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PUMPING STATION DESIGN WITH AN ANALYSIS OF VARIABILITY OF DEMAND AND CONSIDERING TECHNO-ECONOMIC AND ENVIRONMENTAL CRITERIA THROUGH THE AHP METHOD

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Abstract

Pumping Station costs including capital and operational costs are some of the highest costs in urban water distribution systems. A proper pumping station design could be defined as the solution with the minimum life cycle cost and satisfying extreme scenarios in water distribution system. These costs are associated with investment, operational, and maintenance costs. However, there are some important aspects to consider in a pumping station design, such as the feasibility of infrastructure construction, the size of the infrastructure, and the complexity of operation in the pumping station. These aspects are associated with technical criteria. In a classical pumping station design, the number of pumps is determined in arbitrary form according to the criteria of the engineer, and the pump model is selected according to the maximum requirements of flow and pressure of the network. In summary, these variables in a pumping station design are not usually analyzed deeply. In addition, global warming acceleration in the last decades has gained momentum to be considered in engineering problems to mitigate the environmental impact. Hence, it is imperative to consider environmental aspects, such as greenhouse emissions, energetic efficiency of the pump in modern pumping systems of water distribution networks. Finally, the most suitable solution is determined only by analyzing economic aspects. Therefore, this work proposed a methodology to design pumping stations in urban water networks considering technical, environmental, and economic criteria and link them together through the Analytic Hierarchy Process (AHP) method. This method proposes to determine the importance priority of these aspects to assess the possible solutions and determine the most suitable solution in the pumping station design. In addition, this work considers the variability of demand pattern. This work analyses several scenarios of demand patterns from the minimum possible demand to the maximum possible demand in a water distribution network and the respective probabilities of non-exceedance. It allows the pumping station design be more robust. This methodology has been applied in different case studies to analyze how affects to determine the most suitable solution when the characteristics of the network change.

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

1. INTRODUCTION

Water demand has increased constantly around a rate of 1% per year because of the development of urban settlements. It has led to an increase in water stress in the last century. In addition, water distribution systems (WDS)consume a great amount of energy. Approximately 95% of this energy consumption is due to pump station (PS) operation [1]. Hence, climate change issues, such as greenhouse gas (GHG) emissions have been increasing in the last decades. All these problems have been of concern to the authorities in the world. The United Nations (UN) established the Sustainable Development Goals (SDG) of the 2030 agenda, SDG 6 dedicated to water and sanitation, and SDG 7 dedicated to affordable and non-polluting energy. Therefore, water management companies have made efforts to focus on reducing energy consumption and improving the operation and service in WDS.

Urban supply systems are one of the infrastructures of the most vulnerable to climate change; therefore, it is necessary that their projection is made considering energy efficiency, and responding to the variability of demands, without neglecting the optimization of the costs of investment and operation. Life Cycle Costs (LCC) supposes to be a major component in the analysis of a pumping station in closed networks. These costs are mainly composed of operational costs associated with energy consumption, maintenance costs, and investment costs. In fact, the reduction of energy consumption and maintenance costs are the most common efforts to improve the operation and water service for WDS [2].

The main element of the annual operating budget in a WDS is the energy consumption costs of the PS. Therefore, the most common objective in the design of closed networks is to optimize energy consumption. Chang Y. et al. [3] developed a methodology to save energy costs for water networks by transferring the water demand at storage systems when the unit price of energy is high and the amount of water demand is increased when the unit price of energy is low. On the other hand, Lipiwattanakarn S. et al. [4] created a theoretical estimation of assessing the energy efficiency of water distribution systems based on energy balance. These components of energy were: outgoing energy through water loss, friction energy loss, and energy associated with water loss. Besides, Giudicianni et al. [5] developed a methodology to improve the management and monitoring of water distribution systems based on regrouping the original network into dynamic district metered areas. The idea of this proposed framework is to locate determined energy recovery devices and reduce water leakage in a water network.

In addition, several works deepened the operation of PS. For example, Walsky and Creaco[6] evaluated different pumping configurations for closed networks combining a different number of Fixed Speed pumps (FSP) with different sizes and adding a Variable Speed pump (VSP) to select the most suitable configuration for different scenarios of flow and required head. Then, Leon Celi et al. [7] optimized the allocation of flow and the energy consumption in water networks with multiple PSs determining the optimal set-point curve in every PS. This term is referred to the head required of PSs to satisfy demand requirements in the critical node maintaining the minimum service pressure throughout the time. In a similar way, Briceño et al. [14] create a new methodology of control system for PSs to determine the optimal number of pumps and decrease energy consumption using the set-point curve concept.

There are other improvements of pumping systems, such as multiobjective optimizations including, energy costs, maintenance costs, and treatment costs [8], [9] or optimizing energy costs and maximizing the reliability of the systems [10], [11]. In addition, Mahar and Singh [12] developed a methodology to optimize capital and operational costs for PSs. Similarly, Nault and Papa (2015) improved the operational costs of PSs considering environmental aspects, such as GHG emissions associated to pump operation. Then, Candilejo et al. [13] optimized the construction cost and energy cost in a pressurized water network with variable flow demands based in an equivalent flow rate and equivalent volume.

In the last decades, several research have proved that projects related to serving WDS including PS design could be potentially harmful to the climate change [13] [14]. However, there are few works that faced the environmental impact. These works are related with reducing GHG emissions [15] and leakage in pumping systems [16].

In general, most of the previous works in pumping systems aimed to assess the solution from an economical point of view, such as the minimization of operational and construction costs. However, there are hidden important aspects were not considered in the design and could be hardly determined in economic terms. For example, the viability of required size in the construction stage and the flexibility of operation are usually neglected in PS design. These aspects are closely related to the number of pumps, which is arbitrary defined according to the designer's judgement or experience. Another important aspect that is difficult to convert in economic terms is the complexity of the operation of the pumping system. The optimization of the pump operation needs sophisticated devices, especially Programmer Logic Control (PLC). However, it supposed that PS operation be more complex. For example, In real-time control operation of water networks that use Supervisory Control and Data Acquisition (SCADA), it is too complex to schedule the pumps with the PLCs [17], [18]. Another problem of the previous works lies in the fact that they omitted the yearly demand variability of the WDS. In fact, they typically consider a single daily demand pattern, and it could make that the operation of the system be less feasible.

Therefore, the idea of this work is to integrate economic aspects with other important aspects that are usually neglected in PS, such as the flexibility of operation, the size of the station, the complexity of operation, and also consider environmental aspects. Some of these aspects have conflict of interest, such as operational costs with the complexity of operation. Throughout the multicriteria analysis can evaluate different criteria and stablish an alternative or group of alternatives that meet all criteria. One of the methods of multicriteria analysis developed in last years is the AHP method that is an important method for complex management decision problems [19].

AHP is a method developed by Saaty [20]. It allows the resolution of complex problems involving multiple criteria. The AHP process requires the decision-maker to do so through subjective assessments regarding a relative importance of each of the criteria and to specify their preference with respect to each of the alternatives for each of the criteria. In fact, in the last decades the AHP method has been widely applied in the hydraulic engineering field. For example, in WDS and sewer system rehabilitation to determine the priorities of maintenance or substitution of the elements of those systems [21] [22], or water management sustainability [23]. Finally, Briceño-León et al. [24] developed a approach of PS design integrating techno-economic factors.

In this way, the objective of this work is to develop a comprehensive methodology for PS design through the multicriteria analysis (the AHP method). One contribution of this work is to determine the priorities of the aspects considered in the design (Technical, Environmental and Economic Factors). Then, this methodology evaluates the potential alternatives integrating the considered aspects for the PS and select the most suitable solution. The alternatives will be gotten from a pump database that will have different number of pumps and different control system alternatives. The criteria considered in this work are technical factors that considered the size of the pumping station, the complexity of regulation mode and the flexibility of operation, economic factors include investment, operational and maintenance costs and environment factors are associated with minimum energy efficiency (MEI), CO2 emissions and perfomance regulation. In addition, another contribution of this work is to consider demand variability and their respective probability of occurrence of every demand scenario. The consideration of different demand scenarios will make the design be more feasibly and robust.

2. METHODOLOGY

2.1 Pumping Station Statement

The design of a PS contemplates three stages. The first stage includes the definition of the set-point curve of the network. It means the required flow (Q) and head (H) of the pump to satisfy the requirements of the network, and the maximum flow (Q_{max}) and the maximum required head (H_c) at the critical node. The second stage is about the selection of the pump model and determine the required number of pumps to satisfy the operation of the system. The third stage includes the selection of type of operation control system for the PS according to the necessities of the system.

Traditionally, the design of PS for closed WDS is made up of centrifugal pumps and their respective number of pumps, usually installed in parallel. The traditional method of selecting the pump model is searching for a pump model that provides the maximum demand flow (Q_{max}) and maximum head (H_{max}) of the network. Once is defined the pump model, the required number of pumps is obtained by the relation of the maximum required flow (Q_{max}) and the flow of a single pump of the model selected (Q_{b1}) associated with the maximum required head (H_{max}). Nevertheless, in some cases, firstly the number of pumps is fixed. Then, the model is selected according to the relation of the maximum flow (Q_{max}) and the number of pumps and also considering the maximum required head (H_{max}). Then, the designer established different pumping configuration modes, including the number of FSP or VSP and the type of control to use: Pressure Control (PC) or Flow Control (FC).

This methodology considers five different control systems. The first (1.- No control system). In this configuration the pumps operate all the time without restrictions. The second configuration (2. _ FSP with PC) operates only FSPs and their operation are associated with fixed switch on/off pressures and the set point curve. The third configuration (3. _ FSP with FC) operates only FSPs and their operation are associated with intersection flows of the pumping curves and the set-point curve. The fourth configuration (4. _ FSP and VSP with PC) is a combination of FSP and VSP and their operation consist of the operational points of the pump (Q, H) follow a fixed pressure. Finally, the fifth configuration (5. _ FSP and VSP with FC) is the combination of FSP and VSP and their operation consist of the operational points of the pumps (Q, H) follow the set-point curve.

In brief, the operational conditions of the system, the characteristic of the pump models, the number of installed pumps, and different control system configurations are the restrictions in a PS design. Hence, these restrictions drives that the design be arbitrary and subjective according to the criteria of the designer. Therefore, the obtained solutions do not guarantee be the optimal in technical, economic, and environmental aspects at the same time. In addition, it drives that the selection of the ultimate solution be not generic.

Therefore, this work aims to diversify the traditional design process of pumping stations, in which the methodological design development is proposed through a multi- criteria perspective based on technical, environ-mental, and economic criteria that respond to the current dynamics of infrastructure projection.

2.2 Hypothesis and Required Data

One assumption of this methodology is that the WDS is a closed system, and the PS injects directly the flow to the consumption nodes. In addition, they hydraulic characteristics of the system (set-point curve, demand pattern) are assumed as known data. In this way, the required data to develop the methodology are the following:

- **Setpoint curve**: it is the definition of the hydraulic requirements. It represents the minimum head necessary leaving of the pumping station to guarantee the demands with the minimum pressure conditions required

$$H_c = \Delta H + R \cdot Q^C \tag{1}$$

The term ΔH is the static head of the PS including the minimum pressure service of the network, R represents energy losses produced in the system, and c is an exponent that depends on the characteristic of the system.

- **Schematic Model of a PS**: Iglesias Rey et al. [25] proposed a parameterized model of a PS. The basic scheme includes a back-up pump to guarantee the reliability of the PS. The scheme is represented in Figure 1. In this figure, the parameters *N1*, *N2* and *N3* are the characteristic lengths of the PS, which are considered proportional to the nominal diameter (ND) of the pipe:

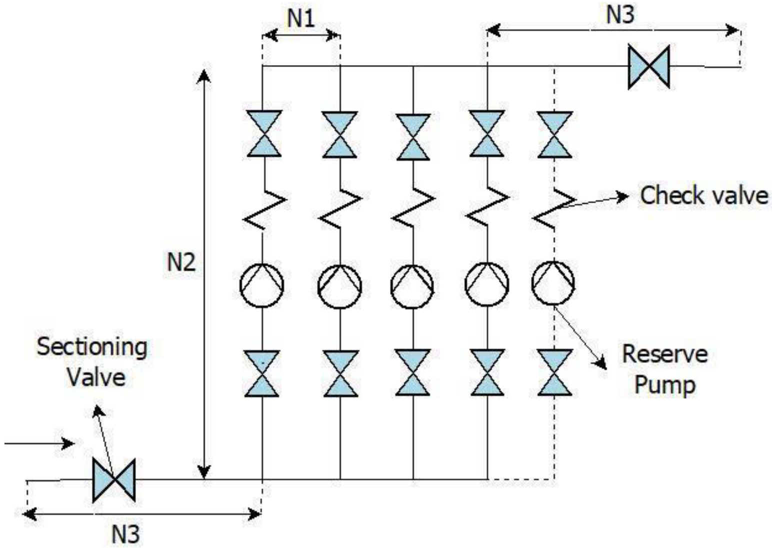

Figure 1. Basic Scheme of a PS.

- **Pump Model Database**: Every pump model in the commercial catalogue is defined by the Best Efficient Point (BEP). 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 variables determine the pumping curve (H-Q) and the efficiency curve (η-Q). The characteristic of the pumping curve is defined by fixed parameters: A, H_1, and B (Equation 2), and the characteristic of the efficiency curve is defined by fixed parameters: E and F (Equation 3). In addition, both curves are defined by the variables: the ratio of the current rotational speed and the nominal rotational speed ($\alpha = N/N_0$), the flow (Q), and the number of installed pumps (b).

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

$$\eta = E \cdot \frac{Q}{\alpha \cdot b} - F \cdot \left(\frac{Q}{\alpha \cdot b}\right)^2 \tag{3}$$

In addition, the parameters of a PS includes the correction of the pump efficiency of the affinity laws developed by Sarbu and Borza [26] (Equation 4). The term η_c is the pump efficiency correction and η is the efficiency of the affinity laws. On the other hand, Briceño et al. [27] developed an expression to estimate the efficiency of the frequency drive (Equation 5). The terms k_1, k_2, k_3 are constant parameters of the equation of the frequency drive efficiency, $\eta_{v,0}$ is the maximum frequency drive efficiency. Finally, P_s in equation (6) is the consumed power of the PS, and Q_{FSP} and Q_{VSP} are the flow delivered by FSP and VSP respectively.

$$\eta_c = 1 - (1-\alpha)^3 \cdot \eta \tag{4}$$

$$\eta_v = \eta_{v,0} \cdot (\beta_v^{k_1} - k_2 \cdot (1-\alpha)^{k_3}) \tag{5}$$

$$P_s = \frac{\gamma \cdot Q_{FSP} \cdot H}{\eta_c} + \frac{\gamma \cdot Q_{VSP} \cdot H}{\eta_c \cdot \eta_v} \tag{6}$$

- **Demand Patterns**: This methodology incorporates the analysis of variability of demand in the PS design. The different scenarios are defined by the probability of non-exceedance of the demand from 0 to 1. Every scenario has its probability of occurrence to determine the number of days of occurrence of every demand scenario.
- **Electricity rates**: correspond to electricity rates that change hourly depending on the type of power contracting that the supply system has.
- **MEI**: Is a dimensionless index that defines the ratio minimum efficiency of the pump between the operating point of 75% of the BEP and the overload of 110% of the BEP. This index is calculated according to EU Regulation 547/2012.
- **CO2 Emission**: This factor is obtained from a local energy maker and it is used to calculate the CO2 Emission by the PS.
- **Economic Factor**: This factor is associated with the annual interest rate to amortize the investment cost in yearly costs.

2.3 Evaluation of the Pump Models

Every pump model in the database is evaluated the feasibility with the hydraulic characteristics of the WDS. The maximum head (H_1) of every pump model must be higher than the maximum required head of the system (H_{max}). The infeasible pump models are discarded, and the feasible pump models could be considered as potential solution. In addition, in every feasible pump model is determined the minimum number of pumps (b_{min}) and checked if b_{min} is not greater than the maximum allowed number of pumps (b_{max})

In every feasible pump model are five different configuration of control system obtaining a maximum potential solution of 5xN_{viable}. In control system configurations 4 and 5, have the combination of m number of FSP and n number of VSP ($m+n=b_{min}$). In these configurations are optimized the number of pumps ($b=m+n$) in every time slot and in every scenario of demand. The optimization process consists of adding a unit number of VSP in every combination of ($b = m + n$) until is not possible to improve the consumed power of the PS. In this context, the optimal number of pumps ($b=m+n$) could be greater than b_{min}. In summary, the optimal configuration of control systems 4 and 5 search the optimal number m FSP and n VSP in operation, and the rotational speed to minimize the consumed power ($P_{T,OP}$). The following figure 2, describes the optimization process of the control system configurations.

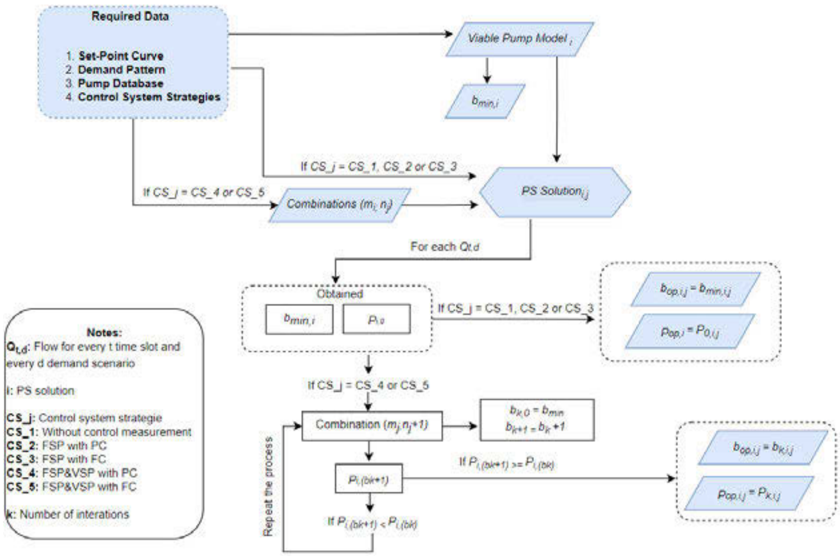

Figure 2. Optimization Process of Control System Configurations

The potential solutions are evaluated in every criterion of technical, environmental, and economic criteria. The obtained results of the potential solutions in every criterion are ranked in a numeric scale of 0 to 1, where 0 is the worst and 1 is the best solution.

The criteria considered in this methodology is described in detail below.

Technical Criteria

1. Size: The size of the PS is in function of the number of pumps installed and the length of the pipelines in the station. A higher score is assigned to this sub-criterion if the installation area is small. In this way, the highest size is assigned a score of 0 and the smallest size is assigned a score of 1.

2. Flexibility: The flexibility of the PS is associated with the number of pumps installed, i.e. as higher is the number of pumps installed, the flexibility is larger. In fact, a greater number of pumps in the PS allows that the perfomance of the system increase. A higher score is assigned to this sub-criterion if the number of pumps installed is large. The potential solution with the highest number of pumps (b) is assigned a score of 1 and the solution with the smallest number of pumps is assigned a score of 0.

3. Complexity of control: This sub-criterion is associated to the number of elements needed in every control system strategy. The control system is considered less complex if the number of control elements in the system is small. Hence, as smaller is the number of control elements installed, the score assigned is higher. Every control system configuration is assigned a numeric score from 0 to 1 (Table 1), where 1 is the least complexity of the control systems and 0 the highest complexity of the control systems. The scores are obtained from pairwise comparisons of the different control system configurations applying the AHP method.

Table 1. Numeric Score of the Control System Configurations

Control System Configuration	Complexity Level	Numeric Score
1. Without CS	1	1.00
2. FSP with PC	2	0.57
3. FSP with FC	3	0.32
4. FSP-VSP with PC	4	0.15
5. FSP-VSP with FC	5	0.07

Economic Criteria

4. Investment cost: It includes the costs of supplying and installing pipes, fittings and control elements, as well as the cost of the pumps. Additionally, it includes the costs of supplying and installing accessories and tubing for the reserve pump and its value. The equations to determine the purchase and installation costs of the accessories were developed by Briceño-León et al. [24]. The investment cost is annualized considering the life cycle of the elements, and the annual interest rate. A higher score is assigned to this sub-criterion if the investment cost is small. In this way, the solution with the lowest investment cost is assigned a score of 1 and 0 to the solution with the highest investment cost.

5. Operational cost: This sub-criterion is associated to the yearly cost of consumption energy (€) for the PS, and it is calculated by the following equation.

$$C_{E,year} = 365 \times \sum_{d=1}^{N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} P_{T,t,d} \times \Delta t \times TE_t \right) \tag{7}$$

The term N_d is the number of demand scenarios, the sub-term d corresponds to each demand scenario, the duration of the time slot is represented by Δt, the sub-term correspond to every time slot, and TE is the electric tariff. The number 365 is used to obtain the number days of occurrence of every demand scenario. The lower the operational cost, the higher the score to be assigned to this sub-criterion. Hence, the lowest operational cost is assigned a score of 1 to the solution and the highest operational cost is assigned a score of 0 to the solution.

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 costs are obtained by a database to determine the annual maintenance costs. A higher score is assigned to this sub-criterion if the maintenance cost is small. In this way, the solution with the lowest maintenance cost has a score of 1 and 0 the solution with the highest maintenance cost.

Environmental Criteria

7. MEI: The EU regulation 547/2012 developed the calculation of the MEI index. 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. These scores are detailed in the following table 2:

Table 2. Numeric Scale for MEI Index values

MEI Index	Numeric Score
0.1	0.05
0.2	0.07
0.3	0.12
0.4	0.27
0.5	0.40
0.6	0.61
0.7	1.00

8. CO2 Emission: It represents the amount of CO2 produced by the PS when it is in operation. CO2 emission is obtained by the multiplication of energy consumed by the PS with an emission factor *EF*. This sub-criterion is evaluated in terms of Kg of C02 in a year.

$$GHG_{e,year} = EF \times C_{E,year} \tag{8}$$

A high score is assigned to this sub-criterion if the CO2 emission is low. Therefore, the solution with the lowest CO2 emission is assigned a score of 1 and 0 the solution with the highest CO2 emission.

9. Performance of regulation: The performance of the regulation system (η_{RS}) relates to the ratio 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 in every time slot (t) (Equation 9). The constraint is that $H \geq H_c$. A high value of this ratio means that the PS is working close to the set-point curve, resulting in an improvement of energy wastes. The overall performance of the regulation system is obtained as the flow of PS-weighted average of η_{RS} in all time slots and in all demand scenarios.

$$\eta_{RS,t} = \frac{H_{,t}}{H_{c,t}} \tag{9}$$

A high score is assigned to this sub-criterion if the performance of regulation is high. Hence, the highest perfomance regulation of a solution is assigned a score of 1 and 0 with the lowest perfomance regulation of a solution.

2.4 Adaptation of the AHP method in PS Design

The propose to apply the AHP method is to determine the importance weight or the priority of every criterion and sub-criterion in a PS Design. These priorities are obtained by the judgment of group of experts in PS. Saaty established a numeric scale to compare how important is a criterion over another in pairwise comparison and organized in a quadratic matrix. The scale is established by the following values: 1. The value corresponds to equal importance between one criterion and another; 3. Moderate importance of one criterion over another; 5. Strong importance of one criterion over another; 7. Very strong or proven importance of one criterion over another; and 9. Extreme importance of one criterion over another.

In this way, technical, environmental, and economic criteria are compared among themselves and organized in the comparison matrix to obtain an eigenvector of the importance weight of every criterion. In the same way, the sub-criteria of every criterion are compared among themselves in the comparison matrix to obtain a local eigenvector of the importance weight of the sub-criteria with respect to the criterion it belongs. Finally, the product of the importance weight of the criteria with the local importance weight of the sub-criteria determines the global importance weight of the sub-criteria.

Another element of the AHP is the "Consistency ratio" (CR), which corresponds a tool that allows controlling the consistency of paired comparisons. Being subjective value judgments, consistency is not absolute in the comparison procedure. Saaty [20] defined that the CR should not be higher than 0.1 regardless of the nature of the problem. Consistency does not imply a "good" final selection, it only guarantees that there are no conflicts in the comparisons. This methodology proposes to weight the global importance weight of the criteria with the obtained CR to decrease the subjectivity of judgments by the group of experts.

On the other hand, the dominant and dominated solutions of the assessment in every criterion are identified by the Pareto Front. In this way, the dominant solutions are considered as potential solutions and continues in the process of the methodology, whereas the dominant solutions are discarded.

Then, the dominant solutions are assessed weighing the score of every criterion with their importance weight. The global assessments of the solutions are transformed in a numeric score from 0 to 1, where 1 is assigned to the solution with the highest value of the assessment and 0 to the solution with the lowest value of the assessment. Finally, the solution with the best score is considered as the ultimate solution in the PS.

The following flowchart (Figure 3) describes the different stages of the proposed methodology: the required data, determine the feasibility of the pump models to the system, and the assessment of the potential solution and the selection of the ultimate solution.

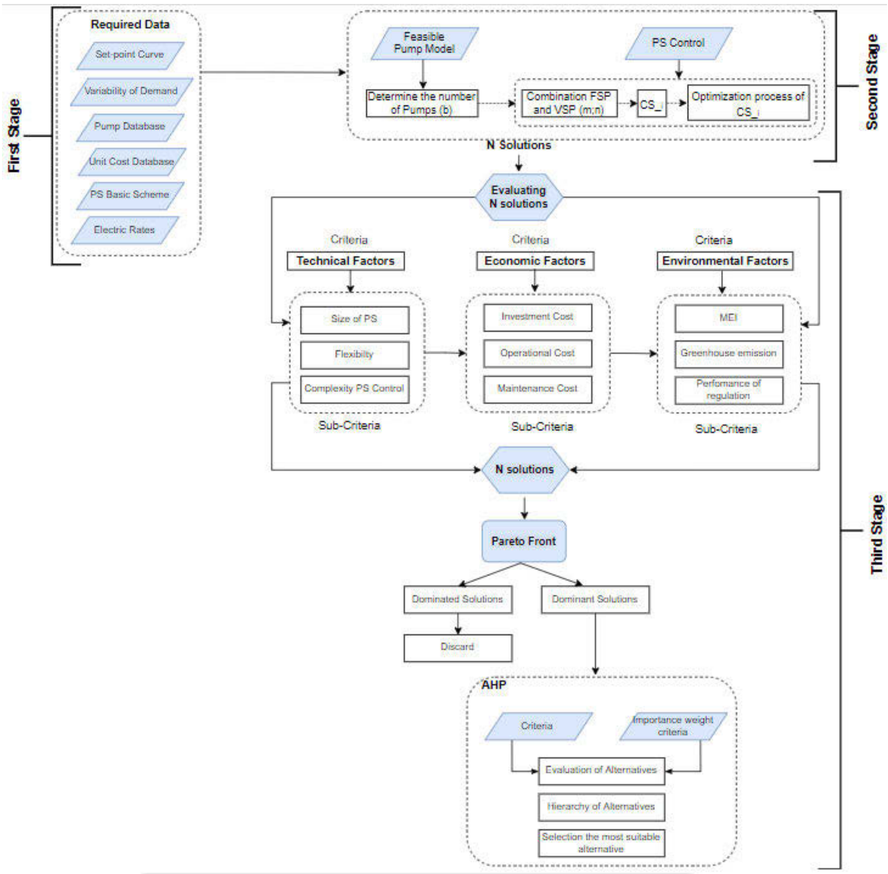

Figure 3. Flowchart of the proposed methodology

3. CASE STUDY

This work considered a closed WDS namely BN for PS design. This WDS feature a yearly average demand of 25.0 L/s. The hydraulic characteristic of the system is represented by the set-point curve (See table 3).

Table 3. Set Point Curve of BN-WDS

Data	ΔH (m)	R	c
	32.50	0.0312	1.75
$H_c = 32.50 + 0.0312 \times Q^{1.73}$			

The database of the pump models used in this work is conformed by 67 different pump models with their respective BEP, the parameters of the head pumping curve and efficiency curve. In addition, every pump model has its purchase cost and its cycle life.

The velocity design considered for the design of the PS scheme is (*V=2.0 m/s*). The parameters for the length of the pipes in the PS are $N_1=20$, $N_2=40$ and $N_3=20$. In addition, the maximum number of installed pumps (b_{max}) allowed in the design is 10 pumps.

This case study considered 21 different scenarios of non-exceedance probabilities (P_c) of BN-WDS demand from 0 to 1 with and interval of 0.05. In this way, the different P_c of demand are featured by (0; 0.05; 0.10; 0.15….. 1.0). These data were obtained from Alvisi and Franchini Work [28]. The probability of occurrence ($P_{r,DP}$) of the maximum and minimum P_c of demand is 2.5 % and the $P_{r,DP}$ of the other P_c of demand is 5.0 % (See Figure 4)

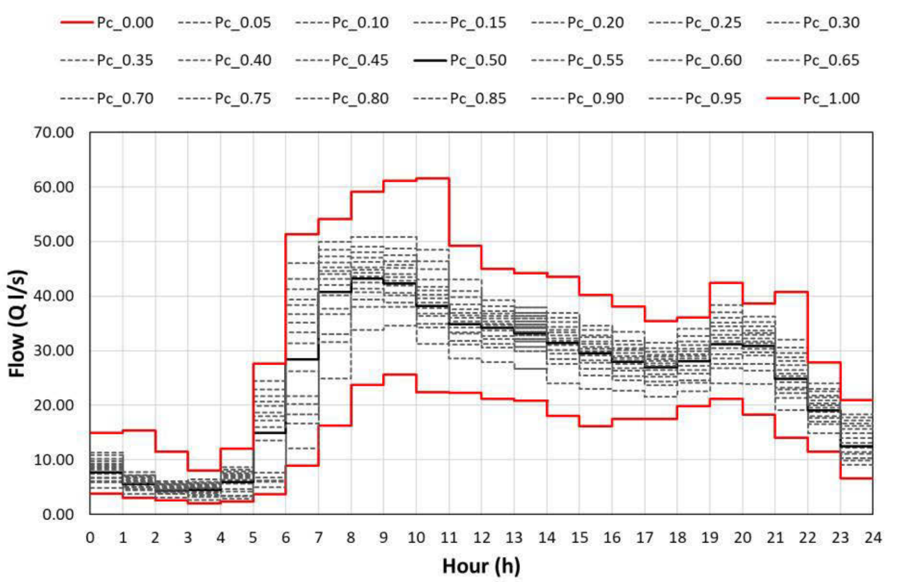

Figure 4. Variability of Demand of BN-WDS

The BN-WDS uses a single Electric Tariff with three kinds of hours: off-peak, peak and plain hours. The costs of the tariff of every kind of hour are specified in the following table 4.

Table 4. Electric Tariff of BN-WDS

Type of hours	Electric Tariff TE (€/kWh)	Initial hour	Final hour
Off-peak hours	0.069	0	8
Peak hours	0.095	11	15
Plain hours	0.088	8	10
		16	23

4. RESULTS

The obtained priorities of the criteria and the obtained local and global priorities of the sub-criteria of every criterion from the judgment of the group of experts in the AHP method are detailed in the Table 5. The priorities are expressed in a numeric scale from 0 to 1. Table 5 shows that the most important criteria in the PS design are Economic and Technical criteria with a score of 0.44 and 0.41, respectively, whereas the environmental criteria have less importance with a score of 0.15. The most important sub-criteria are Complexity of PS and Operational Cost with a scores of 0.18 and 0.16, respectively. Other sub-criteria, such as: Size of the PS, flexibility of the PS, investment cost and maintenance cost have a moderate priority with scores over 0.11. On the other hand, the priority of environmental sub-criteria: MEI, CO2 emission and perfomance of the regulation system are considerably less priority than the others with scores lower of 0.05.

Table 5. Obtained Priorities of the Criteria and Sub-Criteria for the PS Design

Criteria	Priority	Sub-Criteria		Local Priority	Global Priority
Technical Criteria	0.41	C1	Size of the PS	0.26	0.11
		C2	Flexibility of the PS	0.31	0.13
		C3	Complexity of the PS	0.43	0.18
Environmental Criteria	0.15	C4	MEI	0.35	0.05
		C5	CO2 Emission	0.22	0.03
		C6	Perfomance of the regulation system	0.43	0.06
Economic Criteria	0.44	C7	Investment Cost	0.30	0.13
		C8	Operational Cost	0.37	0.16
		C9	Maintenance Cost	0.33	0.14

In this WDS, two different methods of PS were performed. The method 1 is the typical methodology, where it is only considered economic factors. The selection of the ultimate solution is based on the minimization of LCC. The method 2 is the proposed methodology, where it is considered technical, environmental, and economic criteria basing on the AHP method. The solution with the highest overall score is selected as ultimate solution. The objective of this design framework is to analyse the effects of including Technical and Environmental aspects with respect to the classical method considering only economic aspects.

Table 6 shows the ultimate solutions of method 1 and method 2 for the PS design in BN-WDS. In every solution is detailed the BEP of the pump model (Q_0, H_0, η_0), the values and the numeric scores in every of the 9 sub-criteria, and the LCC.

Table 6. The Characteristics of the Ultimate Solutions of Method 1 and Method 2 for BN-WDS

			Method 1 (LCC Minimization)		Method 2 (AHP with Tech. Env. And Eco. Criteria)	
Pump Characteristics		**Pump Model Number**	33		45	
		Q_0	24.32 l/s		9.06 l/s	
		H_0	78.73 m		78.19 m	
		η_0	63%		77%	
			Values	**Score**	**Values**	**Score**
Technical Aspects	**C1**	**Size PS**	151.20 m^2	1.00	158.40 m^2	0.80
	C2	**Flexibility (*b*) *m* FSP; *n* VSP**	0 FSP- 3 VSP	0.01	7 FSP- 0 VSP	0.67
	C3	**Control System**	5	0.07	3	0.32
Environmental Aspects	**C4**	**MEI**	0.11	0.07	0.70	1.00
	C5	**GH Emission**	68,954.94 KgCO2	0.93	74,695.35 KgCO2	0.91
	C6	**Perfomance Regulation System**	100%	1.00	79%	0.49
Economic Aspects	**C7**	**Investment Cost**	6,604.70 €/year	0.92	12,347.87 €/year	0.56
	C8	**Operational Cost**	15,877.26 €/year	0.93	17,182.22 €/year	0.91
	C9	**Maintenance Cost**	1,193.21 € /year	0.90	2,105.30 €/year	0.37
Overall Score			0.96		1.00	
Life Cycle Cost			23,675.17 €/year		31,724.93 €/year	

The following radial chart (Figure 5) shows a comparison of the obtained scores for every sub-criterion of the ultimate solutions of method 1 and method 2. As it can see in this figure, the scores in the sub-criteria of the ultimate solution in Method 2 are over 0.30, whereas the solution in Method 1 has low scores in sub-criteria C2, C3 and C4. Hence, the ultimate solution in Method 2 is more equilibrate with the 9 sub-criteria than the solution in Method 1.

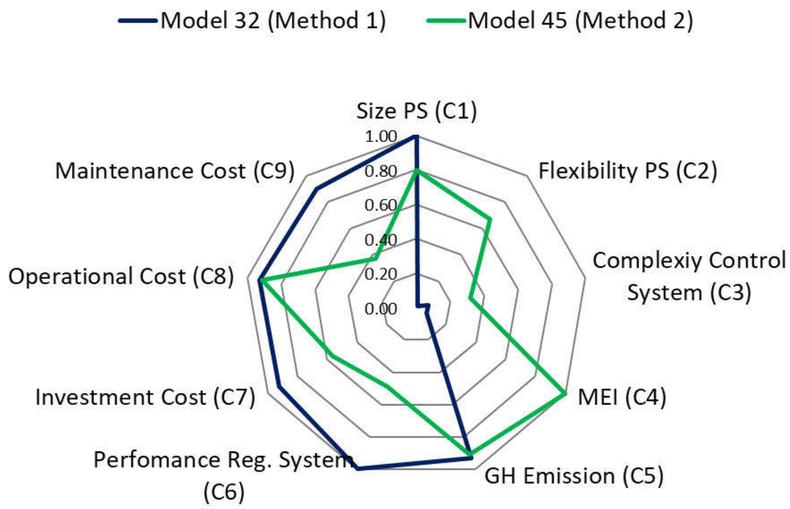

Figure 5. Radial chart of the scores for every sub-criterion of Method 1 and Method 2

The figures 6 and 7 show the number of pumps in operation (b) and the consumed power of the PS (P_T) in every time slot and for every scenario probability of non-exceedance of the demand (P_c). The scenarios considered in these figures are P_c_0.00, P_c_0.25, P_c_0.50, P_c_0.75, and P_c_1.00. The objective to display these figures is to feature how is the operating behaviour of the ultimate solution in the method 2. As it can see in these figures, the number of pumps in operation (b) and the Consumed Power (P_T) of the PS increase as the demand is higher.

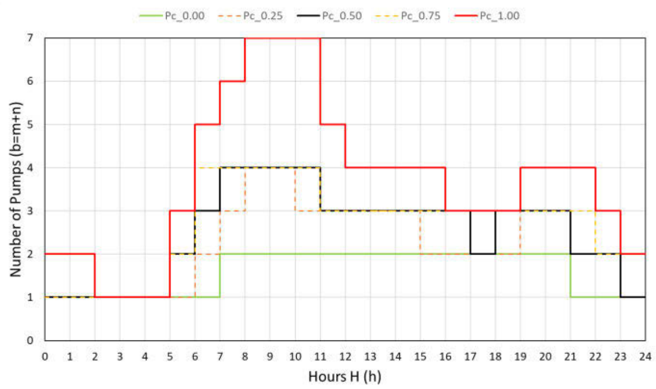

Figure 6. Number of pumps (b) in operation for every time slot and in every demand scenario

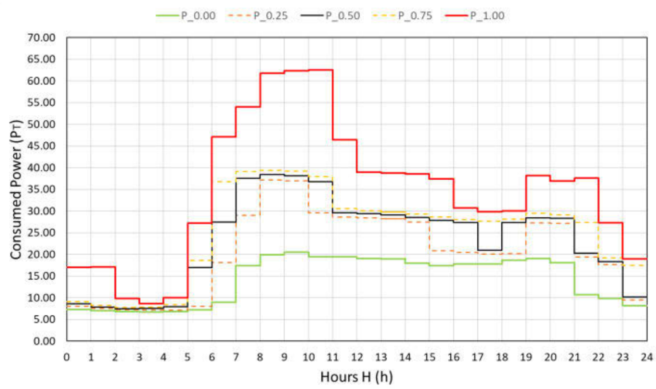

Figure 7. Consumed Power (P_T) for every time slot and in every demand scenario

5. DISCUSSION

The obtained solutions show interesting insights with different methodologies of a PS design, including the differences and effects of considering technical, environmental, and economic criteria based on the AHP method in contrast with classical method based on minimization the LCC.

The ultimate solution of Method 1 has a configuration of 0 FSP- 3 VSP with a FC system. It yields low investment cost, operational cost, and maintenance cost with scores over 0.90. This method is based on minimization LCC, so this solution has the lowest LCC of all the potential solutions considered. In addition, this solution yields low Kg of CO2 consumption and an excellent perfomance of regulation (100%) because are closely related with operational cost.

On the other hand, the ultimate solution of Method 2 has a configuration of 7 FSP- 0 VSP with a FC system. This method besides considering economic criteria considers technical and environmental criteria. Hence, this solution yields good qualities with the criteria: size of the PS and flexibility of operation with scores over 0.67. While the complexity of control system of this solution has a score of 0.32, but less complex than the control system of the solution of Method 1. In addition, the solution of Method 2 has excellent qualities of the environmental criteria: MEI and CO2 consumption with scores over 0.92, while the score of the sub-criterion perfomance of regulation is only 0.49. The environmental criteria have low importance weight with an overall weight of 0.15 in the PS design. The solution of Method 2 yields low operational costs with a score of 0.91, whereas the scores for investment costs and maintenance costs are 0.56 and 0.37, respectively.

In summary, the main effects of considering technical, economic, and environmental criteria in a PS design in contrast with only considering the minimization of LCC lie in that the ultimate solution of Method 2 uses greater number of pumps than in the Method 1, but the size of the pump model in terms of flow in Method 2 is lower than in the Method 1. In addition, the configuration of the control system in the Method 2 is less complex than in the Method 1. These obtained results could be justified because the sub-criterion complexity of control system has the highest importance weight in the AHP method. In addition, the importance weight of technical criteria obtained in the AHP method are high with an overall value of 0.41.

6. CONCLUSIONS

This work developed a methodology for a PS design that consider together technical, environmental, and economic criteria in the design. The process of this methodology is based in the AHP method. This methodology proposed a quantitative assessment of the potential solutions in every one of the criteria. In this way, this work has achieved that the methodology be standardized and could be applied in any kind of PS. In addition, this methodology, has solved the limitations of the classical PS design including technical aspects in the design process.

This methodology has introduced an optimization process in the control systems strategies searching the optimal number of pumps in operation and the current rotational speed to minimize energy consumption in the PS. This contribution has achieved to mitigate polluted energy produced in the PS and be friendly to the environment.

The principal effect of design a PS with the proposed methodology (Method 2) in contrast to the classical methodology (Method 1) is in the configuration of the PS. The ultimate solution based on Method 2 tends to use a greater number of pumps than in Method 1, but with a smaller flow in the pumps. The control system of the solution in Method 2 is less complex than the solution in Method 1. In summary, the principal effects of Method 2 in contrast with Method 1 are visualized the characteristics in technical aspects because the importance weight of these criteria obtained in the AHP method is high with a weight of 0.41

The inclusion of environmental aspects in a PS design (Method 2) allow that the ultimate solution could have better characteristic in environmental criteria, especially in the MEI, though the importance weight of this criteria is low in comparison with other technical or economic criteria.

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