already installed*. Furthermore, the actual demand growth rate which took place in the first construction step (t_1-t_0) at the nodes which appeared at time $t = t_0$ is known. Then, demand D_{n,t_i} with $t_i > t_1$, *for nodes featuring* $t_{n,init} = t_0$, is calculated by eq.(8), with

$\alpha_n^{pr} = \alpha_{n,1}^{act}$. In particular, the future demand growth rate at the n-th node, present since $t = t_0$, is now assumed to be equal to that observed in the last construction step, since the latter value is a reasonable estimation of the future demand growth rate.

As to the n nodes in which the appearance time is $t_{n,init} \geq t_1$, the demand growth rate cannot be updated since there is no observation.

At time $t = t_1$ the design is carried out again considering all the remaining construction steps up to $t = T$. The costs of all the interventions is converted into present worth cost at time $t = t_0$.

The instructions described above are repeated for each construction step, that is at each time t_i characterizing the beginning of a new step of network expansion (see Figure 3 as an example). Time after time, the *future* demand growth rate, in the n nodes which appeared at time instants preceding t_i, is updated to the demand growth rate value observed in the last construction step (i.e. in the construction step preceding time t_i when design is made).

Summing up, this design is repeated at the beginning of each construction step while having a vision of all the subsequent steps up to $t = T$. This marks a clear difference from the single step design, which does *not* have a vision of all the remaining construction steps though it is repeated step after step. As to the demand growth rate, a real prediction operation is made only at time $t = t_{init}$ since, as for the single step design, for all the construction steps following the appearance of the various nodes, the demand growth rate is set at the value observed in the last construction step preceding time t_i when the design is carried out. Shortly, the method requires definition, for each node, of one *first prediction* demand growth rate, and of *actually observed* demand growth rates.

Applications

Network

The case study considered here makes reference to the network of a town of northern Italy. A skeletonised layout, obtained by Farina et al. (2013) from the original network (Creaco and Franchini, 2013) by discarding pipes which only play distribution function, was taken into account because the problem of phasing of construction mainly concerns transmission mains. This layout is made up of 26 nodes with outflow and 31 sites for pipe laying (Figure 2). The network is fed by n_0 = 1 reservoir (node 26), which presents a value of the head equal to 38 m with respect to all the nodes (whose ground elevation is assumed to be 0 m a.s.l.). In the work, it is assumed that no new sources are added to the original source during the planning horizon and that, instead, the original source is strictly enlarged in order to cope with an increasing demand. In a system where growth is managed by adding new wells (boreholes) at different locations, the problem and, subsequently, the results would be much different from those presented hereinafter.

The lengths of the possible pipes (i.e. the first pipe to be laid and the subsequent potential parallel pipes) were reported by Creaco et al. (2014). Pipe Manning roughness coefficients were assumed equal to 0.015 $s/m^{1/3}$ and variations over time were not considered. The layout in Figure 2 comprises the whole group of nodes and connections at the end of the T=100 year long construction period.

The network was assumed to grow according to the five Δt= 20 year long expansion steps illustrated in Figure 3. The information relative to the initial demand $D_{n,init}$ (L/s) and to the year $t_{n,init}$ of appearance of the various nodes is reported in Table 1.

The pipe diameters and associated unit costs adopted for the design are reported in the following Table 2. As to pipes laid at a certain site in parallel to previously existing pipes, the related cost was calculated by considering a penalty coefficient equal to 1.2 raised to the number of pipes already present, in order to take account of the fact that laying a pipe in parallel could be more burdensome than laying it a new site (Creaco et al., 2013; 2014).

During optimizations, a discount rate R=0.02 was used for the evaluation of present worth costs. The three approaches presented above are hereinafter indicated as: approach 1: single step design; approach 2: multi step design without feedback; approach 3: multi step design with feedback. As to the demand growth rate, representative of the *first prediction* values (made at time t=$t_{n,init}$, i.e. when the node appears, for approach 1 and at time t = t_0 for approaches 2 and 3), and of the *actually* *observed* values (i.e. those occurring in the construction step preceding design time t_i when the n-th node features an appearance time $t_{n,init} < t_i$), values ranging from 0.02 to 0.08 L/(s yr) were considered and applied to the three approaches presented above. In detail, one scenario with constant and uniform value of the demand growth rate equal to 0.05 L(s yr) (average value between 0.02 and 0.08 L/(s yr)) was considered and other 99 scenarios were constructed by randomly generating the demand growth rate values from a uniform probability distribution with range 0.02-0.08. In these 99 scenarios, the demand growth coefficients (*first prediction* values and *actually observed* values) used at the various design times t_i (see time axis in Figure 4) were assumed to be variable from node to node and from time to time. The trend of the *total network demand* as a function of time in the 100 scenarios considered in shown in Figure 5.

As an example, Table 3 reports the $\alpha_{n,i}^{pr}$ and $\alpha_{n,i}^{act}$ values for the various nodes of the network and for the various times t_i when the design is performed in scenario 26, that is one of the 99 randomly generated scenarios. The values of $\alpha_{n,i}^{pr}$ (relative to nodal first appearance time $t_{n,init}$ – i.e *first prediction*) are reported in bold whereas the values of $\alpha_{n,i}^{act}$ (relative to the subsequent design times t_i up to the time which marks the last construction step on the left – i.e. *actually observed*) are reported in italics.

The minimum desired pressure head h_{des} for the network demanding nodes was set at 20 m at all construction steps and for all the demanding nodes.

In the various approaches, a genetic optimization algorithm was applied to each construction step considering a number of individuals equal to 2 × the number of pipe sites × the number of construction steps to be optimized. The number of generations considered was set at 1.5 × the number of individuals. These values were assessed in order to have at the same time accurate results and acceptable computation times.

It has to be noted that design approach 2 requires a single optimization for each scenario, as was stated above, only based on the demand growth rates predicted at time $t = t_0$ and highlighted in bold in Table 3. Approaches 1 and 3 require, for each scenario, a number of optimizations equal to the number of construction steps or times of design (5 in this case). The 5 optimizations of approach 3 are more burdensome than those of approach 1 from the computational viewpoint since they require multiple construction steps to be simultaneously optimized. Each optimization of approach 1, instead, requires a single construction step to be optimized at a time.

Results

As an example of the results, Table 4 reports the diameters of the pipes laid in the various construction steps, obtained by applying design approach 1 to scenario 26. The analysis of this table shows that designing without phasing of construction may cause the laying of too numerous pipes in parallel in the same site, with respect to common engineering practice (see for instance 4 parallel pipes at site 23). The table also reports, for each step, the present worth cost and the minimum *actual* value of the difference h-h_{des}, between the nodal pressure head h and the desired pressure head h_{des}, with pressure head values h being evaluated by applying a simulation model (Todini and Pilati, 1988) to the *actual demand* at the generic time. This value makes it possible to understand whether there is a pressure deficit with respect to h_{des} at the end of a certain construction step. The last data of Table 4 concern the maximum pressure head deficit d_{max} (i.e max(abs(h-h_{des})) when $h<h_{des}$, computed in the most critical node with reference to all the time steps), the total pressure head deficit d_{tot} computed in the most critical node (sum(abs(h-h_{des})) when $h<h_{des}$, where the summation is extended on all the time steps) and the total cost $C_{a1,tot}$ of the construction. The analysis of the data points out that designing according to approach 1 can cause the occurrence of significant pressure head deficit in the network.

Table 5 reports the results of the application of design approach 2 to scenario 26. The analysis of the table shows that designing with the phasing of construction helps reducing the number of parallel pipes at the same site (never larger than 3). The comparison between Table 4 and Table 5 shows a smaller total construction cost for design approach 2, despite the smaller first step cost featured by design approach 1. However, not taking account of the actual demand growth, as is done in design approach 2, always entails the occurrence of some pressure deficits (phase 80-100).

Table 6 reports the results of the application of design approach 3 to scenario 26. Since approach 3 is based on phasing of construction as approach 2, it similarly features a low number of parallel pipes (never larger than 3). The comparison of Table 6 with Tables 4 and 5 shows that approach 3 yields a construction cost which is smaller than both approaches 2 and 3. The cost of the first step obtained in design approach 3 is, as expected, equal to that obtained in design approach 2, since approach 2 and 3 are identical in the first construction step. As to pressure deficit, design approach 3 is better than design approaches 1 and 2. In fact, design approach 3, based on the multiple step and considering the actual demand growth, is able to eliminate the occurrence of pressure deficits in the network. The better performance of approach 3 than approach 1 are due to the fact that the multiple step design slightly oversizes the first construction steps and this makes the network more flexible to adapt itself to uncertain demand variations in time.

The analysis reported above was also made for the other scenarios. The overall results are synthetically reported in the graphs in Figure 6, where the cumulated frequency F curve were constructed for variables C_{tot} (total construction cost), C_1 (first step cost), d_{max} (maximum pressure head deficit) and d_{tot} (total pressure head deficit).

In particular, Figure 6 shows that approaches 2 and 3 (based on multiple step design) tend to yield very close total construction costs, which are lower than those obtained by approach 1. As to the first step, approach 1 is that which yields the lowest cost. In terms of pressure head deficits (d_{max} and d_{tot}), approach 3 yields the best results. Summing up, results show that considering the multiple steps and the actual demand growth in the network as feedback for future demand assessment leads to a more reliable and less expensive design. The better reliability is obtained in approach 3 through a slight and suitable oversize of the first construction steps, which render the construction more flexible. Nevertheless, a comment has to be made as far as the pressure head deficits in the construction are concerned. In fact, graphs c and d in Figure 6 show that, though able to attenuate

d_{max} and d_{tot} with respect to approaches 1 and 2, approach 3 is not always able to reduce those variables to 0. In almost 20% of the scenarios, d_{max} and d_{tot} turn out to be larger than 5 m and thus not negligible. On the other hand, it has to be noted that quite large construction steps (20 year long) were considered herein for simplifying purposes. In real applications, the use of shorter construction steps should prevent large deficits from occurring.

A last analysis was made in order to show that the group of 100 scenarios considered for the applications is really representative to analyze and compare the features of the three design approaches. To this end, sub sample (made up of 80 scenarios) was extracted from the whole group of 100 scenarios. With reference to variables C_1 and d_{max} respectively, the graphs a and b in Figure 7 report the cumulated frequency curves relative to design approach 3 for the whole group of scenarios and for the sub group. The analysis of the graphs show that in either graphs the results obtained considering the sub-group of scenarios are very close to those of the whole group of scenarios. This entails that a number of randomly generated scenarios larger than 80 is already sufficient to analyze and compare the results of the three design approaches considered.

Conclusions

In this work, three approaches for the design of the main skeleton of a water distribution network were analyzed and compared. These approaches consider the different phases of construction of the water network and the spatial and temporal variation of the demand growth rate. However, the first approach considers one phase at once and the growth demand rate prediction is performed on the basis of the last value actually observed during the previous phase in the already constructed network; the second approach considers all the phases simultaneously but performs the design only once at the initial time instant by using the predicted growth demand rates without upgrading them as time goes by; the third and last approach, similarly to the first approach repeats the design at the beginning of each phase, but, similarly to the second approach, considers all the remaining phases simultaneously, while the growth demand rates are updated on the basis of the actually values observed.

The results of the comparison showed that using demand feedback for demand projection helps attenuating the occurrence of pressure deficits in the network in the various construction steps and that using the multi-step design instead of the single-step design makes it possible to reduce the overall present worth cost of the construction. As a consequence of this, the multi-step design with the demand feedback is the most reliable because it make it possible to attenuate the occurrence of pressure deficits in the various construction steps of the network as well as to reduce the overall construction costs.

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