Economic Design of Water Distribution Systems in Buildings

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Abstract

Once the design flows and geometric characteristics of the circuits are known, the sizing of a water piping system should be found by computing the most adequate diameters for the various sections in order to guarantee the fulfilment of boundary conditions, based upon limits and restrictions related to velocities and pressures. This paper describes a new criterion for the sizing of water distribution piping in buildings, called the economic sizing criterion, which seems to be of particular interest for systems of large dimensions with extensive critical circuits. These characteristics can be found in several buildings, such as hospitals, hotels, shopping centres and airports.

In systems that are conditioned by pressures, this criterion requires the computation of the values of the diameters to be applied to the various sections of the water distribution piping that minimize the overall installation cost according to some boundary conditions. So this criterion leads to a nonlinear optimisation problem that should be processed by an appropriate solver.

A description of the new criterion and corresponding optimisation model is first introduced and discussed in detail. A practical problem related to a large hospital is also considered in order to illustrate the importance of the proposed criterion in practice. The associated optimisation problem is processed by the well-known GAMS/MINOS nonlinear optimisation solver. Computational results for this special instance are included and indicate the advantages of using the new criterion over traditional criteria for finding sizing of piping systems.

1 Introduction

Once the design flows and the geometric characteristics of the circuit are known, the sizing of a water piping system should be found by computing, in technical and economical terms, the most adequate diameters for the various sections in order to guarantee the fulfilment of boundary conditions, based upon limits and restrictions related to speeds and pressures.
The fundamental equations in hydraulics, particularly the equation of continuity and the Bernoulli equation, in their simplified formula, provide easy relationships among the different variables that enable the solution of the hydraulic design problems. One of the two following sizing criteria is usually used in practice:

a) The maximum admissible velocities criterion;
b) The maximum total admissible head losses criterion.

The first criterion leads to a more economic solution and it is the right option when it can be used in practice. In this criterion, once the design flows in each line are known, the diameters are computed in order to minimize the pipes sizing and satisfying the admited maximum velocities. The calculation of the diameters allows the direct computation of the head losses and the control of the residual pressures in the fixtures.
This criterion obviously produces more head losses in the water distribution system, implying the existence of an adequate available head to secure the minimum residual pressures in the fixtures.
When dealing with inadequate residual pressures or when some circuits suffer from too high head losses involving disproportionate pressure fluctuations, the second criterion should be adopted, if the availabe head is still adequate to the supply without using pumping stations or boosters.
In this particular case, the maximum total possible head loss (ΔH_M) is established in the most unfavourable circuit[1], which allows the computation of a medium value for the unitary friction loss (J_m) in the circuit[2]. Once the design flows (Qc) and the value for J_m are known, the diameters in each line can at once be computed and the velocities can be checked with the established limits.
It should be noted that the application of this second sizing criterion can be justified only in “critical” circuits concerning residual pressures or pressure fluctuations. It is of particular relevance, for obvious economical reasons, the preservation of criterion a) in the remaining circuits.
Both sizing criteria are usually the ones referred to in the literature, but as discussed in this paper it is also possible to establish two further sizing criteria, that will be described as “ the maximum admissible unitary friction losses criterion” and “the economic design criterium “.
The maximum admissible unitary friction losses criterion is not exactly a new one, but a variant of the maximum admissible velocities criterion. It follows the same sizing method and only differs from this latter one in the fact that it establishes in each line maximum unitary friction losses, instead of maximum velocities.
According to some authors [1], the use of this criterion is justified when the unitary friction losses restriction is offered in alternative to the velocities restriction.
Although the economic design criterion shows some similarity to criterion b) and can be applied in the same situations, it is a new one as far as the water distribution piping in buildings is concerned.
This last criterion is introduced in the next section and is justified since the computation based upon a median value of the unitary friction loss, although satisfying the boundary conditions, does not bear in mind economic aspects and therefore does not guarantee the best solution, considering the overall water distribution system cost.

1 The computation of the most unfavourable circuit, although requiring consideration of various items (circuits length, fixtures instalation levels, and their residual pressures, etc.), is in practical terms an obvious option in most situations. In any case, a further test of the water distribution system allows a rapid detection of the existence of other possibly unfavourable circuits.

2 A length for the sizing larger than the real length is generally adopted in order to consider the local head losses without introduction any addition to the sizing complexity. Nevertheless this procedure should not be applied to some acessories (globe valves, for instance) because it is inadequate. In this case the local head losses must be computed individually and must be deducted to the maximum total possible head loss, in order to find the unitary friction loss.

In systems with long “critical” circuits , usually associated with specific buildings, the cost difference may justify the increase of the computing complexity resulting from this criterion, especially in direct supply conditions from the public water distribution system (or from a gravity tank).

2 Economic design criterion

2.1 General considerations

The economic design criterion is concerned with the computation of the diameters to be fitted in the various water distribution system lines that satisfy the imposed boundary conditions and minimise the global installation cost. Therefore this criterion leads to an optimisation model.
It is obvious that the objective function to be minimised is a global cost function. Furthermore, assuming a direct supply from the water distribution system or from a gravity tank, the decision variables are the inner diameters of the various lines. Other parameters, such as the geometric features of the circuit, the pressure levels at the entry point, minimum residual pressures in the fixtures and pipe material, are considered to be problem data.
The boundary conditions to be established are concerned with velocity limits and restrictions and head losses. With respect to the velocities, in addition to regulation limits, other maximum limits for each line that observe comfort criteria can be established. Concerning head losses, the total should not go beyond the value of the available head or the value that coresponds to the maximum established pressure fluctuations.
Optimisation models are usually classified as linear or nonlinear depending on the functions involved in the objective and in the constraints. In some models the decision variables are forced to take values among a compilation of previously defined values (e.g., range of commercial diameters). In this latter case a so-called discrete optimisation model is obtained.
The model to be discussed in this paper belongs to this last category. Some authors have successfully considered these type of discrete optimisation models in public networks that have been solved by integer programming techniques [2]. In these models the values obtained for the decision variables satisfy the respective commercial range. Hence a better efficiency in the sizing is attained than by any other mean, which may justify the great increase in the computational work to find an optimal solution. However, finding an optimal solution in these models is in many situations a formidable task, particularly if the ojective function and the constraints are nonlinear.
As it is shown in this paper, the proposed economic sizing model leads to an optimization problem with nonlinear objective function and nonlinear constraints, that can be considered as a simplification of a model based upon integer programming in the above conditions[3]. When the local head losses are not at stake, it is possible, by using simple transformations in the variables, to obtain an optimisation problem in which a nonlinear objective function is minimised in a set consisting of a linear inequality constraint and limits on the variables. This optimisation problem is much simpler from the mathematical point of view than the previous one, and can be easily solved by commercial optimisation solvers available in the market.

2.2 Objective function

The main parts of a water piping system are the pipes (including fittings), the piping acessories (valves and meters) and the equipments (treatment, heating, etc).

[3] The problem that results from the discrete variables can also be formulated by considering as decision variables in each line the lengths associated to each one of the possible commercial diameters. In this case each line may include elements from all the commercial diameters, the length of each one of these elements being computed by the optimisation study. However, this alternative procedure is not discussed in this paper.

In order to apply the proposed sizing criterion it is required to define cost functions that relate unitary costs with inner diameters for every parts whose characteristics depend on the values attributed to the decision variables.
As the characteristics of the meters, treatment and heating equipments are usually established based upon the water flow, it is necessary to establish cost functions for the pipes and valves that may be installed in the circuits. This unitary cost must be global, that is, it must be take into consideration all the acessories and work needed for the installation.
In Portugal the cost function for stainless steel pipes can be expressed as a polynomial of degree two of the following form

$$CC = -3.2 \times 10^3\, Di^2 + 873\, Di - 4.5 \quad , \qquad (1)$$

where CC *is* the unitary cost of the installed pipe, in €/meter, and Di the inner diameter of the pipe, in metres. On the other hand the cost function for the valves can be represented as the following third-
-degree polynomial,

$$CV = -450 \times 10^3\, Di^3 + 80.5 \times 10^3\, Di^2 - 2.2 \times 10^3\, Di + 21.3 \quad , \qquad (2)$$

where CV is the cost of the installed valve, in euros, and, as before, Di the inner diameter of the pipe, in metres.
As discussed above, these two expressions imply that the overall cost function, denoted by CT, is given, in a circuit with n lines and s valves, by

$$CT = \sum_{k=1}^{n} CC_k\, L_k + \sum_{j=1}^{s} CV_j = \sum_{k=1}^{n} (-3.2 \times 10^3\, Di_k^{\,2} + 873\, Di_k - 4.5)\, L_k +$$

$$+ \sum_{j=1}^{s} (-450 \times 10^3\, Di_j^{\,3} + 80.5 \times 10^3\, Di_j^2 - 2.2 \times 10^3\, Di_j + 21.3) \quad , \qquad (3)$$

where L_k represents the length of the different lines (k = 1,2,...,n).

2.3 Constraints and limits

Portuguese regulations require that the velocities in each line should have a lower and upper limit of 0.50 and 2.00 m/s respectively. By expressing these limiting conditions in order of the diameter, with the design flow (Qc) in m^3/s and Di in meters, we obtain, in a circuit with n lines,

$$Di_k \geq 0.798\, Qc_k^{\,0.5} \;, \qquad k = 1,2,...,n \;, \qquad (4)$$

$$Di_k \leq 1.596\, Qc_k^{\,0.5} \;, \qquad k = 1,2,...,n \;. \qquad (5)$$

As discussed above, additional limits can be imposed for comfort reasons. It should be noted that one of the limits is active in each line.
In order to find the constraints associated with head losses, the Flamant formula can be adopted, considering an increase of 25% on the circuit length to support the head losses in fittings. So in each line, with ΔH in metres, Qc in m^3/s and Di in metres, we have

$$\Delta H_k = 1.069 \times 10^{-3}\, Qc_k^{\,1.75}\, Di_k^{\,-4.75}\, L_k \;, \qquad k = 1,2,...n \;. \qquad (6)$$

We may assume, as an initial hypothesis, that no valves are presented. Hence the restriction for the total head loss simplifies to

$$\Delta H_t = \sum_{k=1}^{n} \Delta H_k \leq \Delta H_M \quad ,$$

or

$$\Delta H_M \geq \sum_{k=1}^{n} (1.069 \text{ x } 10^6 \, Qc_k^{1.75} Di_k^{-4.75} L_k) \quad , \tag{7}$$

where ΔH_t is the total head loss and ΔH_M is the maximum possible or admissible head loss.
It is obvious that this restriction is not a linear on the decision variables. Nevertheless, with a simple variable transformation, it is possible to turn it into a linear constraint and this simplifies the optimization problem. Let us consider new decision variables*, X,* defined as

$$X_k = Di_k^{-4.75} \quad , \tag{8}$$

i.e.,

$$Di_k = X_k^{-0.2105} \quad . \tag{9}$$

So the restriction (7) can be written as

$$\Delta H_M \geq \sum_{k=1}^{n} (1.069 \text{ x } 10^6 \, Qc_k^{1.75} X_k L_k) \quad , \tag{10}$$

Therefore we obtain the following limits for the velocities

$$X_k \leq 2.921 \, Qc_k^{-2.375} \, , \qquad k = 1,2,...,n \; , \tag{11}$$

$$X_k \geq 0.1085 \, Qc_k^{-2.375} \, , \qquad k = 1,2,...,n \; . \tag{12}$$

The objective function can then be rewritten in terms of the X variables and takes the form

$$CT = \sum_{k=1}^{n} (-3.2 \text{ x } 10^3 \, X_k^{-0.4210} + 873 \, X_k^{-0.2105} - 4.5) \, L_k \quad . \tag{13}$$

In the usual procedures, when the installation of section valves in some places is antecipated, two situations can occur. If the head losses in the valve in set position (total outlet) are not significant (e.g., gate valves), the problem will be reduced to the previous model, simply with a change in the objective function that will have a complete expression (3). This procedure does not imply a substancial increase in the sizing complexity. If the head losses are significant (e.g., globe valves) the simplified formula cannot be applied and the head losses should be considered individually.
Nevertheless, since these local head losses are also a function of the decision variables, it is not possible to transform the problem into a linearly constrained using the previous change of variables, and this increases significantly the complexity of the problem.
In pratical terms, considering that the number of the valves installed in each circuit is generally small, this inconvenience can be overcome solving the simplified optimization problem for various hypotheses of diameters in lines with valves. Then the optimal solutions are compared in order to get the best solution for the model. The implementation of such procedure becomes easy and fast in general terms.

2.4 Criterion application

2.4.1 Sizing procedure systematisation

Consider the simplified problem of the previous section, that is, the nonlinear program consisting of a nonlinear function given by (13) and a set of linear constraints (10), (11), (12) that results from the original model by the variable transformation discussed in the previous section. Hence the main steps to find a good solution that satisfies the economic design criterion are as follows:

a) Introduce the problem data (length of the various lines and its design flows, calculated by the accumulated flows or by any other method) and the adopted expressions for the objective function as well as for the limits and restrictions;

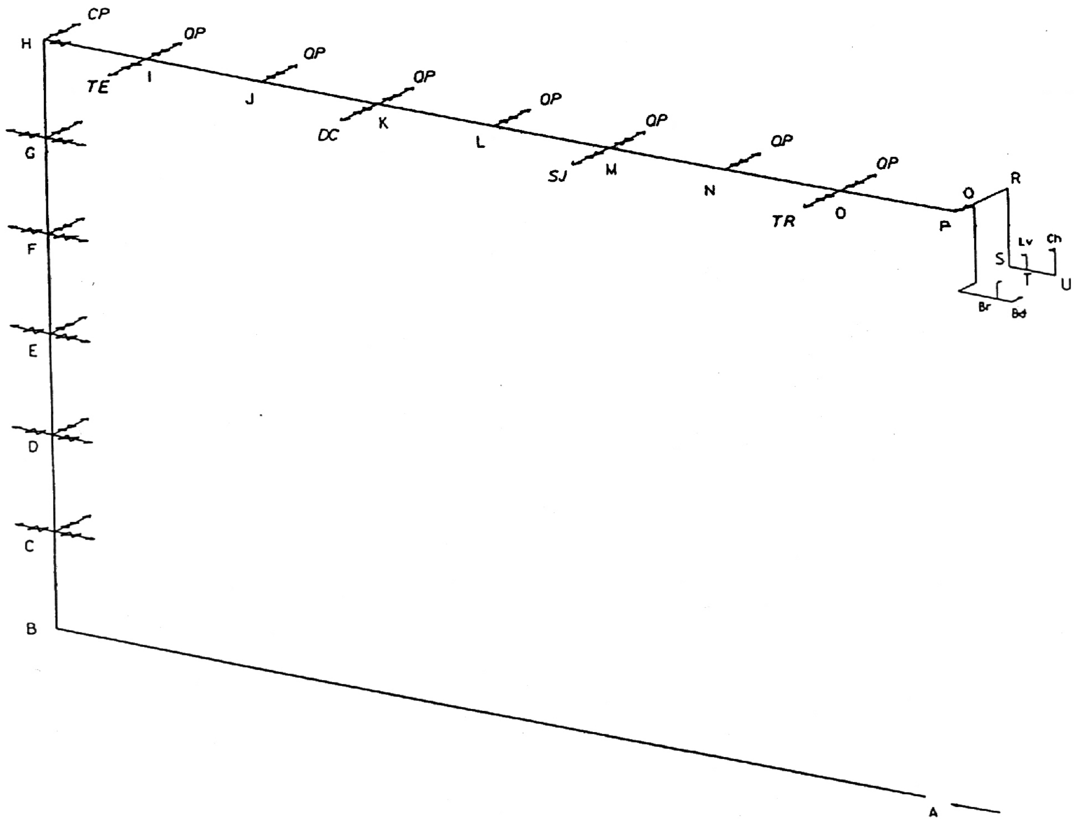
b) Compute the maximum possible or admissible head loss and introduce its value. When head losses in the valves must be considered, the program should be run for the various hypotheses of possible diameters in the lines with valves, deducting to the total head loss, in each sizing hypothesis, local head losses, whose computation is based upon the diameters considered.

c) After changing to the current unities, approximate the values associated to the decision variables (optimal values) according to the commercial diameters range;

d) Check, for the adopted diameters in the commercial range, that both the limits and the relative constraint are satisfied and calculate of the correct final cost.

2.4.2 An application example

Let us consider as an example a six-storey hospital .The floors, except for the top floor, are built in two symmetric rows, with a central pantry (CP) equiped with a sink.
In each row, eight private rooms (QP) with bathroom are planned. All the rooms have a bidet (Bd), a toilet with flush tank (Br) ,a lavatory (Lv) and shower (Ch). In each floor are also planned a nursing service room (TE), with a lavatory, a beds desinfection room (DC), with a bed desinfection device, a room for soiled materials (SJ), with a hospital pan washer, a bedpan washer machine and lavatory and a teatment room (TR), with lavatory and a service sink
Figure 1 represents the axionometric perspective of the circuit considered as the most unfavourable, corresponding to the shower (Ch) supply in the last bathroom on the 6th floor.
The minimum pressure on the entry of the circuit (A point) is 500 kPa and, for confort reasons and equipments demands, minimum residual pressures of 250 kPa should be guaranteed.
The valves (in lines HI and PQ) are of the globe type and they show high head losses even in the outlet position. In this particular case, their values have been taken from tables included in the literature and have been individually considered in the sizing.



The design flows have been calculated on the basis of the portuguese regulation. Besides the velocities limits due to the regulation, that are given by the expressions (4) and (5), other maximum speed limits have been used, following the recommendation in Silva-Afonso [3] for providing a high confort level in the installation.

Table 1 illustrates the application of the traditionally used criteria and of the economic design criterion on the case study introduced in this section. The results included in this table clearly show that the maximum admissible speed criterion allows the most economical solution, but it is not adequate due to insufficient head available in the more unfavourable fixture. The maximum total admissible head loss criterion allows a fair solution but implies a higher cost. The economic design criterion provides a solution that is fair from the hydraulic point of view and minimises the overall cost. It should be added that the optimisation problem required by this last criterion has been processed by the comercial optimisation solver GAMS/MINOS 5.4 [4].

Table 1: Sizing of a critical circuit by different criterions. Comparasion of results

SIZING CRITERION	**RESIDUAL PRESSURE IN Ch** (kPa)	**CRITICAL CIRCUIT COST** (€)
Maximum admissible velocities criterion	237.1 (< 250.0)	2 610,00

Maximum admissible total head loss criterion	256.4	2 895,00
Economic design criterion	250.2	2 730,00

3 Conclusion

Although the example in the previous section is concerned with a fairly short critical circuit, a relevant economy in percentual terms (about 6%) has been achieved by using the econmic design criterion proposed in this paper. In global terms the results are obviously not so significant, due to the relatively low cost of the water piping system. It should be stressed the reduced computational effort required by this optimization procedure, and that all the computational work has been done by using a commercial solver available in the market. These features show great promise for this methodology to deal with large systems with long critical circuits, that can be found in buildings such as hospitals, shopping centres and airports.

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