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INTEGRATING DEMAND VARIABILITY, AND TECHNICAL, ENVIRONMENTAL, AND ECONOMIC CRITERIA IN THE DESIGN OF PUMPING STATIONS SERVING CLOSED DISTRIBUTION NETWORKS

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ABSTRACT

This paper presents an innovative and comprehensive methodology considering yearly demand variability and environmental factors in the design of pumping stations serving closed distribution systems. While a single daily pattern of demand is typically considered for the design in most cases in the scientific literature, the new methodology considers a set of potential daily patterns of demand, each of which with its own probability of occurrence, both to obtain an accurate estimation of yearly operational costs and to guarantee the feasibility of the pumping station during the yearly demand peak. As an additional novelty of this work, environmental criteria, such as the impact in terms of greenhouse gas emissions, are also considered in the design and combined with technical and economical criteria, to rank various design alternatives based on the Analytic Hierarchy Process (AHP). The application proves that it can yield cost-effective, technically sound, and environmentally friendly solutions in systems with various characteristics.

Keywords: Pumping station, AHP, technical criteria, environmental criteria, and economic criteria.

PRACTICAL APPLICATIONS

The main contribution of this work is that it presents a standardized methodology for pumping station design in Water Distribution Networks. An important advantage of this method is that it reduces the degree of subjectivity of the designer and avoids assumptions during the design process by applying a multi-criteria decision analysis in the methodology. This new method of pumping station design brings a different point of view to traditional design methods. While traditional design methods focus on minimizing the project costs and operational costs, this new methodology considers technical, environmental, and economic aspects in a comprehensive manner during the design process. In addition, this methodology considers demand variability in the design process, highlighting its effects and its importance in the case studies presented in this work. In short, this methodology could be applied in any kind of pumping station design for real water distribution networks of different size. The results that this methodology yields demonstrate that the solutions of pumping station can be technically feasible and simple, economically profitable and environmentally sound.

INTRODUCTION

In the most recent century, the world population growth and economic development in urban settlements have caused the increase and pattern variations in water consumption. Two of the seventeen sustainable development goals (SDG) issued by The United Nations (2020), i.e. SDG 6 (water-sanitation) and SDG7 (non-polluted energy), are related to water. Therefore, a lot of efforts in water distribution management are currently being dedicated to the reduction of water and energy wastes and the sustainability of water consumption services. This significantly impacts on the design of pumping stations (PSs), which is typically performed in three stages for closed water distribution networks (WDNs). A closed WDN is made up of a WDN that is directly fed by one or various PSs that take(s) water from the source(s) (Walski and Creaco 2016). As water supply is guaranteed by the operation of pumps, this configuration of WDN requires at least one pump to always be active in each pumping station. Though featuring high operational costs and potentially incurring in issues of reliability, it is often preferred by water utility managers to the open WDN configuration, in which storage tanks lie in between PSs and the remainder of the WDN. This is because the construction of elevated storage tanks may sometimes be infeasible or aesthetically unpleasant in urban centers. As an example, the WDN of Milan is supplied by PSs with no intermediate storage tanks (Creaco et al., 2016). The first stage of PS design for closed WDNs analyses the requirements of flow and pressure of the PS to meet demand and service pressure in the WDN. The second stage determines the minimum head required in the PS to supply the critical node in the network for every flow rate (set-point curve) and selects the suitable number and model of pumps to meet this curve. Finally, the third stage contemplates the infrastructure design, such as infrastructure implantation, electrical installation, and selection of the control system operation in the PS. The main component of Life Cycle Cost (LCC), which plays a major role in PS design, is the operational cost associated with energy consumption, which must be minimized. In fact, the optimization of LCC has economic benefits associated with the reduction in energy and maintenance costs (Bunn and Reynolds

2009), as well as environmental benefits, such as the decrease in greenhouse gas (GHG) emission and leakage (Creaco et al. 2016; Torregrossa and Capitanescu 2019).

Several works developed methodologies to optimize PS operation in the context of WDN design. For example, Lamaddalena and Khila (2013) developed different control system configurations combining pressure and flow controls with Fixed Speed Pumps (FSPs) and Variable Speed Pumps (VSPs) to optimize energy consumption in irrigation networks. Then, León-Celi et al. (2018) optimized the energy consumption in water networks with multiple PSs using the set-point curve concept. Similarly, Briceño-León et al. (2021a) deepened the optimization of the pumping control system and determined the optimal number of pumps and pumping configurations for every flow rate. In addition, they considered the variability in frequency driver performance to obtain more accurate results on energy consumption. A characteristic of these previous works is that the optimization of the PS operation is performed after the pump model and the number of pumps in the installation were previously defined. Furthermore, other works brought about significant improvements, such as minimization of energy, maintenance, and water treatment costs. Mahar and Singh (2014) developed a methodology to optimize the total LCC (infrastructure and operational costs) of PSs. Then, Nault and Papa (2015) improved the operational costs of PSs considering environmental aspects, such as greenhouse gas emissions connected to pump operation. Similarly, Beygi et al. (2019) optimized the total cost of water transportation systems and the reliability of the system based on the Best Efficient Point (BEP) of the pumps.

Summing up, most of the previous works in PS design aimed to assess the solution from an economical point of view, such as the minimization of operational and construction costs. However, several important aspects were not considered in the design, which can hardly be expressed in economic terms, including the feasibility of the construction and the flexibility of the operation, associated with space restrictions in the station and with the number of pumps installed. In fact, a larger number of pumps provides better operating flexibility, which means meeting higher and lower demands with better efficiency. Indeed, the number of pumps is arbitrary and typically left to the designer’s judgment or experience. Another important aspect that is usually neglected is the complexity of the operation of the pumping control system. Therefore, there is the necessity to include technical criteria in addition to economic criteria in engineering projects, such as PS projects (Naval and Yusta 2021). In real case studies, various levels of complexity can be found in the PS serving closed WDNs, ranging between the (almost) total absence of control and the widespread use of flow and pressure control, frequency driver, and Programmer Logic Control (PLC) (Khatavkar and Mays 2019). These control systems are used for the PSs to operate close to the set-point curve of the network in order to reduce energy consumption and leakage. In this context it must be noted that a complex control system may increase the cost of the electrical installation and may make the economic viability of a project more difficult to assess (Leiby and Burke 2011). On the other hand, simple and robust control methodologies are sometimes preferred when pump scheduling is performed in real time to optimize pump operation (Salomons et al. 2020; Manteigas et al. 2021).

Another aspect that is important to consider in the design of PSs is represented by environmental factors, such as the size of GHG emissions produced. In fact, previous works proved WDS management to be potentially harmful to the environment in our era of climate change (Herstein et al. 2011; Blinco et al. 2016; Hajibabaei et al. 2020). However, to the best of our knowledge, only a limited number of works (e.g., Nault and Papa 2015) have so far tried to incorporate this aspect into PS design.

Though the works described above have brought about significant contributions, the scientific literature is still missing a comprehensive methodology integrating economic, technical, and environmental factors in the design of PSs. A recent contribution to PS design was given by the work of (Briceño-León et al. 2021b), who integrated technical and economic criteria divided in 5 sub-criteria, i.e., number of pumps, complexity, investment, operational, and maintenance costs. However, (Briceño-León et al. 2021b) failed to consider environmental criteria. Furthermore, a common limitation of the previous works lies in the fact that they neglected the yearly demand variability of the WDN. In fact, they typically considered a single daily demand pattern to test the feasibility of the PS and to evaluate yearly operational costs. Another limitation is that the optimization of PS operation is usually missed during the selection of pump model and number of pumps in the design process. In fact, it almost always happens that the optimization of PS operation is performed only after the pumping configuration has been defined.

This work tries to bridge this research gap in the context of PSs serving closed WDNs, by combining the optimization of pump control according to various strategies and the Analytic Hierarchy Process (AHP) developed by (Saaty 1980, 2008; Saaty and Sodenkamp 2010) for the multi-criteria decision analysis (Greco J. et al. 2016) of economic, technical and environmental factors. In this way, this work contemplates a different analysis to determine the priorities of the criteria based on the opinion of groups of experts by modifying the conventional AHP scale (Saaty 2008). In addition, this work considers the optimization of PS operation in the design process to determine the number of pumps. Finally, it considers multiple daily demand patterns, each of which with its own probability of occurrence, to better reproduce the yearly demand variability, resulting in a more reliable test of PS feasibility and in a more accurate assessment of operational costs.

METHODS

Pumping Station Design Statement

The design of a PS typically contemplates three stages. The first stage includes finding all the data useful for PS design. The second stage is about the selection of the pump model and the determination of the number of pumps. The third stage includes the infrastructure and installation of the different control system configurations according to the necessities of the network. In the present work, as will be described below, the second and third stages usually considered in PS design are combined into a single iterative stage yielding a set of potential solutions to be assessed by means of the multi-criteria analysis of economic, technical, and environmental factors. This third stage of multi-criteria analysis, which is innovative especially due to the inclusion of environmental factors and the modification of the AHP scale, is meant to help decision-makers in the selection of the ultimate PS design solution with a reduced level of arbitrarily. The flowchart of the proposed methodology is shown in Figure 1, where the three methodological stages are distinguished. These stages concern the required data, the selection of the potential pump model solutions and the application of the AHP method to select the ultimate solution based on a multicriteria analysis of technical, economic and environmental criteria, respectively. Here follows the detailed description of the three methodological stages along with all the elements present in the flowchart.

First Stage

The required data for PS design are listed below:

- Pump model database: Every pump model in a commercial catalog is defined by the best efficiency point (BEP). This term is referred to the operational point of the pump featuring maximum efficiency. The BEP includes the nominal Head (H_0), the nominal flow (Q_0), the nominal efficiency (η_0), and the nominal rotational speed (N_0). These parameters determine the head curve (H-Q) and the efficiency curve (η-Q). The following relationships (1-7) characterize the pump operation:

$$H = H_1 \alpha^2 - \alpha^{(2-B)} A \cdot \left(\frac{Q}{b}\right)^B \text{ head curve} \tag{1}$$

$$\eta = E \cdot \frac{Q}{\alpha \cdot b} - F \cdot \left(\frac{Q}{\alpha \cdot b}\right)^2 \text{ efficiency curve} \tag{2}$$

$$\alpha = \frac{N}{N_0} \text{ rotational speed ratio} \tag{3}$$

$$\eta_c = 1 - (1-\alpha)^3 \cdot \eta \text{ correction for pump efficiency} \quad (4)$$

$$\eta_v = \eta_{v,0} \cdot (\beta_v^{k_1} - k_2 \cdot (1-\alpha)^{k_3}) \text{ efficiency of the frequency drive} \quad (5)$$

$$\eta_S = \eta_c \cdot \eta_v \text{ global efficiency} \quad (6)$$

$$P_T = \frac{\gamma \cdot Q \cdot H}{\eta_s} \text{ consumed power} \quad (7)$$

The term H_I is associated with the maximum head that a pump can supply when the flow (Q) is null. The coefficients A and B characterize the head curve (H-Q) of the pump model whereas the coefficients E and F characterize the efficiency curve (η-Q). All coefficients are obtained by regression techniques to best fit the operating points of the head curve and efficiency curve of a catalog data. The term b is the number of pumps in operation in the PS, and α is the ratio of current to nominal rotational speed (N/N_0). Here it is assumed that all the operating VSPs are of the same model and have the same rotational speed, being connected to the same frequency drive. The term η_c is the correction of the efficiency estimation of the pump by the affinity laws. The equation of this term is based on the (Coelho, Bernardet; Andrade-Campos 2016) formulation. η_v describes the efficiency of the frequency drive, as was developed by (Briceño-León et al. 2021a). The terms k_1, k_2, and k_3 are constant parameters for the best fit of the equation to catalog data. The term η_s is the global efficiency of the PS. Finally, the term P_T is the consumed power by the PS and the term γ is the specific gravity of water.

- Installation layout: This work is based on the basic layout of PS proposed by (Briceño-León et al. 2021b) with its principal components. This layout assumes that the pump units of the PS are connected in parallel and there is a backup pump if any unit pump fails. Upstream and downstream of the PS installation are section valves. Every branch of a unit pump is equipped with one check valve and one section valve. The layout of the PS is shown in Figure 2.

The size of the PS is defined basically by 3 types of lengths in the basic layout: the length of separation of each branch ($L1$), the length of each branch ($L2$), and the length upstream and downstream of the PS ($L3$). These lengths are set proportionally to the nominal diameter of the pipes (ND_i) by using a constant factor (f_i). The sub-index i represents the type of length (1, 2, or 3).

$$L_i = f_i \cdot ND_i \quad (8)$$

- Set-Point Curve: It represents the required dynamic head (H_c) for every flow rate (Q) in the PS for satisfying the minimum pressure service in the nodes of the network, with special attention to the critical node. The main characteristic of this curve is that the resistance produced by consumption nodes is replaced by a constant value that is the minimum pressure of service for consumptions nodes in any time instant. Therefore, there is only one set-point curve for every PS (León-Celi et al. 2018). This curve is expressed by the following equation:

$$H_c = \Delta H + R \cdot Q^C \qquad (9)$$

The terms ΔH, R, and c are the static head of the PS including the minimum pressure service on the consumed nodes of the network, the resistance produced by the pipelines in the network, and an exponent that depends on the characteristic of the system, respectively.

The choice of the quadratic curve in equation (9) can be motivated as follows. Based on the results of numerical simulations on the whole WDN served by a pumping station and modelled considering a stochastic demand approach, Creaco and Walski (2018) proved that, in the local real time control of pumping stations, there is a conservative quadratic relationship between the pressure setting to adopt for the downstream pressure head for guaranteeing a satisfactory service pressure in the whole WDN and the water discharge in the station. Since the dynamic head is the difference between the upstream pressure head, which is typically constant, and the downstream pressure head, expressible by means of a quadratic curve, the same kind of relationship can also be calibrated by means of hydraulic modelling to express the minimum desired dynamic head as a function of the water discharge in the station. Of course, other kinds of relationships may be used without loss of generality for the methodology described in the paper.

In figure 3, the operational curve of a PS made up of three pumps and the set-point curve of a system are shown for explicatory purposes. The intersections of the set-point curve and the pump curve of every pump determine Q_1, Q_2, Q_3 and also define the limit of operation of every pump. In addition, the intersection of the maximum required head (H_{max}) and the set-point curve defines the maximum flow of the system. In general, the purpose of the control system operation is that the operation points of the pumps (Q, H) should be as close as possible to the set-point curve.

- Variability of Demand Pattern: While a single daily pattern of demand is typically considered in most previous works for PS design, this work proposes the use of multiple scenarios of demand. Based on the demand pattern observed in the network analyzed or in another network with similar characteristics during a long time horizon (e.g., one year), demand values can be calculated for each hourly slot for a certain number N_p of non-exceedance probabilities (e.g., $P_{c,j}$ = 0.05, 0.1, …0.95, 1.0). By putting together the demand values associated with the various hourly time slots and with a certain prefixed value $P_{c,j}$ of the non-exceedance probability, the generic *j-th* scenario of demand is obtained. Its probability $P_{rDP,j}$ of occurrence is simply calculated as:

$$P_{rDP,j} = \begin{cases} \dfrac{P_{c,j+1}}{2} & j = 1 \\ P_{c,j+1} - P_{c,j-1} & 1 < j < N_p \\ \dfrac{1 - P_{c,j-1}}{2} & j = N_p \end{cases} \tag{10}$$

The first and the third expression of equation (10) are used to determine the probability of occurrence $P_{rDP,j}$ for the first and last scenario of demand and correspond to the non-exceedance probability ($P_{c,j} = 0.05$ and $P_{c,j} = 1.0$). The second expression of equation (10) is used to determine the probability of occurrence of the other scenarios of demand with non-exceedance probability ($P_{c,j} = 0.10, 0.15 \ldots 0.95$).

The advantage of using a set of multiple daily scenarios of demand, instead of a single scenario, is twofold. On the one hand, it enables better validation of the feasibility of the PS, since the PS is expected to tackle not only the demand peak in the average day of operation but also the demand peak and low demands in the long-time horizon. On the other hand, it enables better estimation of the yearly operational costs, which may differ from those in the average demand scenario.

- Electric tariff: The price of electricity and different kind of tariffs are usually established by the electricity utility. This present work assumes a daily electricity tariff with variable hourly tariffs to differentiate the electricity price in peak hours, off-peak hours, and plain hours. However, daily electricity tariffs can also be variable across the demand scenarios defined above.

- Factor of CO_2 emission: This emission factor is obtained from a local energy marker.

- Control System Strategies: The different strategies of control system are classified depending on the kind of pumps used in the PS (FSPs and/or VSPs) and the type of measurement control: Pressure Control (PC) or Flow Control (FC) as described (Briceño-León et al. 2021b). Specifically, five strategies of operation are considered for this methodology: 1. No control system; 2. FSPs with PC; 3. FSPs with FC; 4 FSPs and/or VSPs with PC; and 5. FSPs and/or VSPs with FC. The first strategy of operation (no control) is not really a control configuration. However, this methodology considers this operating mode to compare the obtained results of energy consumption with the other control system strategies. This methodology contemplates the need for a PLC when the control system has analogic inputs of flow or pressure to regulate the operation of the PS, as it happens in modes 3, 4 and 5. The type of elements to implement the 5 different operating strategies in the PS are defined in the following table 1.

- Database of Unit Costs in a PS: This database contains the unit costs of the elements considered in a PS. This unit cost includes the purchase and installation cost of every element. These elements are the pumps, section valves, check valves, pipes, and all the necessary equipment for every control system. In addition, this database defines the maintenance program of these elements and the frequency of maintenance with its cost.

Second Stage

All the pump models in the database are evaluated to determine the viable pump models for the network. Since the pumps in the PS are connected in parallel (see Figure 3), the feasibility check for each pump model is that the maximum head (H_l) of the pump model must be higher than the maximum required head (H_{max}) required by the network. This methodology considers that the pump models in the PS have the same characteristics. Then, if the pump model does not pass the feasibility check, it is discarded. If it does, it can be considered a viable pump model. For the generic of the N_{viable} viable pump models, the minimum number b_{min} of pumps to install is calculated as the ratio of the peak demand (Q_{max}) of the network to the water discharge of a single pump model selected (Q_{b1}) associated with H_{max}. The peak demand (Q_{max}) is a value obtained from the stochastic analysis of demands previously performed. Of course, the value of b_{min} is rounded up to the highest integer. Configurations featuring a number b of pumps larger than b_{min} and made up of m FSPs and n VSPs, with $b=m+n$, are the result of an optimization process for control system strategies 4 and 5 that will be explained later in the present work.

Since each of the N_d demand scenarios is made up of N_t time slots, a set of flow rates $Q_{t,d}$ ($t=1,\ldots,N_t$ and $d=1,\ldots,N_d$) is obtained to test the PSs. In correspondence to each value $Q_{t,d}$, the value $H_{c,t,d}$ of the required head is obtained from equation 9. Therefore, a set of pairs ($Q_{t,d}$, $H_{c,t,d}$) is finally obtained for PS testing. The iterative procedure described below is applied to each viable pump model and for each of the control system strategies 4 and 5.

For a number of pumps b equals to minimum b_{min} and for each control system, all combinations of m FSPs and n VSPs are analyzed in terms of yearly energy consumption (E_{year}). All of them are evaluated as the average of the daily values of PS consumption, weighted with the demand scenario occurrence probabilities P_r, by means of the following formula:

$$E_{year} = 365 \times \sum_{d=1}^{N_d} P_{rDP,d} \left(\sum_{t=1}^{N_t} P_{T,t,d} \times \Delta t \right) \tag{11}$$

The number 365 in equation (11) is useful for determining the number of days of occurrence of every demand scenario. In this equation $P_{T,t,d}$ (KW) is the consumed power at the t-th time slot in the d-th demand scenario, associated with the pair ($Q_{t,d}$, $H_{c,t,d}$), and Δt (hours) is the time slot duration. In this context, the optimal number of pumps (b_{OP}), the number of FSPs and VSPs in operation, and the optimal pump settings (on/off for FSPs and rotational velocity for VSPs) are optimized to obtain the minimum power $P_{OP,t,d}$ at each time slot and demand scenario. In this optimization process performed in control modes 4 and 5, the benefits of an increased number of installed pumps (b) compared to b_{min} are iteratively estimated in each time slot, by adding a growing number of VSPs till it is beneficial in terms of consumed energy. This procedure generates an optimal number of pumps at each instant ($b_{OP,t}$), whereas the total number of pumps to install ($b_{T,}$) is the value of $b_{OP,t}$ when the demand is equal to the peak (Q_{max}) in the long-time horizon. On the other hand, for control modes 1, 2, and 3, the minimum number of pumps (b_{min}) is the optimal number of pumps ($b_{OP,t}$) for each time slot ($b_{OP,t} = b_{min}$). Hence, the optimal consumed power (P_{OP}) in each time slot is the consumed power obtained from b_{min} (P_0).

At the end of the second stage, there will be a maximum number of potential PS solutions equal to 5xN_{viable}. However, there could be control systems that are not feasible with a pump model, especially with the control system 2 (FSPs with PC) when a pressure switch is greater than the operational range of pressure of the pump model ($0 – H_I$). Then, each PS solution based on a single pump model will feature a certain control system and a certain number of FSPs and VSPs as a result of the PS operating optimization process explained above. The optimal settings of the PS are determined for each PS solution, for all the N_t time slots, and for all the N_d demand scenarios.

Third stage

The second stage of design yields a set of potential PS solutions, among which the ultimate solution can be selected based on Technical, Economic, and Environmental criteria. For each of the criteria, various sub-criteria are considered, as is described in detail below.

Technical Criteria

1. Size: The size of the PS is a growing function of the number of pumps installed, i.e., the higher the number of pumps installed, the higher is the surface size of the PS. A higher score is assigned to this sub-criterion if the installation area is small.

2. Flexibility: The flexibility of the PS is also a growing function of the number of pumps installed, i.e., the higher the number of pumps installed, the larger the flexibility. In fact, a greater number of pumps in the PS allows them to fit the set-point curve better, thus resulting in the improvement of PS performance. A higher score is assigned to this sub-criterion if the number of pumps installed is large.

3. Complexity of control: This relates to the number of elements needed in every control system strategy. A higher score is assigned to this sub-criterion if the number of control elements installed is small. This sub-criterion is evaluated in a numeric score. This score is detailed in the appendix section.

Economic Criteria

4. Investment cost: It relates to the purchase and installation costs for the PS and the control system. The installation costs of the various elements are defined by a database of unit costs and mathematical expressions. These equations were obtained by using parameters that best fit the unit costs represented in a curve. These expressions are better explained in the appendix section. The total investment cost is annualized by considering the cycle life of the elements, as was provided by the manufacturer, and the interest rate. A higher score is assigned to this sub-criterion if the investment cost is small.

5. Operational cost: It relates to the yearly cost of electricity C_E (€) for pump operation and can be calculated with the following equation, which is similar to equation (11) and in which the tariff TE_t (€/KWh), i.e., the unit cost of electricity at time t, appears:

$$C_{E,year} = 365 \times \sum_{d=1}^{N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} P_{T,t,d} \times \Delta t \times TE_t \right) \tag{12}$$

The lower the operational cost, the higher the score to be assigned to this sub-criterion.

6. Maintenance cost: It represents the cost of maintenance activities to implement in the PS to keep it under good conditions. The frequency of maintenance activities for the elements of the PS and their unit costs are obtained by a database to determine the annual maintenance costs. A mathematical expression for this cost was developed, as is explained in the appendix section. Though not explicitly considered in the present version of the methodology, the maintenance cost could be expanded to include the number of status switches in the actual operation of the pump(s) present in the station. A higher score is assigned to this sub-criterion if the maintenance cost is small.

Environmental Criteria

7. MEI: The MEI is an index that describes the energetic efficiency of a commercial pump model in the European Union, and it can therefore be considered an environmental sub-criterion. This index is obtained as the ratio of the minimum efficiency on a dimensionless scale of the pump to the hydraulic efficiency of the pump. This efficiency considers three characteristic points of the pump: the BEP, a point of partial load where the flow rate is 75% of the BEP, and the overload point where the flow rate is 110% of the BEP. The European Union Comission (2012) developed the calculation of the MEI index based on scales. According to this regulation, a MEI value of 0.7 is excellent, whereas a MEI below 0.4 is not acceptable. This sub-criterion is evaluated in a numeric score, where a high score is assigned if the MEI index is high. This score is detailed in the appendix section.

8. Greenhouse gas (GHG) emissions: They represent the amount of CO_2 produced by the PS when it is in operation and they impact on environment health significantly. CO_2 emission is obtained by the multiplication of energy consumed by the PS by an emission factor EF. The EF was obtained from Ministerio Para la Transformación Ecológica y Reto Demográfico (2022). The formula for the assessment of the yearly GHG (Kg) differs from equation (12), due to the presence of EF (Kg/KWh) instead of TE_t (€/KWh):

$$GHG_{e,year} = 365 \times \sum_{d=1}^{N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} P_{T,t,d} \times \Delta t \times EF \right) \tag{13}$$

A high score is assigned to this sub-criterion if the GHG emission is low.

9. Performance of regulation: The performance of the regulation system relates to the ratio η_{RS} of the head of the set-point curve (H_c), to the head of the PS (H) obtained as a result of the application of the control strategy. Under the constraint $H \geq H_c$, a high value of this ratio entails that the PS is working close to the set-point curve, resulting in a improvement of the PS performance in the environmentally friendly reduction of energy wastes. The overall performance of the regulation system is obtained as the PS water discharge Q-weighted average of η_{RS} in all time slots and in all demand scenarios, calculated as:

$$\eta_{RS} = \frac{\sum_{d=1}^{j=N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} Q_{,d,t} \cdot \eta_{RS,d,t} \right)}{\sum_{d=1}^{j=N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} Q_{,d,t} \right)} \tag{14}$$

A high score is assigned to this subcriterion if the performance of regulation is high.

The ranking of the 5xN_{viable} viable solutions obtained at the end of the second stage is performed by means of the AHP method based on the hierarchy construction, in order to obtain the best ultimate solution for the PS with no arbitrarily. The method used to select the best solution is a modification of the conventional AHP scale to determine the priorities of the criteria.

For each criterion and sub-criterion mentioned above, the importance weight is estimated by leaning on the judgment of a group of experts in PS. This group of experts is made up of seven sub-groups, namely academic, commercial, construction, consultancy, management, operation, and direction.

To accomplish this, a survey must be conducted in these sub-groups to evaluate how important the generic criterion is in comparison with the others through a pairwise comparison organized in a quadratic matrix. Traditionally, the AHP method uses a numeric scale from 1 to 9 to compare the importance of the generic criterion to the others ($a_{i,j}$). However, this work proposes a new numeric scale to carry out the comparisons more consistently with the viewpoint of the groups of experts. The modification concerns the importance percentages for the pairwise comparison of subcriteria (C_i, C_j), as they do not change gradually in the traditional Saaty (2008) scale. In the new scale, instead, the percentages are increasing or decreasing gradually in an interval of 5%, leading to more regular values of ratios, i.e., 1, 1.22, 1.5, 1.86, 2.33, 3, 4, 5.67, and 9. For example, a value of 1 in the ratio scale indicates that the same importance is given to two generic sub-criteria C_i and C_j (50% for C_i and 50% for C_j). When the value is 1.22, 55% goes to C_i and 45% goes to C_j. When the value is 1.5, 60% is for C_i and 40% is for C_j, etc. More details about importance percentages of every criterion and numerical scales can be found in the appendix section.

Inside the AHP, manipulations on importance percentages and numerical scales lead to the calculation of the importance weight for the generic sub-criterion. In this work, the consistency ratio (CR) is also considered in these manipulations, to express how consistent the judgment of inter-criteria comparisons is according to the generic group of experts. If CR<=0.10, the comparison of sub-criteria is considered reasonable (Saaty 1980). One contribution of this methodology is to obtain the general importance weight of every sub-criterion by weighing the importance weight of every group of experts with their obtained CR.

The use of AHP therefore enables each of viable solution to be evaluated in every technical, environmental, and economic sub-criterion. Then, the dominant and dominated solutions are identified and discarded, respectively. Incidentally, a dominant solution is a solution that is not inferior to the others according to all sub-criteria at the same time. A solution that is not dominant is a dominated solution. The predefined assessment of the dominant solutions for every sub-criterion are based on the proposal of (Briceño-León et al. 2021b). Nevertheless, in this work, these obtained values are normalized between 0 to 1 for quantitative criteria (size of the PS, flexibility of the PS, GHG emission, performance of regulation, investment, operational and maintenance costs), where 0 represents the worst value and 1 the best value of every one of the quantitative criteria. The qualitative criteria (Complexity of the PS and MEI) are assessed by a group of experts in pairwise comparisons based on the modified scale of AHP. These obtained values are normalized between 0 to 1 (See the appendix section). Then, the dominant solutions are scored through a general ranking weighing the normalized assess of every criterion with their respective importance weight (see the flowchart Figure 1). Finally, the best solution with the highest score is considered the best ultimate design solution for the PS.

In summary, the main contribution of this work is to systematize the AHP methodology in any pumping system design in order that the designer does not need to survey a group of experts again in a new design.

APPLICATIONS

Case study

Three case studies were considered for PS design, namely the CAT, TF1 and TF2 closed WDN. The three networks feature a yearly average demand of 35.50 L/s, 10.61 L/s, and 21.23 L/s respectively.

Overall, 67 different pump models with their respective parameters of the head curve (Q, H) and efficiency curve (Q, η), and with their database of purchase, installation, and maintenance costs of pumps and accessories (See Figure 1 and Table 1) were considered.

In PS design, a maximum number of b_{max} = 10 pumps inside the station was assumed as a constraint, and a tariff distinguishing off-peak, peak, and plain hours was adopted for all networks (see Table 2).

Based on the demand patterns observed in two works in the scientific literature (Alvisi and Franchini 2017; Fiorillo et al. 2020) with similar demand patterns, a set of N_d=21 daily demand scenarios was constructed as explained in the methodological section. The lowest and highest demand scenarios, with a probability of non-exceedance (P_c) equal to 0.05 and 1 respectively, feature a probability of occurrence P_{rDP} = 2.5%. The other scenarios, with probabilities of non-exceedance (P_c) equal to 0.1, 0.15,.., 0.90, 0.95, feature a probability of occurrence P_{rDP} = 5.0% . The probability of occurrence of the demands (P_{rDP}) is obtained from the expressions in equation (10). The demand pattern for TF1 and TF2 network is the same, whreas the demand pattern for CAT network is different.

The Demand Scenarios for the CAT, TF1 and TF2 network are reported in Figure 4.

The importance priorities of technical, environmental, and economic criteria and their respective sub-criteria obtained from the pairwise comparison based on the results of the surveys in different groups of experts are shown in Table 3. The results are expressed with a number from 0 to 1. The higher the score, the higher priority the criterion has in PS design. Overall, Table 3 shows that the most important sub-criterion in PS design is C8 (Operational costs) with a score of 0.19, followed by C3 (Complexity of the control system) with a score of 0.15. In addition, there are other important sub-criteria, such as: C2 (Flexibility of the PS), C7 (Investment costs), and C9 (Maintenance costs) with a score of 0.13. Meanwhile, environmental sub-criteria (C4, C5, and C6) have lower priority than the other criteria, though still being not negligible. Summing up, the scores of technical, economic, and environmental criteria are 0.36, 0.45, and 0.19, respectively.

In each network, five optimization runs were performed in the design. The objective of the optimization framework is to analyze the effects of environmental subcriteria and demand variability in PS design. Specifically, Runs 0 and 1 represent the method commonly used in PS design based on LCC minimization. The difference of Run 0 and Run 1 lies in the fact that Run 1 considers the optimization of control system and Run 0 is based on classical operational modes of control system. Run 2 is drawn from the work of Briceño-León et al. (2021) as a benchmark and applies AHP to technical and economic criteria in the third stage of the methodology. Runs 3 and 4 were performed in the context of the present work. Run 3 is an upgrade of Run 2, incorporating environmental criteria in the AHP. Run 0, Run 1 and Run 2 consider a single demand scenario, i.e. the yearly average day of operation, in the first two stages of the methodology (see Figure 1). Finally, Run 4 is an upgrade of Run 3, incorporating the multiple demand scenarios in the first and second stages of the methodology.

Results

Table 4, Table 5, and Table 6 show the hydraulic characteristics of the three networks in terms of the set-point curve, and the ultimate solutions for the five optimization runs for the three WDNs. Every solution includes the characteristic of the best efficiency point of the pump model selected (Q_0, H_0, η_0) and the values of the 9 different criteria, which enables score evaluation in the context of AHP.

To show the impact of AHP on PS design, the AHP scores for the nine criteria considered in the third stage of the methodology were calculated for the PS solutions obtained in runs 1, 2, and 3 for the CAT network. These scores were obtained by postprocessing the three ultimate solutions with the AHP based on technical, environmental, and economic criteria. Figure 5 reports these scores in a radial chart, highlighting that the solution obtained in run 3, which considers AHP explicitly in the design, have more balanced performance scores than the LCC-based (run 1) and the AHP Techno-Economic (run 2) solutions over the whole set of economic, technical and environmental subcriteria. The pump models obtained in runs 1 and 2 are identical with the only difference in the control system, The solution in run 1 has a better score in the operational costs, being based on LCC minimization. The solution obtained in run 3 is different from the solutions obtained in runs 1 and 2 in terms of pump model, due to the influence of environmental sub-criteria in run 3.

As an additional example of the results yielded by the methodology, Figures 6 and Figure 7 show, for the ultimate solution of run 4, the temporal pattern of the number *b* of pumps in operation, and the rotational speed *α* for the VSPs and the consumed power P_T, respectively, for 5 of the 21 demand scenarios. As expected, the figures show that the values of *b*, *α,* and P_T tend to increase when the probability of non-exceedance of the demand scenario increases, to respond to increasingly stressing conditions of demand.

Discussion

The results of the methodology give some interesting insights into various aspects of PS design, including the effect of considering PS operating optimization in the traditional design aimed at LCC minimization, the comparison of the AHP-based with the traditional PS design, the effects of considering environmental subcriteria in AHP, and the impact of demand variability.

Comparison of design based on minimization of LCC without and with optimization in the control system

These effects can be analyzed by comparing the results of run 0 (LCC minimization without optimization in the control system) and run 1 (LCC minimization with optimization in the control system) in the three networks (see Tables 4, 5, and 6). Run 0 and Run 1 yield identical solutions with the same pump model, number of pumps and same control system. In CAT and TF2 network the solution are (2 VSPs with FC). In the TF1 network, the solution is instead (2 VSPs with PC). The difference between Run 0 and Run 1 lies in the mode of operation in the control system. The control system of the solution in run 0 is based on the classical control system, where the number of pumps in operation is restricted by the minimum number of pumps in every flow operational range in the PS (Briceño-León et al. 2021a). The optimization of control system in run 1 consists of searching for the optimal m FSPs and n VSPs and for the rotational speed of the VSPs in every time step. Therefore, the solutions in run 1 have better performance in operational cost, GHG emission and of course lower LCC.

Comparison of design based on minimization of LCC and on AHP

As Table 4 , 5, 6 show, the CAT and TF1 network have similar characteristics with an almost flat set-point curve, but there is a higher average demand in the CAT network. Both networks have not much variable stressing conditions. In the TF2 network, the average demand is greater than the TF1 network and the slope of the set-point curve is high. Therefore, the variable stressing conditions in the TF2 network are higher than in the CAT and TF1 networks. In each network, Run 1 and Run 2 yielded solutions featuring the same pump model, but with different control systems. In the three networks, run 1 yielded solutions of VSPs with PC/FC because this method considers LCC and tends to minimize operational costs. For example, Run 1 yielded a solution of (2 VSP with FC) for CAT and TF2. In the case of the TF1 network in run 1 the solution is still based on 2 VSPs, but with PC, because the variation of stressing conditions is smaller than in the CAT network. Run 2 yielded, instead, solutions with simple control systems in the three networks. For example, In each network, Run 2 yielded solutions (2 FSPs with no control) because the variation in stressing conditions of CAT and TF1 networks are small. Furthermore, the design based on AHP with Techno-Economic criteria does not encourage the adoption of a complex control system. In the case of TF2 network, the variation in stressing conditions is higher than in the CAT and TF1 network, thus making the adoption of a control system more useful: the ultimate solution in run 2 is (2 FSPs with PC). Though the LCC of the ultimate solutions of the three networks in run 2 is larger than that of the ultimate solutions in run 1, these solutions are selected by run 2 because AHP also considers technical subcriteria, such as the size of the PS, the complexity of the control system, and the flexibility of the PS, all of which have a great importance weight in PS design. In fact, AHP generally aims to find a solution that features low investment and operational costs, simple control system, and high flexibility (high number of pumps) at the same time.

Effects of considering environmental subcriteria

These effects can be simply analyzed by comparing the results of run 2 (AHP neglecting environmental subcriteria) and run 3 (AHP including environmental subcriteria) in the three networks (Tables 4, 5, 6). Due to the inclusion of environmental criteria in Run 3 yields solutions with pump models that provides better characteristic in the set of environmental subcriteria, in spite of the low importance weights assigned to this subcriteria, as a result of the surveys conducted in the groups of experts. For example, in CAT and TF1 network, the difference of run 2 and run 3 lies only in the pump model and the number of pumps. In CAT network (4 FSPs with low flow and no control). In TF1 network, the solution (2 FSPs and no control). In the case of TF2 network, which slope of the set point curve is higher than CAT and TF1 network, the difference of run 2 and run 3 lies in pump model, the number of pumps and the control system (4 FSPs with low flow and FC).

Effects of demand variability

These effects can be simply investigated by comparing the results of run 3 (AHP with single demand scenario) and run 4 (AHP with multiple demand scenarios) in the three networks (Table 4, 5 and 6). In the three networks, the adoption of multiple demand scenarios played a significant role. In the case of the CAT network, it forced the AHP to select a solution based on a pump model with the same number of pumps, but a larger flow and on a more complex control (4

VSPs with PC), which becomes preferable in the presence of highly variable stressing conditions for the PS. It is important to highlight that the number of pumps ($b = 4$ pumps) in run 4 is greater than the minimum required ($b_{min} = 3$). The optimization process of the control system played an important role in the solution of run 4 improving the flexibility, operational costs, and GHG emissions. In theTF1 network, featuring small variation in the stressing conditions, it forced the AHP to select a solution with the same number of pumps, but larger flow and a control system with a moderate regulation (2 FSPs with large flow and PC). Finally, in the TF2 network, featuring high stressing conditions of demand and high required head, it forced the optimizer to select a solution with a greater number of pumps, but lower flow and a control system with excellent regulation mode (1 FSP- 5 VSP with FC), to make the PS capable of meeting extreme conditions of demand and required head with good environmental performance.

CONCLUSIONS

In this work, a novel methodology was proposed for the design of pumping stations (PSs) supplying closed distribution networks. The procedure includes three stages necessary for i) definition of preliminary data, ii) feasibility check, optimization, and performance evaluation for the set of feasible PS solutions, and iii) application of the analytical hierarchy process (AHP) for the selection of the ultimate solution. The methodology was applied to three networks of different sizes, yielding the following conclusions:

- in comparison with the traditional approach based on life cycle cost minimization, AHP considering technical and economic aspects yields solutions that are more acceptable to decision-makers considering a large set of technical and economic subcriteria. In summary, AHP tends to provide solutions with better flexibility of operation (greater number of pumps) and/or simple control system operation according to the variability in the stressing conditions of the network;
- the inclusion of environmental subcriteria can impact the selection of the ultimate solution, by privileging PSs with better MEI index, lower greenhouse gas emissions and better performance of regulation, though this may entail larger investment costs;
- considering demand variability significantly impacts on PS design, as it leads to the choice of ultimate solutions featuring pump models with larger flow, more numerous pumps and control system with better regulation, since the PS must be capable of meeting more diversified demand conditions.

Future developments of the present work will concern the extension of the present methodology to PSs with storage.

DATA AVAILABILITY STATEMENT

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Abdallah, M., and Kapelan, Z. (2017). "Iterative Extended Lexicographic Goal Programming Method for Fast and Optimal Pump Scheduling in Water Distribution Networks." Journal of Water Resources Planning and Management, 143(11), 04017066.

Abdallah, M., and Kapelan, Z. (2019). "Fast Pump Scheduling Method for Optimum Energy Cost and Water Quality in Water Distribution Networks with Fixed and Variable Speed Pumps." Journal of Water Resources Planning and Management, 145(12), 04019055.

Alvisi, S., and Franchini, M. (2017). "A robust approach based on time variable trigger levels for pump control." Journal of Hydroinformatics, 19(6), 811–822.

Beygi, S., Tabesh, M., and Liu, S. (2019). "Multi-Objective Optimization Model for Design and Operation of Water Transmission Systems Using a Power Resilience Index for Assessing Hydraulic Reliability." Water Resources Management, 33(10), 3433–3447.

Blinco, L. J., Simpson, A. R., Asce, M., Lambert, M. F., Asce, M., and Marchi, A. (2016). "Comparison of Pumping Regimes for Water Distribution Systems to Minimize Cost and Greenhouse Gases." Water Resources Management, 142(6), 04016010.

Briceño-León, C. X., Iglesias-Rey, P. L., Martinez-Solano, F. J., Mora-Meliá, D., and Fuertes-Miquel, V. S. (2021a). "Use of Fixed and Variable Speed Pumps in Water Distribution Networks with Different Control Strategies." Water (Switzerland), 13(4), 479.

Briceño-León, C. X., Sanchez-Ferrer, D. S., Iglesias-Rey, P. L., Martinez-Solano, F. J., and Mora-Meliá, D. (2021b). "Methodology for pumping station design based on analytic hierarchy process (AHP)." Water (Switzerland), 13(20), 2886.

Bunn, S. M., and Reynolds, L. (2009). "The energy-efficiency benefits of pump scheduling optimization for potable water supplies." IBM Journal of Research and Development, 53(3), 1–13.

Coelho, B., and Andrade-Campos, A. (2016). "A new approach for the prediction of speed-adjusted pump efficiency curves." Journal of Hydraulic Research, 54, 586–593.

Creaco, E., Lanfranchi, E., Chiesa, C., Fantozzi, M., Carrettini, C. A., and Franchini, M. (2016). "Optimisation of leakage and energy in the Abbiategrasso district." Civil Engineering and Environmental Systems, 33(1), 22–34.

Creaco, E., and Walski, T. (2018). "Operation and Cost-Effectiveness of Local and Remote RTC." J. Water Resour. Plann. Manage., 2018, 144(11): 04018068.

Fiorillo, D., Galuppini, G., Creaco, E., De Paola, F., and Giugni, M. (2020). "Identification of Influential User Locations for Smart Meter Installation to Reconstruct the Urban Demand Pattern." Journal of Water Resources Planning and Management, 146(8), 04020070.

Greco, S., Figueira, J., and Ehrgott, M. (2016). Multiple Criteria Decision Analysis. Springer, New York, NY, USA.

Hajibabaei, M., Hesarkazzazi, S., Lima, M., and Gschösser, F. (2020). "Environmental assessment of construction and renovation of water distribution networks considering uncertainty analysis." Urban Water Journal, Taylor & Francis, 17(8), 723–734.

Herstein, L. M., Filion, Y. R., and Hall, K. R. (2011). "Evaluating the Environmental Impacts of Water Distribution Systems by Using EIO-LCA-Based Multiobjective Optimization." 137(April), 162–172.

Khatavkar, P., and Mays, L. W. (2019). "Optimization-simulation model for real-time pump and valve operation of water distribution systems under critical conditions." Urban Water Journal, Taylor & Francis, 16(1), 45–55.

Lamaddalena, N., and Khila, S. (2013). "Efficiency-driven pumping station regulation in on-demand irrigation systems." Irrigation Science, 31(3), 395–410.

Leiby, V. M., and Burke, M. E. (2011). Energy efficiency best practices for North American drinking water utilities. Water Research Foundation & New York State Energy Research and Development Authority. Albany, New York.

León-Celi, C. F., Iglesias-Rey, P. L., Martínez-Solano, F. J., and Savic, D. (2018). "Operation of Multiple Pumped-Water Sources with No Storage." Journal of Water Resources Planning and Management, 144(9), 04018050.

Mahar, P. S., and Singh, R. P. (2014). "Optimal Design of Pumping Mains Considering Pump Characteristics." Journal of Pipeline Systems Engineering and Practice, 5(1), 04013010.

Manteigas, M., Andrade-Campos, A., André, A., and Coelho, B. (2022). "Cost-Efficient Algorithms for a Pump Horizon Control in Water Supply System." Journal of Water Resources Planning and Management, 148(1), 04021091.

Ministerio Para La Transformación Ecológica y El Reto Demográfico. (2022). "Factores de emisión Registro de Huella de Carbono, Compensacion y Proyectos de Absorción de Dióxido de Carbono." Gobierno España, <https://www.miteco.gob.es/es/cambio-climatico/temas/mitigacion-politicas-y medidas/factoresemision_tcm30-479095.pdf>.

Nault, J., and Papa, F. (2015). "Lifecycle Assessment of a Water Distribution System Pump." Journal of Water Resource Planning and Management, 141(12), A4015004.

Naval, N., and Yusta, J. M. (2021). "Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation." Journal of Cleaner Production, Elsevier Ltd, 316, 128386.

Saaty, T. L. (1980). The Analytic Hierarchy Process. McGraw-Hill. New York, NY, USA.

Saaty, T. L. (2008). "Decision making with the analytic hierarchy process." International journal of services sciences, 1(1), 83–98.

Saaty, T. L., and Sodenkamp, M. (2010). "The Analytic Hierarchy and Analytic Network Measurement Processes: The Measurement of Intangibles." In *Handbook of multicriteria analysis* (pp. 91-166). Springer, Berlin, Heidelberg.

Salomons, E., Housh, M., and Asce, M. (2020). "A Practical Optimization Scheme for Real-Time Operation of Water Distribution Systems." Journal of Water Resource Planning and Management, 146(4), 04020016.

The European Union Comission. (2012). "Commission Regulation (EU) N0 547/2012." <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012R0547> (Jan. 3, 2022).

Torregrossa, D., and Capitanescu, F. (2019). "Optimization models to save energy and enlarge the operational life of water pumping systems." Journal of Cleaner Production, 213, 89–98.

United Nations Water Members. (2020). The United Nations World Water Development Report 2020: Water And Climate Change. Paris.

Walski, T., and Creaco, E. (2016). “Selection of Pumping Configuration for Closed Water Distribution Systems.” Journal of Water Resources Planning and Management, 142(6), 04016009.

FIGURE CAPTIONS

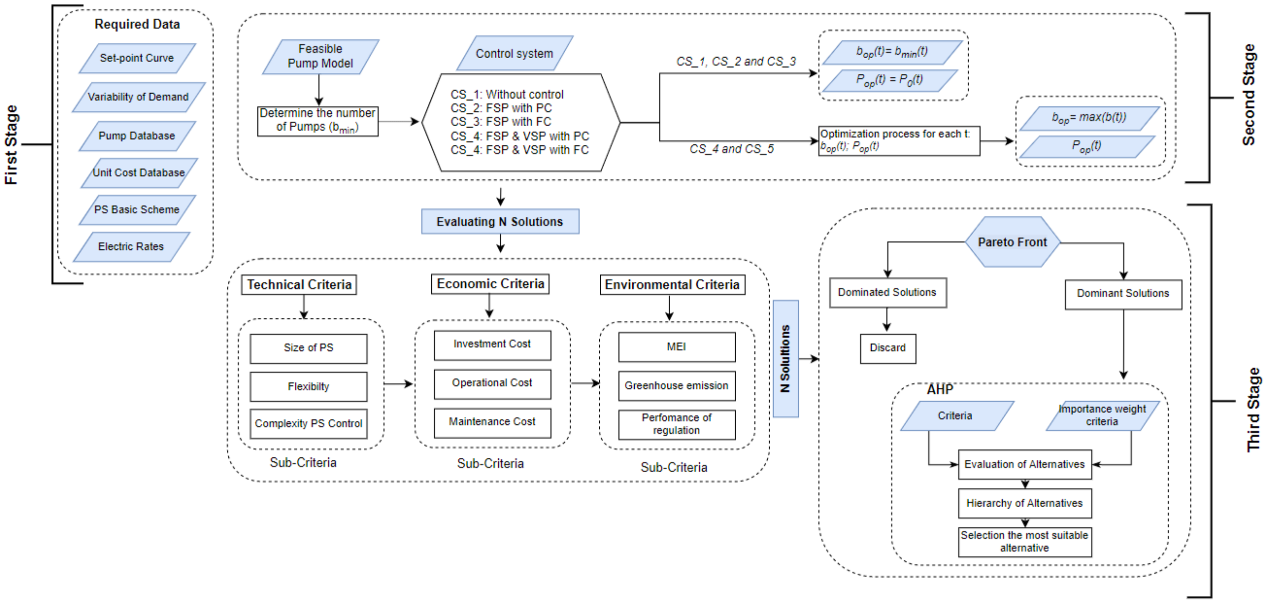

Fig. 1. Flowchart of the proposed methodology

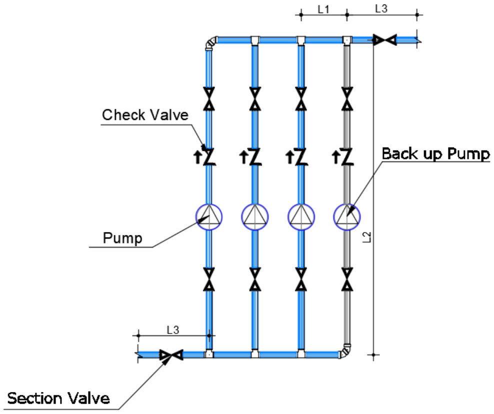

Fig. 2. Basic layout of the Pumping Station

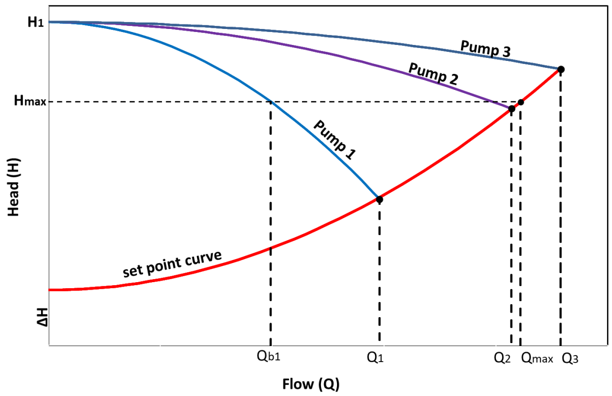

Fig. 3. Set-point curve and Pump curves.

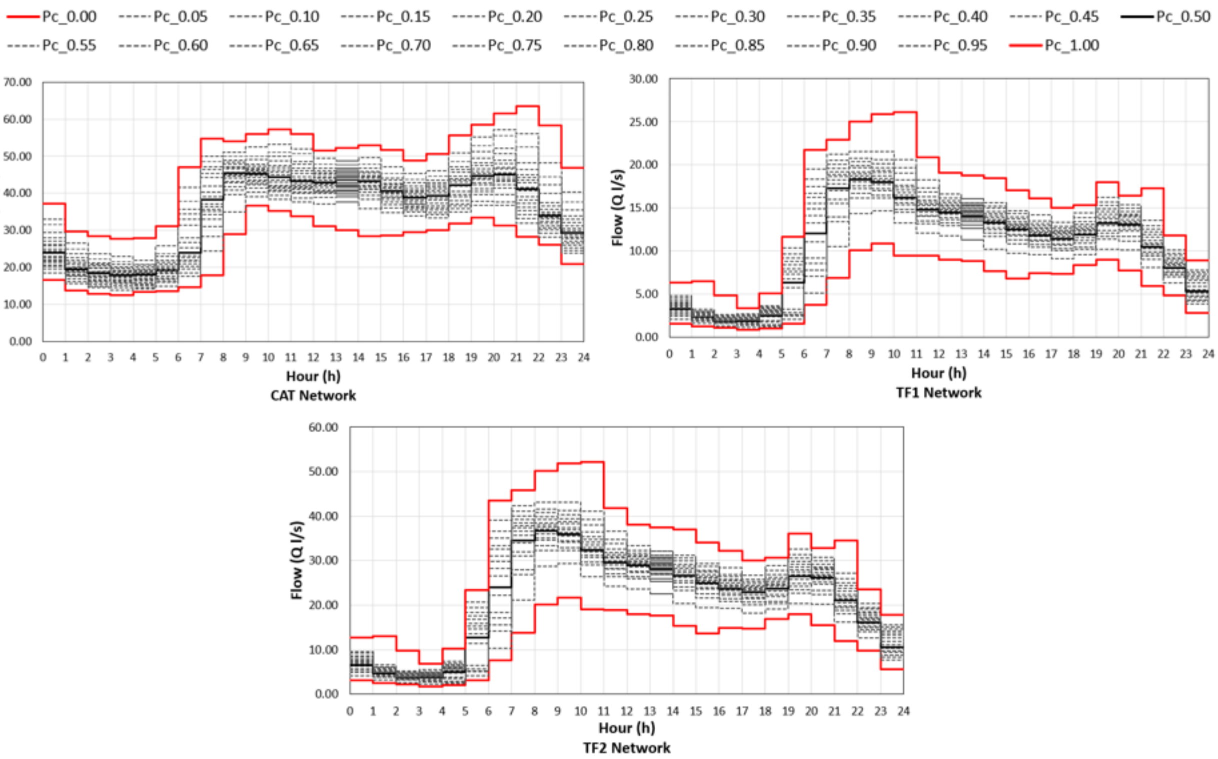

Fig. 4. Demand Pattern Scenarios for CAT-PS, TF1-PS and TF2-PS WDNs.

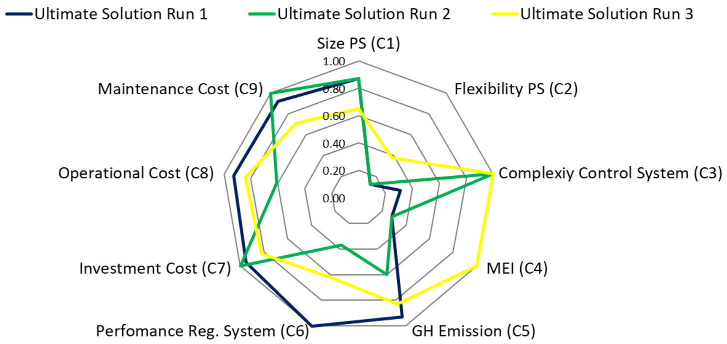

Fig. 5. Radial Chart of AHP scores of the nine subcriteria considered in AHP for the three ultimate solutions of Run 1, Run2, and Run 3 in PS design in the CAT network.

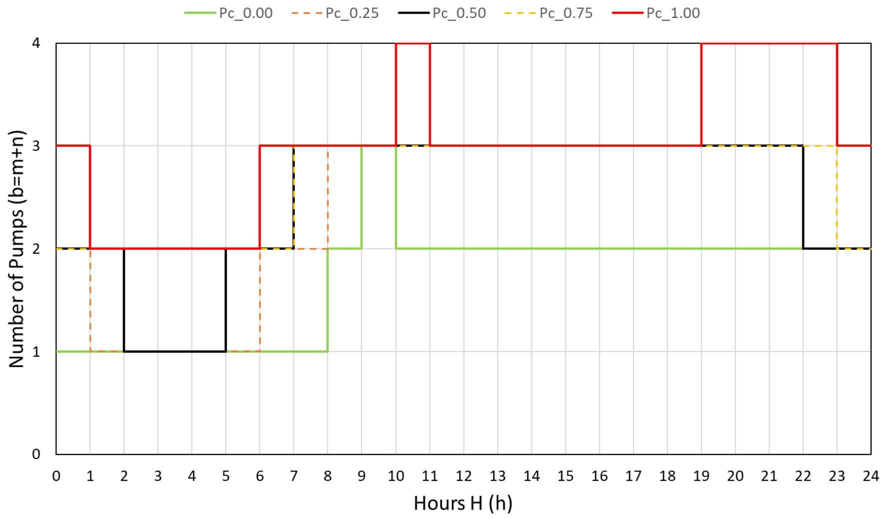

Fig. 6. Number of Pumps in operation (*b =0 FSP-4 VSPs*) in CAT-PS (run 4) in every time slot for different demand pattern scenarios.

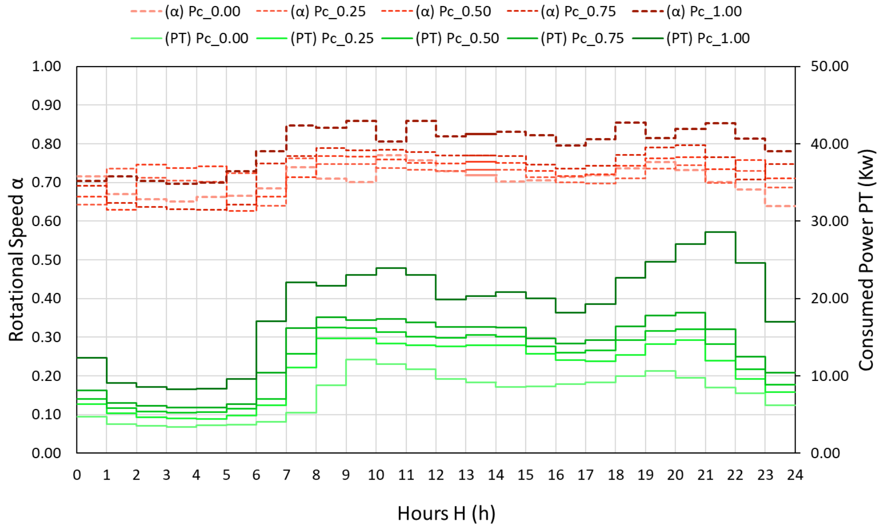

Fig. 7. Ratio of rotational speed ratio ($\alpha = N/N_0$) of VSPs (a single value for all the pumps) and Consumed Power (P_T) in CAT-PS (run 4) in every time slot for different demand pattern scenarios.

TABLES

Table 1. Required elements in every Control System Strategy

Control System		Frequency Inverter	Pressure Switches	Pressure Transducer	Flowmeter	PLC	Type of control elements
1.	No control						0
2.	FSPs with PC		X				1
3.	FSPs with FC				X	X	2
4.	FSPs and/or VSPs with PC	X		X		X	3
5.	FSPs and/or VSPs with PC	X		X	X	X	4

Table 2. Electricity Tariff for the networks

Type of hours	Electric Tariff *TE* (€/kWh)	Initial hour	Final hour
Off-peak hours	0.069	0	8
Peak hours	0.095	10	15
Plain hours	0.088	8	10
		15	23

Table 3. Importance priority of criteria and sub-criteria in every group of experts. C1 Size of the PS, C2 Flexibility of the PS (number of pumps), C3 Complexity of the control system, C4 MEI; C5 Greenhouse emission, C6 Performance of the regulation system, C7 Investment costs, C8 Operational costs, and C9 Maintenance costs.

				Tech. Criteria			Env. Criteria			Ec. Criteria		
	Tech. Criteria	Env. Criteria	Ec. Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
Overall	0.36	0.19	0.45	0.08	0.13	0.15	0.06	0.05	0.08	0.13	0.19	0.13
Academy	0.43	0.21	0.36	0.04	0.2	0.2	0.05	0.05	0.1	0.11	0.2	0.05
Commercial	0.34	0.1	0.56	0.11	0.12	0.15	0.05	0.02	0.03	0.06	0.3	0.2
Construction	0.38	0.14	0.48	0.15	0.07	0.15	0.05	0.04	0.05	0.15	0.16	0.17
Consultancy	0.2	0.31	0.49	0.03	0.07	0.09	0.1	0.04	0.17	0.13	0.24	0.13
Management	0.16	0.10	0.74	0.03	0.09	0.04	0.02	0.01	0.07	0.1	0.39	0.25
Operation	0.28	0.17	0.55	0.05	0.13	0.11	0.06	0.04	0.07	0.2	0.13	0.21
Direction	0.43	0.4	0.17	0.19	0.19	0.05	0.16	0.21	0.03	0.02	0.08	0.08

Table 4. Ultimate solutions (CAT-PS) for 5 Run optimizations

		CAT-PS				
		Single Demand				Var. Demand
		Run 0 LCC min.	Run 1 LCC min. + opt.	Run 2 AHP (Tec-Eco)	Run 3 AHP (Tec-Eco-Env)	Run 4 AHP (Tec-Eco-Env)
Network Characteristics	**Q_m (l/s)**	35.5				
	Q_{max} (l/s)	45.4				63.6

		CAT-PS				
		Single Demand				Var. Demand
		Run 0 LCC min.	**Run 1 LCC min. + opt.**	**Run 2 AHP (Tec-Eco)**	**Run 3 AHP (Tec-Eco-Env)**	**Run 4 AHP (Tec-Eco-Env)**
	Q_{min} (l/s)	17.9				12.5
	ΔH (m)	20.00				
	R	0.0040				
	c	2				
	H_{max} (m)	28.2				36.00
	H_{min} (m)	21.3				20.6
Pump Characteristics	**Model**	28	28	28	49	61
	Q_0 (l/s)	24.25	24.25	24.25	10.98	19.16
	H_0 (m)	32.72	32.72	32.72	29.71	48.81
	η_0 (%)	77%	77%	77%	84%	83%
	b_{min}	2	2	2	4	3
Technical Criteria	**C1 (Size) (m^2)**	129.6	129.6	129.6	140.8	192.5
	C2 (b)	2	2	2	4	4
	C3 (C. System)	2 VSP with FC	2 VSP with FC	2 FSP no control	4 FSP no control	4 VSP with FC
Environmental Criteria	**C4 (MEI)**	0.36	0.36	0.36	0.7	0.7
	C5 (GHG) (kg)	40025	40025	59885	46098	39021
	C6 (η_{REG}) (%)	100%	100%	72%	83%	100%
Economic Criteria	**C7 (Inv. Cost) (€)**	3,153.30	3,153.30	2489.42	5,022.77	12,762.06
	C8 (Ope. Cost) (€)	9,465.32	9,308.87	13558.05	10,442.70	9,033.59
	C9 Man. Cost (€)	890.95	890.95	731.00	1,279.92	1,341.26
LCC (€)		13,509.57	13,353.12	16,778.47	16,745.39	26,136.91

Footnote: H_{max}: Maximum head of the set-point curve; H_{min}: Minimum Head of the set-point curve; A table in the Appendix reports the full list of pump modes used in the analysis.

Table 5. Ultimate solutions (TF1-PS) for 5 Run optimizations.

		TF1-PS				
		Single Demand				Var. Demand
		Run 0 LCC min.	**Run 1 LCC min. + opt.**	**Run 2 AHP (Tec-Eco)**	**Run 3 AHP (Tec-Eco-Env)**	**Run 4 AHP (Tec-Eco-Env)**
Network Characteristics	**Q_m (l/s)**	10.61				
	Q_{max} (l/s)	18.3				26.1
	Q_{min} (l/s)	1.9				0.8
	ΔH (m)	51.19				
	R	0.0059				
	c	2				
	H_{max} (m)	53.2				55.2
	H_{min} (m)	51.2				51.2

		TF1-PS				
		Single Demand				Var. Demand
		Run 0 LCC min.	**Run 1 LCC min. + opt.**	**Run 2 AHP (Tec-Eco)**	**Run 3 AHP (Tec-Eco-Env)**	**Run 4 AHP (Tec-Eco-Env)**
Pump Characteristics	**Model**	43	43	43	62	30
	Q_0 (l/s)	8.08	8.08	8.08	12.53	19.47
	H_0 (m)	62.06	62.06	62.06	47.06	47.65
	η_0 (%)	73%	73%	73%	83%	70%
	b_{min}	2	2	2	2	2
Technical Criteria	**C1 (Size) (m^2)**	51.75	51.75	51.75	51.75	77.40
	C2 (b)	2	2	2	2	2
	C3 (C. System)	2 VSP with PC	2 VSP with PC	2 FSP no control	2 FSP no control	2 FSP with PC
Environmental Criteria	**C4 (MEI)**	0.70	0.70	0.70	0.70	0.10
	C5 (GHG) (kg)	27434	26890	38686	36714	40544
	C6 (η_{REG}) (%)	98%	98%	78%	90%	90%
Economic Criteria	**C7 (Inv. Cost) (€)**	4,290.27	4,290.27	3,574.13	2,214.51	2,359.91
	C8 (Ope. Cost) (€)	6,324.40	6,200.03	8,761.07	8,295.10	9,113.48
	C9 Man. Cost (€)	801.82	801.82	700.12	700.12	717.77
LCC (€)		11,415.99	11,292.11	13,035.32	11,209.73	12,191.16

Footnote: H_{max}: Maximum head of the set-point curve; H_{min}: Minimum Head of the set-point curve; A table in the Appendix reports the full list of pump modes used in the analysis.

Table 6. Ultimate solutions (TF2-PS) for 5 Run optimizations.

		TF2-PS				
		Single Demand				Var. Demand
		Run 0 LCC min.	**Run 1 LCC min. + opt.**	**Run 2 AHP (Tec-Eco)**	**Run 3 AHP (Tec-Eco-Env)**	**Run 4 AHP (Tec-Eco-Env)**
Network Characteristics	**Q_m (l/s)**	21.23				
	Q_{max} (l/s)	36.7				52.3
	Q_{min} (l/s)	3.8				1.7
	ΔH (m)	30.0				
	R	0.0142				
	c	2				
	H_{max} (m)	49.1				68.8
	H_{min} (m)	30.2				30
Pump Characteristics	**Model**	30	30	30	52	44
	Q_0 (l/s)	19.47	19.47	19.47	11.92	8.71
	H_0 (m)	41.61	41.61	41.61	44.71	70.09
	η_0 (%)	70%	70%	70%	80%	75%
	b_{min}	2	2	2	4	6
	C1 (Size) (m^2)	129.6	129.6	129.6	115.20	192.5

		TF2-PS				
		Single Demand				Var. Demand
		Run 0 LCC min.	**Run 1 LCC min. + opt.**	**Run 2 AHP (Tec-Eco)**	**Run 3 AHP (Tec-Eco-Env)**	**Run 4 AHP (Tec-Eco-Env)**
Technical Criteria	**C2 (b)**	2	2	2	4	6
	C3 (C. System)	2 VSP with FC	2 VSP with FC	2 FSP with PC	4 FSP with FC	1 FSP- 5 VSP with FC
Environmental Criteria	**C4 (MEI)**	0.26	0.26	0.26	0.7	0.7
	C5 (GHG) (kg)	44479	43656	56706	42578	40098
	C6 (η_{REG}) (%)	100%	100%	81%	86%	100%
Economic Criteria	**C7 (Inv. Cost) (€)**	3,423.57	3,423.57	2,705.50	7,001.67	11,363.13
	C8 (Ope. Cost) (€)	10,267.82	10,078.69	13,041.15	9,779.13	9,259.79
	C9 Man. Cost (€)	890.95	890.95	737.07	1,366.95	2,050.51
LCC (€)		14,581.44	14,393.21	16,483.72	18,147.75	22,673.44

Footnote: H_{max}: Maximum head of the set-point curve; H_{min}: Minimum Head of the set-point curve; A table in the Appendix reports the full list of pump modes used in the analysis.