UNIVERSITAT POLITÈCNICA DE VALÈNCIA

DOCTORAL PROGRAM OF WATER AND ENVIRONMENTAL ENGINEERING

DOCTORAL THESIS

CONTRIBUTIONS TO THE DESIGN OF PUMPING STATIONS IN WATER DISTRIBUTION NETWORKS CONSIDERING TECHNICAL, ECONOMIC, AND ENVIRONMENTAL ASPECTS

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"The roots of all goodness lie in the soil of appreciation for goodness" Quoting from Dalai Lama

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ABSTRACT

The energy consumption of a pumping station (PS) represents the largest energy consumption of water distribution network (WDN). Climate changes issues, such as water stress, and high greenhouse gases emission leads the necessity of optimize the operation of WDN. One of the most important aspects in the operating optimization in WDN lies in a proper design and operation of PS.

A proper operation of a PS consists of the operating points of head and flow of the PS meet with the set-point curve of the network, so the energy consumption of the PS be optimal. The set-point curve is defined as the required head of the water source i.e., PS that satisfy the critical consumption node of the network maintaining the minimum required pressure of the network in the horizon time.

There are several control system configurations in the pumping station able to meet with the set point curve such as, the combination of fixed speed pumps (FSP) and variable speed pumps (VSP). However, the usual operation of this control system is restricted to the number of pumps in the PS previously defined. Moreover, the number of FSP and VSP in operation are limited to the operational ranges of the system. These operational ranges are determined by the intersection of the pumping curve of each number of pumps and the set-point curve. These simplifications affect the development of a proper operating optimization in PS. Another limitation of classic operation in this control system are the simplifications to calculate the efficiency in the PS. The efficiency of VSP is approximated using the pump affinity laws. In addition, it is usually assumed a fixed efficiency of frequency drive in VPS, even though this efficiency varies according to the rotational speed of the VSP. These approximations in the efficiency calculation in PS lead to inaccuracies to evaluate the energy consumption in PS. In this way, it is imperative to develop a methodology of operating optimization for control system in PS that allows to improve the operation of classic control system configurations.

One of the most important contributions of this work was the development of a standardized methodology for operating optimization of control systems in PS. This optimization methodology is based in the use of the set-point curve in the control system operation combining FSP and VSP. This methodology aims to determine the optimal number of FSP and VSP in operation and the rotational speed of VSP for any flow rate in a time step, so the energy consumption of the PS be minimum in that flow rate. This allows to redefine the total number of pumps in a PS design, where the number of pumps is usually defined according to the experience or criterion of the designer. An important aspect of this methodology of operating optimization in PS is the improvement in the calculation of the efficiency in PS. This methodology considered a correction factor in the efficiency of VSP determined by the affinity laws. In addition, it has developed a mathematical expression to determine the efficiency of frequency drive in VPS when the rotational speed changes. These calculation improvements allow to evaluate the energy consumption in PS with better accuracy.

A proper PS design consist of three fundamental aspects. One aspect is an optimum selection of the pump model. The second aspect is defining a PS layout. It is related to determine the number of pumps, the length and diameter of the pipelines in the PS. The third aspect is the optimum selection of control system configuration in the pumping station. This aspect is related to select the type of pump (i.e, FSP and/or VSP) and the type of control of operation (i.e., pressure control or flow control). Usually, the selection of these three aspects in a PS design is based on the minimization of life cycle cost (LCC). LCC is defined by annual investment costs, annual operational costs, and annual maintenance costs. However, there are other important factors to consider in the selection the most optimum solution in a PS design. For example, the required space for the installation of the PS, the flexibility of operation in the PS, and the complexity of operation in the PS are technical factors that should be considered to select the most suitable solution in a PS design. In addition, environmental factors, such as the minimum efficiency index (MEI) of the pump, greenhouse gases emissions, the efficiency of regulation in the PS should also be considered to select the most suitable solution in a PS. The consideration of technical, environmental, and economic criteria in a PS design allows that the selected solution be technically, economically feasible and environmentally responsible.

Another important aspect in this work is the development of a novelty methodology for PS design based on multicriteria decision analysis. As first version, this work has proposed a PS design methodology considering technical and economic criteria. The multicriteria decision method applied in this PS design methodology was the analytic hierarchy process (AHP). The technical criteria considered in this methodology are the number of pumps and the complexity of control system operation. On the other hand, the economic criteria considered are investment, operational and maintenance costs. This methodology consists of three fundamental stages. The first stage is related with required data for the PS design, such as database of pump models, hydraulic conditions of the network, and analysis of the demand. In this stage is determined the feasible pump models for the network. The second stage is related to define the possible solutions in the PS and assess them with the technical and economic criteria. In this stage it is defined the number of pumps of the feasible pump models, and it is defined the feasible control system configuration for each pump model. All these combinations generate a several possible solutions for the PS. Finally, the third stage is related to apply the AHP method to the potential solutions in order to define the ultimate solution in the PS design. In this stage all the alternatives of solutions defined in the previous stage are assessed in a pareto front to define the potential solutions for the PS. These potential solutions are scored in every criterion, and it is obtained an overall score of the potential solutions. Finally, the solution with the highest score is selected as ultimate solution.

This first developed methodology for PS design presents some limitations. One limitation is that this methodology did not consider environmental criteria for the design of the PS. In addition, this methodology neglected the operating optimization of the control system of the PS. Another limitation of this methodology is related with the scale used in the AHP method. This scale could present problems in the consistency in the evaluation of the criteria.

Therefore, this work developed a second version of a PS design to solve the limitations of the first approach of the PS design. In this way, this updated approach of PS design considered environmental criteria in addition to technical and economic criteria. This methodology included the size of the PS and the flexibility of operation as technical criteria, which are associated with the number of pumps. The environmental criteria considered in this methodology are the MEI, greenhouse emissions and efficiency of regulation in the PS. In addition, this update version of PS design methodology considered the operating optimization of the control system configurations in the second stage of the design process. In addition, this second approach considered the analysis of variability of daily demand during the design process to improve the robustness of the PS design. An important aspect to highlight in this second version of PS design is that it was proposed a new scale in the AHP method to improve the consistency of the obtained priorities of the criteria in the PS design.

Two water distribution networks (AN and EF networks) were presented as case studies to demonstrate the validity of the methodologies developed throughout this work. The purpose of these case studies is to show the saving of energy consumption when this methodology of operating optimization is performed in the control system of the PS. In addition, the PS of both networks were designed under several proposals of design. The purpose of these case studies is to analyse the effect of considering technical criteria, environmental criteria, and the variability of demand in a PS design.

In summary, the most important contribution of this thesis is the development of a methodology of an optimization control system in PS that allows minimize the energy consumption and redefine the number of pumps in the PS. Another contribution of this work is the development of a new methodology for PS design. This methodology pretends to minimize the level of subjectivity of the designer through the application of multicriteria decision analysis in the PS design. In addition, the purpose of this methodology is to robust and improve the reliability in a PS design considering the variability of yearly demand in the analysis of the PS design.

RESUMEN

El consumo de energía de una estación de bombeo (PS, del inglés pumping station) representa el mayor consumo de energía de la red de distribución de agua (WDN, del inglés water distribution network). Debido a los problemas relacionados con el cambio climático, como el estrés hídrico y la elevada emisión de gases de efecto invernadero por el consumo de energía no renovable conducen a la necesidad de optimizar las WDN. Uno de los aspectos más importantes en la optimización del funcionamiento de una red de distribución de agua reside en un diseño y funcionamiento adecuado de una PS.

Un correcto funcionamiento de una PS consiste en que los puntos de funcionamiento de las bombas cumplan con la curva de consigna, de forma que la PS consuma la energía requerida de la red. La curva de consigna se define como la altura requerida de la fuente de suministro, es decir, la PS y que satisfaga el nudo de consumo crítico de la red manteniendo la presión mínima requerida de la red en el tiempo.

Existen varias configuraciones de sistemas de control en la estación de bombeo capaces de cumplir con la curva de consigna como, por ejemplo, la combinación de bombas de velocidad fija (FSP, del inglés fixed speed pump) y bombas de velocidad variable (VSP, del inglés variable speed pump). Sin embargo, el funcionamiento habitual de este sistema de control está restringido por el número de bombas de la PS previamente definido. Además, el número de FSP y VSP en funcionamiento están limitados a los rangos operativos del sistema. Estos rangos operativos están determinados por la intersección de la curva de bombeo de cada número de bombas y la curva de consigna. Estas simplificaciones afectan al desarrollo de una adecuada optimización de operación en la PS. Otra limitación de esta operación clásica en estos sistemas de control son las simplificaciones para calcular la eficiencia en la PS. La eficiencia de la VSP es aproximada de acuerdo con las leyes de afinidad de las bombas. Además, se suele asumir una eficiencia fija del variador de frecuencia en la VSP, aunque esta eficiencia varía en función de la velocidad de giro de la VSP. Estas aproximaciones en el cálculo de la eficiencia en la PS conducen a inexactitudes para evaluar el consumo de energía en la PS. De este modo, es imperativo desarrollar una metodología de optimización de funcionamiento para los sistemas de control en PS que permitan mejorar la operación de los sistemas de control en la PS.

Una de las contribuciones más importantes de este trabajo es el desarrollo de una metodología estandarizada para la optimización de la operación de los sistemas de control en la PS. Esta metodología de optimización se basa en el uso de la curva de consigna en la operación del sistema de control combinando VSP y FSP. Esta metodología tiene como objetivo determinar el número óptimo de VSP y FSP en funcionamiento y la velocidad de giro de las VSP para cualquier caudal en un intervalo de tiempo, de forma que el consumo energético de la PS sea mínimo en ese caudal. Esto permitirá redefinir el número total de bombas en un diseño de PS, donde este número de bombas suele definirse según la experiencia o el criterio del diseñador. Un aspecto importante de esta metodología de optimización en PS es la mejora en el cálculo del rendimiento en la PS. Esta metodología ha considerado un factor de corrección en la eficiencia en VSP determinado por las leyes de afinidad. Además, se ha desarrollado una expresión matemática

para determinar la eficiencia del variador de frecuencia en VSP cuando la velocidad de rotación cambia. Estas mejoras de cálculo permitirán evaluar el consumo de energía en los PS con mayor precisión.

Un diseño adecuado de una PS consta de tres aspectos fundamentales. Un aspecto es la selección óptima del modelo de bomba. El segundo aspecto es la definición del diseño de la PS. Esto está relacionado con la determinación del número de bombas, la longitud y el diámetro de las tuberías de la estación. El tercer aspecto es la selección óptima de la configuración del sistema de control en la PS. Este aspecto está relacionado con la selección del tipo de bomba (es decir, FSP y/o VSP) y el tipo de control de funcionamiento (es decir, control de presión o control de caudal). Normalmente, la selección de estos tres aspectos en un diseño de PS se basa en la minimización del coste del ciclo de vida (LCC). Los LCC están compuestos por los costes anuales de inversión, costes anuales de operación y costes anuales de mantenimiento. Sin embargo, hay otros factores importantes a tener en cuenta en la selección de la solución óptima en el diseño de una PS. Por ejemplo, el espacio necesario para la instalación de la PS, la flexibilidad de operación en la PS y la complejidad de funcionamiento en el PS son factores técnicos que deben considerarse para seleccionar la solución más adecuada en una PS. Además, factores medioambientales, como el Índice de Eficiencia Mínima (MEI, del inglés minimun efficiency index) de la bomba, la emisión de gases de efecto invernadero y la eficiencia de la regulación en la red de distribución, también deben tenerse en cuenta para seleccionar la solución más adecuada en una red de distribución. La consideración de criterios técnicos, medioambientales y económicos en el diseño de una PS permite que la solución seleccionada sea técnica, económicamente viable y medioambientalmente responsable.

Otro aspecto importante en este trabajo ha sido el desarrollo de una metodología novedosa para el diseño de una PS basado en un análisis multicriterio. Como primera versión, este trabajo ha propuesto una metodología de diseño de PS considerando criterios técnicos y económicos. El método de decisión multicriterio aplicado en esta metodología de diseño de una PS fue el Proceso Analítico Jerárquico (AHP, del inglés analytic hierarchy process). Los criterios técnicos considerados en esta metodología son el número de bombas y la complejidad de operación en los sistemas de control. Los criterios económicos considerados son los costes de inversión, operación y mantenimiento. Esta metodología consta fundamentalmente de tres etapas. La primera etapa está relacionada con los datos necesarios para el diseño de la PS, como la base de datos de modelos de bombas, las condiciones hidráulicas de la red y el análisis de la demanda. En esta etapa se determinan los modelos de bombeo factibles para la red. La segunda etapa está relacionada con la definición de las posibles soluciones en la PS y su evaluación con los criterios técnicos y económicos. En esta etapa se define el número de bombas de los modelos de bombeo factibles, y se define la configuración de sistemas de control factibles para cada modelo de bomba. Todas estas combinaciones generan varias soluciones para la PS. Finalmente, la tercera etapa está relacionada con la aplicación del método AHP a las posibles soluciones para definir la solución definitiva en el diseño de la PS. En esta etapa se evalúan todas las soluciones definidas en la etapa anterior en un frente de Pareto para definir las soluciones potenciales para la PS. Estas soluciones potenciales son puntuadas en cada criterio, y se obtiene una puntuación global de las soluciones potenciales. Finalmente, la solución con la mayor puntuación se selecciona como solución definitiva.

Esta primera metodología desarrollada para el diseño del PS presenta algunas limitaciones. Una de ellas es que esta metodología no tuvo en cuenta los criterios medioambientales para el diseño de la PS. Además, esta metodología no tuvo en cuenta la optimización de operación de los sistemas de control en la PS. Otra limitación de esta metodología está relacionada con la escala utilizada en el método AHP. Esta escala puede presentar problemas de consistencia en la evaluación de los criterios.

Por lo tanto, este trabajo desarrolló una segunda versión del diseño de la PS para resolver las limitaciones de la primera versión del diseño de una PS. De este modo, esta versión actualizada considera los criterios medioambientales además de los técnicos y económicos para el diseño de la PS. Esta metodología incluyó criterios técnicos como el tamaño de la PS y la flexibilidad de operación, que están asociados con el número de bombas. Los criterios medioambientales considerados en esta metodología son el MEI, las emisiones de efecto invernadero y la eficiencia de la regulación en la PS. Además, esta versión actualizada consideró la optimización de operación de las configuraciones de sistemas de control en la segunda etapa del proceso de diseño. Además, este segundo enfoque consideró el análisis de la variabilidad de la demanda diaria durante el proceso de diseño para mejorar la robustez del diseño de la PS. Un aspecto importante para destacar en esta segunda versión de diseño de una PS es que se propuso una nueva escala en el método AHP para mejorar la consistencia de las prioridades obtenidas de los criterios en el diseño de la PS.

Se presentaron dos redes de distribución de agua (redes AN y EF) como casos de estudio para demostrar la validez de las metodologías desarrolladas en este trabajo. El objetivo de estos estudios de caso es mostrar el ahorro de consumo de energía cuando se realiza la optimización propuesta en la operación del sistema de control en una PS. Adicionalmente, en ambas redes se diseñaron las PS bajo diferentes propuestas de diseño. El objetivo de estos casos de estudio es analizar el efecto de la consideración de los criterios técnicos, los criterios medioambientales y la variabilidad de la demanda en un diseño de una PS.

En resumen, las contribuciones más importantes de esta tesis es el desarrollo de una metodología de un sistema de control de optimización en PS que permite minimizar el consumo de energía y redefinir el número de bombas en el PS. Otra contribución de este trabajo es el desarrollo de una nueva metodología para el diseño de PS. Esta metodología pretende minimizar el nivel de subjetividad del diseñador mediante la aplicación del análisis de decisión multicriterio en el diseño de la PS. Además, el propósito de la novedosa metodología es robustecer y mejorar la fiabilidad en el diseño de un PS considerando la variabilidad de la demanda anual en el análisis del diseño del PS.

RESUM

El consum d'energia d'una estació de bombament (PS) representa el major consum d'energia de la xarxa de distribució d'aigua. A causa dels problemes relacionats amb el canvi climàtic, com l'estrés hídric i l'elevada emissió de gasos d'efecte d'hivernacle pel consum d'energia no renovable en les xarxes de distribució d'aigua, és imprescindible optimitzar les xarxes de distribució d'aigua. Un dels aspectes més importants en l'optimització del funcionament d'una xarxa de distribució d'aigua resideix en un disseny i funcionament adequat d'una PS.

Un correcte funcionament d'una PS consisteix en el fet que els punts de funcionament de les bombes complisquen amb la corba de consigna, de manera que la PS consumisca l'energia requerida de la xarxa. La corba de consigna es defineix com l'altura requerida de la font de subministrament, és a dir, la PS i que satisfaça el nus de consum crític de la xarxa mantenint la pressió mínima requerida de la xarxa en el temps.

Existeixen diverses configuracions de sistemes de control en l'estació de bombament capaços de complir amb la corba de consigna com, per exemple, la combinació de bombes de velocitat fixa (BVF) i bombes de velocitat variable (VSP). No obstant això, el funcionament habitual d'aquest sistema de control està restringit pel nombre de bombes de la PS prèviament definit. A més, el número de BVF i BVV en funcionament estan limitats als rangs operatius del sistema. Aquests rangs operatius estan determinats per la intersecció de la corba de bombament de cada nombre de bombes i la corba de consigna. Aquestes simplificacions afecten el desenvolupament d'una adequada optimització d'operació en la PS. Una altra limitació d'aquesta operació clàssica en aquests sistemes de control són les simplificacions per a calcular l'eficiència en la PS. L'eficiència de la BVV és aproximada d'acord amb les lleis d'afinitat de les bombes. A més, se sol assumir una eficiència fixa del variador de freqüència en la VSP, encara que aquesta eficiència varia en funció de la velocitat de gir de la VSP. Aquestes aproximacions en el càlcul de l'eficiència en la condueixen a inexactituds per a avaluar el consum d'energia en la PS. D'aquesta manera, és imperatiu desenvolupar una metodologia d'optimització de funcionament per als sistemes de control en PS que permeten millorar l'operació dels sistemes de control en PS.

Una de les contribucions més importants d'aquest treball va ser el desenvolupament d'una metodologia estandarditzada per a l'optimització de l'operació dels sistemes de control en PS. Aquesta metodologia d'optimització es basa en l'ús de la corba de consigna en l'operació del sistema de control combinant FSP i VSP. Aquesta metodologia té com a objectiu determinar el número òptim de FSP i VSP en funcionament i la velocitat de gir de les VSP per a qualsevol cabal en un interval de temps, de manera que el consum energètic de la PS siga mínim en aqueix cabal. Això permetrà redefinir el nombre total de bombes en un disseny de PS, on aquest nombre de bombes sol definir-se segons l'experiència o el criteri del dissenyador. Un aspecte important d'aquesta metodologia d'optimització en PS és la millora en el càlcul del rendiment en la PS. Aquesta metodologia ha considerat un factor de correcció en l'eficiència en VSP determinat per les lleis d'afinitat. A més, s'ha desenvolupat una expressió matemàtica per a determinar l'eficiència del variador de freqüència en VSP quan la velocitat de rotació canvia. Aquestes millores de càlcul permetran avaluar el consum d'energia en els PS amb major precisió.

Un disseny adequat d'una PS consta de tres aspectes fonamentals. Un aspecte és la selecció òptima del model de bomba. El segon aspecte és la definició del disseny de la PS. Això està relacionat amb la determinació del nombre de bombes, la longitud i el diàmetre de les canonades de l'estació. El tercer aspecte és la selecció òptima de la configuració del sistema de control en la PS. Aquest aspecte està relacionat amb la selecció de la mena de bomba (és a dir, FSP i/o VSP) i el tipus de control de funcionament (és a dir, control de pressió o control de cabal). Normalment, la selecció d'aquests tres aspectes en un disseny de PS es basa en la minimització del cost del cicle de vida (LCC). Els LCC estan compostos pels costos anuals d'inversió, costos anuals d'operació i costos anuals de manteniment. No obstant això, hi ha altres factors importants a tindre en compte en la selecció de la solució òptima en el disseny d'una PS. Per exemple, l'espai necessari per a la instal·lació de la PS, la flexibilitat d'operació en la PS i la complexitat de funcionament en el PS són factors tècnics que han de considerar-se per a seleccionar la solució més adequada en una PS. A més, factors mediambientals, com l'Índex d'Eficiència Mínima (MEI) de la bomba, l'emissió de gasos d'efecte d'hivernacle i l'eficiència de la regulació en la xarxa de distribució, també han de tindre's en compte per a seleccionar la solució més adequada en una xarxa de distribució. La consideració de criteris tècnics, mediambientals i econòmics en el disseny d'una PS permet que la solució seleccionada siga tècnica, econòmicament viable i mediambientalment responsable.

Un altre aspecte important en aquest treball ha sigut el desenvolupament d'una metodologia integral per al disseny d'una PS. Com a primera versió, aquest treball ha proposat una metodologia de disseny de PS considerant criteris tècnics i econòmics basats en una anàlisi de decisió multicriteri. El mètode de decisió multicriteri aplicat en aquesta metodologia de disseny d'una PS va ser el Procés Analític Jeràrquic (AHP). Els criteris tècnics considerats en aquesta metodologia són el nombre de bombes i la complexitat d'operació en els sistemes de control. Els criteris econòmics considerats són els costos d'inversió, operació i manteniment. Aquesta metodologia consta fonamentalment de tres etapes. La primera etapa està relacionada amb les dades necessàries per al disseny de la PS, com la base de dades de models de bombes, les condicions hidràuliques de la xarxa i l'anàlisi de la demanda. En aquesta etapa es determinen els models de bombament factibles per a la xarxa. La segona etapa està relacionada amb la definició de les possibles solucions en la PS i la seua avaluació amb els criteris tècnics i econòmics. En aquesta etapa es defineix el nombre de bombes dels models de bombament factibles, i es defineix la configuració de sistemes de control factibles per a cada model de bomba. Totes aquestes combinacions generen diverses solucions per a la PS. Finalment, la tercera etapa està relacionada amb l'aplicació del mètode AHP a les possibles solucions per a definir la solució definitiva en el disseny de la PS. En aquesta etapa s'avaluen totes les solucions definides en l'etapa anterior en un front de Pareto per a definir les solucions potencials per a la PS. Aquestes solucions potencials són puntuades en cada criteri, i s'obté una puntuació global de les solucions potencials. Finalment, la solució amb la major puntuació se selecciona com a solució definitiva.

Aquesta primera metodologia desenvolupada per al disseny del PS presenta algunes limitacions. Una d'elles és que aquesta metodologia no va tindre en compte els criteris mediambientals per al disseny de la PS. A més, aquesta metodologia no va tindre en compte l'optimització d'operació dels sistemes de control en la PS. Una altra limitació d'aquesta metodologia està relacionada amb l'escala utilitzada en el mètode AHP. Aquesta escala pot presentar problemes de consistència en l'avaluació dels criteris.

Per tant, aquest treball va desenvolupar una segona versió del disseny del PS per a resoldre les limitacions de la primera versió del disseny d'una PS. D'aquesta manera, aquesta versió actualitzada considera els criteris mediambientals a més dels tècnics i econòmics per al disseny de la PS. Aquesta metodologia va incloure criteris tècnics com la grandària de la PS i la flexibilitat d'operació, que estan associats amb el nombre de bombes. Els criteris mediambientals considerats en aquesta metodologia són el MEI, les emissions d'efecte d'hivernacle i l'eficiència de la regulació en la PS. A més, aquesta versió actualitzada va considerar l'optimització d'operació de les configuracions de sistemes de control en la segona etapa del procés de disseny. A més, aquest segon enfocament va considerar l'anàlisi de la variabilitat de la demanda diària durant el procés de disseny per a millorar la robustesa del disseny de la PS. Un aspecte important per a destacar en aquesta segona versió de disseny d'una PS és que es va proposar una nova escala en el mètode AHP per a millorar la consistència de les prioritats obtingudes dels criteris en el disseny de la ES.

Es van presentar dues xarxes de distribució d'aigua (xarxes AN i EF) com a casos d'estudi per a demostrar la validesa de les metodologies desenvolupades en aquest treball. L'objectiu d'aquests estudis de cas és mostrar l'estalvi de consum d'energia quan es realitza l'optimització proposada en l'operació del sistema de control en una PS. Addicionalment, en totes dues xarxes es van dissenyar les PS sota cinc condicions. L'objectiu d'aquests casos és analitzar l'efecte de la consideració dels criteris tècnics, els criteris mediambientals i la variabilitat de la demanda en un disseny d'una PS.

En resum, les contribucions més importants d'aquesta tesi és el desenvolupament d'una metodologia d'un sistema de control d'optimització en PS que permet minimitzar el consum d'energia i redefinir el nombre de bombes en el PS. Una altra contribució d'aquest treball és el desenvolupament d'una nova metodologia per al disseny de PS. Aquesta metodologia pretén minimitzar el nivell de subjectivitat del dissenyador mitjançant l'aplicació de l'anàlisi de decisió multicriteri en el disseny de la PS. A més, el propòsit de la nova metodologia és enrobustir i millorar la fiabilitat en el disseny d'un PS considerant la variabilitat de la demanda anual en l'anàlisi del disseny del PS.

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Chapter 1. Introduction

1.1. Background

In the last decades, the world has undergone several changes, such as population growth, lifestyle, climate changes, and industrial, agricultural, and urban settlement development. These changes have caused the water demand and size of water distribution networks (WDN) to increase significantly. As a result, the water stress and increase in non-renewable energy consumption and energy production are the problems that the world has to face in water management. The consumption of energy for the production, treatment and distribution of potable water and wastewater represents 4% of all the energy consumption in the United States [1]. In addition, a study quantified the amount of energy consumption for water supply in 30 different cities in the world. The average annual energy used in these cities is 100 kWh per capita, where 95% of the energy used is related to water pumping and water distribution [2]. Therefore, the optimization of energy consumption and the reduction of greenhouse emissions are important goals to reach in WDN.

The European Council established three objectives for climate and energy to accomplish in 2030:

- At least 40% reduction of greenhouse gas emissions compared with the levels in 1990.
- A renewable energy target of at least 27% of energy consumption.
- At least 27% improvement in energy efficiency in 2030.

In addition, the United Nations (UN) [3] established 17 sustainable development goals (SDG) to improve the planet's conditions for a better lifestyle for humankind. The most highlighted SDG for WDN are SDG 6 which is focused to improve water and sanitation services, and SDG 7 which is focused to improve sustainable energy.

The Environmental Protection Agency (EPA) [4] defined several strategies to mitigate water stress and save energy consumption in WDN. Adequate size of the pumping stations (PS) and piping layout, reducing the pressure service of the network, optimize the operation of the PS are the most usual strategies to optimize water and energy consumption in WDN.

In the last decades, several researchers have attempted to develop methodologies, mathematical and computational tools to save energy consumption in WDN. Most of these studies are related to minimizing the operational costs of the PS and selecting the pumping configuration that best fits the requirements of the networks through pump scheduling [5] [6]. In this way, the operational points of the PS have to be close as possible to the set point curve of the network for a proper operation of the PS [7]. This curve is referred to the minimum head that a PS must supply to deliver a specific flow rate to satisfy the minimum required pressure in the network [8].

A PS design consist of selecting the pump model, the number of pumps, and the control system configuration that satisfy the constrains of the network [9]. These variables are usually arbitrarily set by the designer according to their experience. The combination of these variables can generate multiple solutions in a PS. The control system aims to bring the operational points of the PS to be as close as possible to the set-point curve, and it is carried out by means of different pump scheduling strategies. A control system of a PS could be made up by Fixed Speed Pumps (FSP) and/or Variable Speed Pump (VSP) and be controlled by pressure or flow mechanism [10]. The optimization of a control system in a PS consists of searching the number of FSP or VSP switched on, and the rotational speed of the VSP in every time slot to minimize the consumed power of the PS. One of the recent research about optimization of PS is the work developed by Leon-Celi [11]. The purpose of this work is to minimize the energy use and operational costs for multiple PS in WDN using the set-point curve. This methodology is based on searching the optimal flow distribution of the PS available in the network and the set-point curve of each PS to minimize operational cost and water production cost of the WDN. Generally, pump scheduling is constrained by the number of pumps previously defined by the designer. In addition, most of pump scheduling methods do not consider the efficiency of frequency drive in the PS. Therefore, it is important to make a deep analysis in the optimization of control systems considering the efficiency of frequency drive in PS in order to determine the total number of pumps in such a way to obtain the minimum possible energy consumption with more feasible results.

On the other hand, traditionally the ultimate solution for a PS design is selected on the basis of the pumping configuration with the lowest Life Cycle Cost (LCC) (i.e., investment, operational and maintenance costs). Up to now, PS design has been focused on optimizing operational, investment and maintenance costs and maximizing the operational reliability [12]. However, it is extremely complex to evaluate from an economic point of view all the elements that are part of a PS. There are some hidden aspects, such as the space required for the installation, electrical installation, staff training for complex operations, among others that are not usually considered in the traditional approach of a PS design [13] [14]. These aspects are related with technical factors, such as the number of pumps and the complexity of the control system. Therefore, it is important to consider technical criteria in a PS design.

In the last decade, the climate change has become a global issue that have affected the humanity. The great amount of Greenhouse Gases (GHG) emission produced, and the energy consumed in pumping systems are one of the principal causes of the global warming [15]. In this way, it is important to analyze and assess this environmental aspect in PS design for WDN. In addition, there are other environmental aspects that should be considered in a PS design, such as the minimum efficiency index (MEI) that a pump must meet, and the efficiency of regulation in the PS (i.e., the relation of the required head and the head of the PS). Moreover, most of previous work related with PS design are based by a single demand pattern in a horizon time analysis (i.e., yearly average demand pattern). Hence, it could be important to analyze the variability of demand in a PS design in order to improve the reliability of the design.

In summary, this work is composed of three phases. The first phase is to develop a methodology to optimize the operation of PS control systems based on the set-point curve to minimize the consumption energy. The second phase consists of developing a methodology to determine the most suitable solution in a PS design considering technical and economic criteria based on a multicriteria decision analysis. Finally, the third phase is an improvement of the second phase of this work adding environmental criteria and considering the variability of demand in the PS design. These three stages developed in this work have been applied in a general case study in order to discuss the obtained results in every stage.

The target of the study cases developed in this work is to analyze the following ideas:

- Show the difference of pumping configuration (i.e., number of FSP and VSP) of the proposed control system optimization with the classic control system strategies in terms of operational costs. In addition, show the influence of considering the efficiency of the VFD to determine the optimal pumping configuration (number of FSP and VSP in every flow rate).
- Identify the effects of including technical aspects in a PS design in comparison to the classic method based only on LCC minimization.
- Point out the effects of analyzing environmental aspects in a PS design in comparison to a PS design considering technical and economic criteria.
- Determine the effects in a PS design when it is considered a single demand pattern and multiple demand scenarios in the analysis.

1.2. Objectives

1.2.1. General objective

Create a standardized methodology for a PS design in WDN to determine the most appropriate configuration including the analysis of variability of demand and integrating technical, economic, and environmental criteria in a multicriteria decision analysis. The purpose of the objective is to reduce the level of arbitrarily of the designer and make the PS design more robust and reliable to different demand scenarios.

1.2.2. Specific objectives

The general objective defined in the previous section feature with the following specific objectives:

- Develop a methodology to optimize the energy consumption in the operation of control systems of PS considering the efficiency of the VFD in VSP. The purpose of this methodology is to determine the optimal combination of FSP and VSP and the optimal number of pumps in operation in every flow rate. Another purpose is to redefine the total number of pumps in the PS so that the energy consumption of the PS be minimum.
- Define the parameters and variables involved in the efficiency of the frequency drive. Represent mathematically the variation of the efficiency of the frequency drive in PS.
- Develop a first approach of PS design methodology considering a multicriteria decision making (e.g., technical, and economic criteria). This methodology consists of

determining the importance weight of the decision criteria in the design and scored the potential solutions in terms of every criterion considered through a multicriteria decision analysis method. This methodology will allow to select the ultimate solution according to the obtained scores.

- Integrate the methodology of optimization of PS control system and the first approach of PS design in a new PS design methodology adding environmental criteria and the variability of demand in the design process.
- Develop a computer tool to automate the methodology of PS design considering technical, economic, and environmental criteria integrating the PS control system optimization and the analysis of variability of demand in the design. Finally, this tool will allow determining the most suitable pump model and pumping configuration in a PS design.

1.3. Hypothesis and assumptions

The definition of assumptions and hypothesis are necessary to develop the proposed methodology in this work (i.e., a standardized methodology of PS design for WDN). The purposes of defining the hypotheses and assumptions of the research are to specify the prerequisites for applying the methodologies and to emphasize the scope of the developed work. In addition, it makes that the developed methodologies be easier to comprehend. In this way, the assumptions defined in this work are the following:

- The pumps in the pumping station are coupled or installed only in parallel.
- A database of the different elements that compose the PS is available. These elements include pump models, minor accessories (e.g., valves), and control system devices. The database includes the operational points of head curve and efficiency curve of the pump modes, the purchase cost of the elements of the PS, the installation cost of these elements, and the maintenance activities of these elements to implement in the PS and their respective execution costs.
- The hydraulic characteristics of the WDN, such as the set-point curve, demand patterns and electric tariff are known data for the development of the methodology.
- Only positive flows and pressures are considered in the pumping operating curves (e.g., head pumping curve and efficiency curve).
- All VSP in a PS will operate with the same kind of frequency drive and same characteristics. Hence, the rotational speed of every VSP in operation will be the same in the control system configurations. However, it has considered the possibility that VSP works as FSP. In this case, the rotational speed of the VSP works at 100% of the nominal rotational speed.
- Cavitation problems are not considered in the PS.
- Transient phenomena problems are not considered in the PS.

1.4. Organization of the document

The development of this document was performed as a compendium of articles. The development of this work is based on three technical papers published in indexed journals. These three articles are presented in three different chapters of this thesis. The nomenclatures used in the articles are maintained in this document. However, the content of these articles such as tables, figures and references are adapted according to the sequence of the present document. The three published articles are next described.

- C. X. Briceño-León, P. L. Iglesias-Rey, F. J. Martinez-Solano, D. Mora-Meliá, and V. S. Fuertes-Miquel, "Use of fixed and variable speed pumps in water distribution networks with different control strategies," Water (Switzerland), vol. 13, no. 4, pp. 479, Feb. 2021, doi: 10.3390/w13040479.
- C. X. Briceño-León, D. S. Sanchez-Ferrer, P. L. Iglesias-Rey, F. J. Martinez-Solano, and D. Mora-Meliá, "Methodology for pumping station design based on analytic hierarchy process (AHP)," Water (Switzerland), vol. 13, no. 20, pp. 2886, Oct. 2021, doi: 10.3390/w13202886.
- C. X. Briceño-León, P. L. Iglesias-Rey, F. J. Martinez-Solano, and E. Creaco, "Integrating demand variability, and technical, environmental and economic criteria in the design of pumping stations serving closed distribution networks" J. Water Resources Planning and Management, vol. 149, Issue 3, pp. 04023002, Jan. 2023, doi: 10.1061/JWRMD5.WRENG-5813.

In this way, the chapters presented in this thesis are next described:

Chapter 2. State of the art. This section describes the design of a PS, its stages, and a review of the elements that comprise it, such as types of control system strategies, pump scheduling, the set-point curve, and the characteristic of pumping curves (i.e., head pumping curve, and efficiency curve). In addition, this section explains the classical method of a PS design.

Chapter 3. Methodology of operating optimization in control system of PS. This chapter presents the article titled: "Use of Fixed and Variable Speed Pumps in Water Distribution Networks with Different Control Strategies". This chapter includes only the manuscript the article. This chapter does not include supplementary material (e.g., extra obtained results). The first stage of this thesis is to develop a methodology of optimization of PS control system. This paper presents an optimization of the control system in a PS in terms of energy consumption by means determining the optimal combination of number of FSP and VSP in every flow rate. In addition, this research proposes an expression to estimate the efficiency of the frequency drive in relation of the rotational speed of the VSP.

Chapter 4. Design of PS considering technical and economic aspects based on the AHP method. This chapter presents the article titled: "Methodology for Pumping Station Design Based on Analytic Hierarchy Process (AHP)". This chapter include the manuscript of the article and the appendix section of the article so that the content of this research can be understood. The second stage of this thesis is to develop a methodology of PS design integrating technical and economic criteria. In this way, the purpose of this second paper is to select the most suitable pumping configuration for a PS design evaluating the technical and economic criteria in the potential solutions through the multicriteria decision analysis method AHP.

Chapter 5. PS design considering technical, environmental and economic criteria based on the AHP method and considering variability of demand. This section reproduces the published article, titled "Integrating demand variability, and technical, environmental and economic criteria in the design of pumpin stations serving closed distribution networks". This chapter includes the manuscript of the article and the appendix section with the purpose that the research can be understood. This chapter does not include supplementary material (e.g., extra obtained results). The last stage of this thesis is an update of the PS design methodology developed in the second stage o this thesis. This last stage includes environmental aspects and demand variability in a PS design. In addition, this methodology integrates the optimization of control system operation in the PS design process. Therefore, the purpose of this third paper is to select the most suitable solution for a PS design considering technical, environmental, and economic criteria, and variability of demand based on AHP method.

Chapter 6. Case study and discussion. This section presents a general case study for the three methodologies developed in this thesis. The purpose of presenting a general case study is to analyze the improvements and compare the different PS design approaches performed in the thesis. First, it is analyzed the difference of classical control system and the proposed control system in terms of energy consumption and LCC. In addition, it is analyzed the effect of the selection of the ultimate solution in a PS design when it is including technical aspects, environmental aspects, and when it is considering variability of demand in the PS design.

Chapter 7. Conclusions. This section comprehends the conclusion from the obtained achievements of the different methodologies developed in the research and the analysis of the results in the case studies. Finally, this section introduces future developments according to the detected limitations of the developed methodologies in this work.

Chapter 8. Quality Indicators. This section shows all the published articles in journals and the participations in different congresses.

Chapter 9. Abbreviations. In this chapter, all the abbreviations used in the manuscript of this work are summarized in a table.

Chapter 10. References. All the references used in the development of this document and the references used in the published articles are presented in this chapter.

Chapter 2. State of the art

2.1. Introduction

The traditional procedure for the design of a PS for WDN is composed of three phases. The first phase consists of knowing the hydraulic requirements and hydraulic constrain of the WDN to serve. The second phase comprehend the selection of the pump model, the number of pumps considering the available site for the construction of the station and installation restrictions that may exist. Finally, the third phase comprehend the selection of the type of control system to operate the PS in a proper form. In this way, the hydraulic requirements and the site of the PS are the constraints of the design, whereas the type of PS, the model and number of pumps, and the control system of operation are the variables of the PS. The combination of these variables set up several potential solutions to select the most suitable solution according to the necessities of the WDN. The selection of the ultimate solution in the design of PS is a difficult process to establish. Generally, the designer selects the type, model and number of pumps, and the control system according to their criterion and knowledge gained from years of experience. However, the designer has to consider several factors in the process of selecting the potential pumping equipment models in the station [17]. These factors are:

- The type and quality of fluid to be pumped (potable water, raw water, wastewater).
- Operating conditions of the system (the set-point curve), extreme conditions. It means the maximum flowrate and head (Q_{max}, H_{max}) and the minimum flowrate and head (Q_{min}, H_{min}).
- The type of station is an influence factor of the selection of type of pump (e.g., horizontal centrifugal pump, vertical turbine pump, or submersible pump). There could be different configuration of PS, such as wastewater PS, well water PS, PS suctioned from a reservoir, in line booster PS. In addition, the final discharge of the PS (e.g., to a storage tank or reservoir, or directly to the network) is another factor to consider in the selection of the type of pump.
- Constraints of the station location including available site and size are factors to consider before the selection of the pump. Hence, the size of the PS is an important aspect to consider in a PS design. This aspect is associated with the number of pumps and sometimes this parameter could be restricted with the site and the available space to install the PS.
- The type of the head pumping (*H*-*Q*) curve of the pump model could influence on the selection of the mode of operation in the PS with FSP or VSP.
- The difficulty of installation of the PS and the devices required are factors to consider in the selection of the pumping equipment. For example, the use of pressure control (PC), flow control (FC), frequency drive, and programmer logic control (PLC) in the control system could be limited with the necessities of operation in WDN.

In summary, the pump selected and the control system strategy of operation in a PS for WDN are usually based on the minimization of energy consumption. In fact, the operational costs related from energy consumption is the main component of the LCC in a PS [18].

2.2. Types and scheme of pumping stations for water distribution networks.

The purpose to define a basic scheme for different PS configurations is to determine important aspects to consider in a PS design such as, the size of the PS, investment costs that are evaluated according to the layout of the PS scheme. The types of PS for WDN can be divided into three different types according to the suction source of origin. These types are: PS from a storage tank, well PS, and Booster PS.

PS from a storage tank consists of a single pump, or a group of pumps coupled in parallel taking suction from the storage tank and boosting to the destination that could be to an elevated tank or directly to the network. The basic scheme of this PS configuration is showed in Figure 1. Generally, this type of PS works with positive suction (i.e., the water level of the tank is above to the suction inlet of the pump). In this case the most common pumps used are horizontal centrifugal pumps. However, there are cases when the PS works with negative suction (i.e., the water level of the tank is under to the suction inlet of the pump). In this case, vertical pumps or pumps with submersible engine could be used. The operating condition of this PS is constrained to the maximum and minimum levels of the water source (storage tank) and to the characteristic curve of the system. For example, if the destination of the system is a storage tank, the PS should operate according to the maximum and minimum level of the tank. If, the destination is the network, the PS should operate according to the demand pattern and required head.

Booster PS is used to reinforce the pressurization of the system by means of a PS taking suction from an already pressurized source (e.g., pressurized main). The installation consists of a single pump or group of pumps connected in parallel taking suction from a common pressurized pipeline (See Figure 2). Every branch of the pump is connected to a common distribution main and finally the water is pumping to the destination (e.g., to the network, or to an elevated tank). In any case, the operating conditions of the PS are subject to the set-point curve of the system. Another configuration of booster PS is with an hydropneumatics tank. In this configuration, the PS maintain a given pressure (maximum and minimum) through the hydropneumatic tank that is installed at the beginning of the impulsion main (see Figure 2). Nevertheless, the hydropneumatic tank is used with small flows of demand (e.g., internal building supply).

The layout of PS from a storage tank and booster PS are similar. The difference of these types of PS lies in the suction source of the PS (i.e., from a tank or from a pressurized pipeline). The scheme of installation of these PS (see Figure 1 and Figure 2) considered in this work consists of a section valve at the suction pipeline. In every branch of the pumps is installed a section valve followed to the pump and then is installed a section valve and a check valve. These branches are unified in a common impulsion main. At the end of this main is installed a section valve to finally pumping the water to the destination. There are three types of lengths in the pipelines of the basic layout of the PS that define the size of the station. The length L_1 corresponds to the spacing between each parallel branch of the pump. L_2 corresponds to the length of the branches of the pumps. Finally, L_3 correspond to the lengths of the suction and impulsion main.

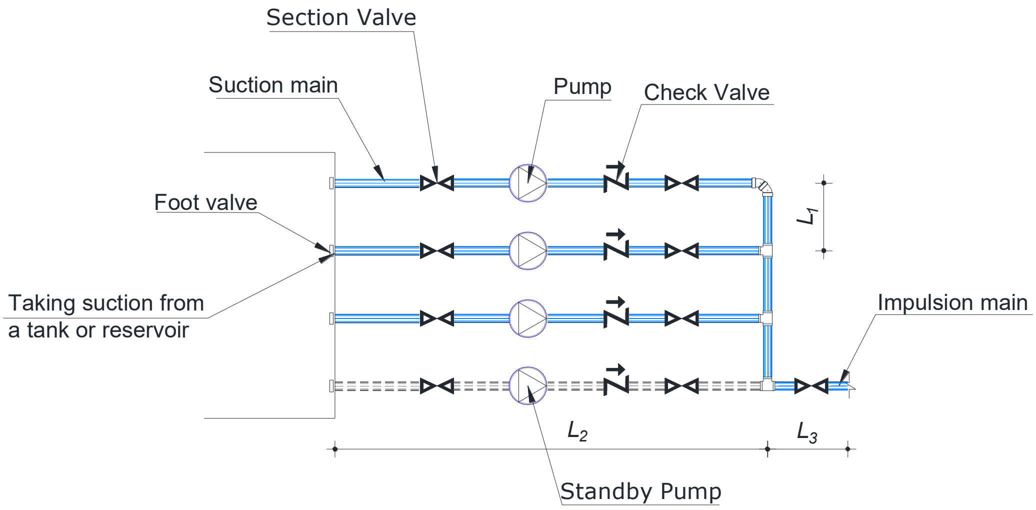


Figure 1. Basic scheme of a Pumping Station From a storage tank

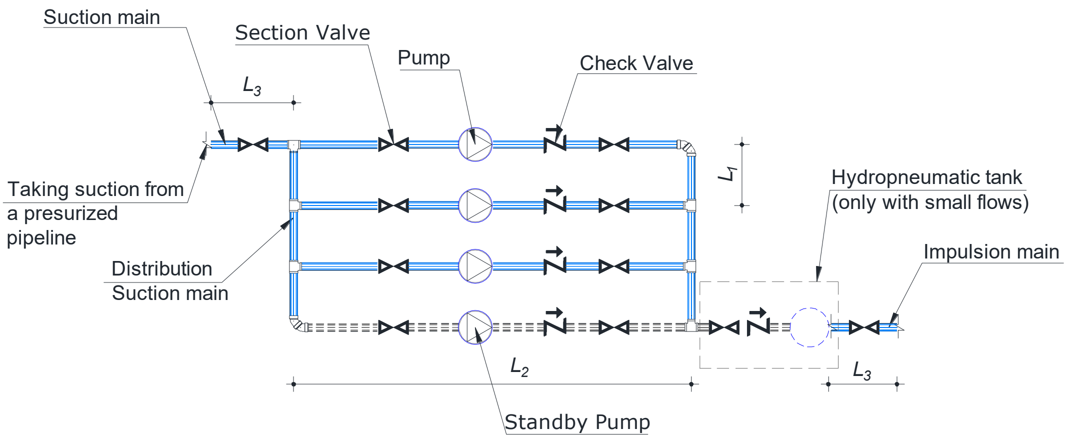


Figure 2. Basic scheme of a Booster Pumping Station

PS of Well Field is type of PS used in wells in which the most commonly pumps used are vertical pumps with submersible engine. This type of station consists of a single or group of well pumps to supply water to the destination (e.g., elevated tank or irrigation network). The engine, the suction and discharge head of the pump are submerged in the well. In PS of well field there are several especial aspects to consider in the design process of the PS, such as hydrogeologic studies of the groundwater aquifer to explode, the location of the wells, and water quality. Therefore, there will be extra expenses in investment costs in comparison with PS from a tank or booster PS.

The basic scheme of installation of well PS (See Figures 3 and Figure 4) consists of a pump with a submerged engine in the well water. The pump takes suction directly of the well water through the submerged suction inlet. A vertical check valve is installed immediately upstream of the vertical submersible pump. An air valve is installed in the top of the impulsion main (i.e., above the ground level). When the pump starts, the water flows at high speed because the total dynamic head is initially zero. Therefore, it is important the air must be allowed to scape slowly so the column of water in the well strikes the check valve and the stationary column of water in the impulsion main too softly to avoid an undue pressure surge. After the air valve, a horizontal check valve and a section valve are installed in the horizontal impulsion main. However, sometimes the check valve is installed after the suction grill in the vertical impulsion main. Finally, the impulsion main of every well pump is joined to a common main and it supply the water to the system. The length L_1 is the branch of every well pump, L_2 is the principal distribution main, and L_3 is the impulsion main to the destination.

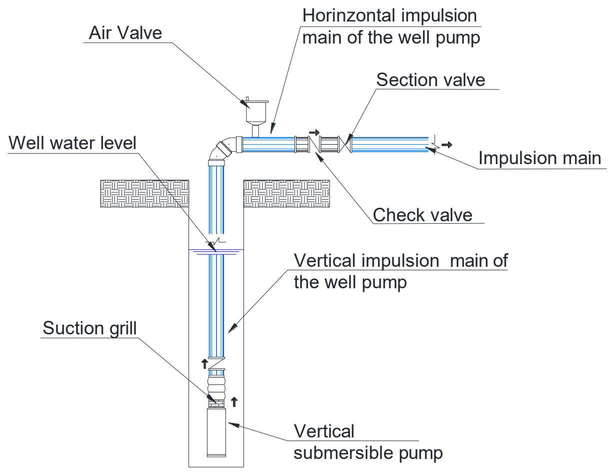


Figure 3. Basic Scheme of a Well Pumping Station (Section View)

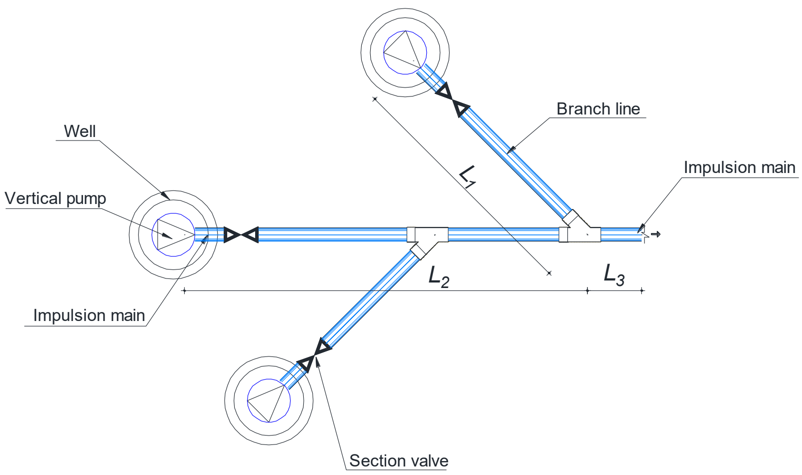


Figure 4. Basic Scheme of a PS of Well Field (Plan View)

PS taking suction from a tank or pressurized main was given as example to explain the developed methodology for PS design in this thesis. However, this methodology could be applied in different types of PS configuration for WDN. In fact, one of the objectives of this work is that the methodology of PS design be standardized for any configuration of PS for WDN reducing the level of subjectivity that the designer might have.

2.3. Control system configurations

A PS for WDN could supply directly to the network or could supply to a storage tank and then it supplies to the network. A proper operation of PS must meet the operational requirements of the destination. The operation of a direct pumping to the network is restricted to the required operational points of flow and head (*Q, H*) of the network that are defined by a set-point curve. This curve is defined as the flow and head required to supply the demanded consumption of the network maintaining the minimum pressure required at the critical consumption node of the network. While, the operational points (*Q, H*) of a pumping to a storage tank is restricted to the maximum and minimum level of the tank. In any case, the proposed methodology of PS design in this work starts from the operating conditions of the PS defined by the set-point curve.

The PS is operated by FSP, VSP or the combination of both. The configurations of control considered in this work are PC, and FC in order to regulate the operational points of the PS (*Q, H*) with the set-point curve. In general, the operation of control systems aim the PS operates in high efficiency zones to optimize the performance of the PS. Another objective of control systems is the PS operates as close as possible to the set-point curve. Besides, the control system should maintain the reliability of the PS when a pump is faulty and minimize excessive the pump switch on and off.

This work focuses on the most common control system mechanisms, which are PC and FC. In this way, it has established 7 different control system configurations in a PS according to different combinations of type of pumps (FSP, VSP) and control mechanisms PC, FC, or with no control (NC). These 7 configurations are described following:

1. FSP with No Control
2. FSP with Pressure Control
3. FSP with Flow Control
4. VSP with Pressure Control
5. VSP with Flow Control
6. FSP and VSP with Pressure Control
7. FSP and VSP with Flow Control.

The operation of these control system configurations is detailed in the appendix section of the chapter 4 of this document.

2.4. Pumping station modelling

The modelling of a PS consists of simulating the dynamics of the water network by including the variability of demand and the changing electric tariff. The variability of demand and the different types of tariffs for electricity allow to make considerable energy consumption saving in water networks by pump scheduling. This problem is based on determining the status of (switch on/ off) and its duration in every pump in each given period in order to minimize the energy consumption in the PS. Finding the optimal solution of pump scheduling is a challenging problem due to the decision variables of the pump status and the nonlinearity of the equations to model water network.

Therefore, in the last three decades, it has been developed a wide variety of algorithms with different approaches to solve pump scheduling problem with FSP. These approaches include, linear programming [19], nonlinear programming [20], dynamic programming [21], mixed programming [22] and stochastic programming [23]. The decision variables and the several hydraulic constraints of the network model makes that these optimization techniques require high computational and memory resources, so the computational time is not efficient. In addition, these approaches greatly simplify the network to address easier the pump scheduling problem. However, these simplifications could exclude potential good solutions in the optimization process. Hence, in the last few years, different approaches of pump scheduling (heuristic techniques) have been developed. For example, Wegly et al. [24] presented the particle swarm optimization and McCormick-Powell [25] presented a simulated annealing heuristic procedure based on linear programming to improve the search space in pump scheduling optimization. In a similar way, Lopez-Ibañez et al. [26] presented the genetic algorithm (GA) ant colony optimization (ACO) to reduce the search space of pump scheduling with binary decision variables. Then, Magalhaes-Costa et al. [27] presented a general routine branch-bound to improve the search process for the global solution in the pump scheduling. The principal characteristic of heuristic algorithms is that it does not need simplification of the hydraulic model, even if the nonlinearity of the model. However, in the calculation process of these heuristic algorithms numerous operations are required. This makes that these algorithms spend large calculation time and computational resources, especially with large networks.

Then, VSP has been used in the operation of PS for WDN in the last two decades. VSP in WDN present several advantages over FSP, especially in terms of flexibility of operating and management of the WDN. Another advantage of using VSP is the reduction of potential damage transient pressure in WDN. The use of VSP combined with FSP enables better control system configurations in PS to follow the set-point curve of the network [7] [28]. In this way, VSP allows to meet the desired operating condition, and this enables to optimize energy consumption in PS [29] or in well field PS [30]. In addition, some benefits of using VSP in PS configuration are the reduction of leakage and the optimization of operational costs in WDN [31]. Nevertheless, pump scheduling with VSP presents complexity in the optimization process and need more computational resources [32] . An important aspect of this pump scheduling problem is to search the rotational speed of the pump to optimize the operation of WDN. It increases the number of decision variables and constraints of the model. In this way, several metaheuristic methods have been used in VSP scheduling , including genetic algorithm GA [33], ant colony optimization ACO [34], shorth path algorithm (SPA) [35].

In the last decade, it has been improved the optimization in pumps scheduling by hybrid algorithms. For instance, Rao and Salmons [36] combined Artificial Neural Network (ANN) and GA to optimize the operation of FSP and VSP in WDN. This hybrid algorithm allows to optimize the pump scheduling with an efficient computational time. In addition, Giacomello et. al. [37] performed linear algorithm and greedy algorithm for pump scheduling problem with high accuracy results and high computationally efficiency. In a similar way, Abdallah and Kapelan [38] developed a fast algorithm optimization combining an iterative algorithm with goal programming to optimize the operational costs in pumping station for real networks in a computationally efficient manner. In summary, the advantages of hybrid algorithms from genetic algorithms are the improvements in search space accuracy and computational efficiency. However, these hybrid algorithms have limitations on the feasibility of pump scheduling on-line.

In the last decade, it has been developed multi-objective optimization in PS modelling because of the necessity for WDN be more robust and to improve the feasibility and reliability of operation in WDN. In this way, Figueiredo et al. [39] improved the energy efficiency of a PS in a water distribution system by optimizing the PS operation and considering the water storage risk. Abdallah and Kapelan [40] presented an iterative hybrid algorithm to optimize the consumption energy by FSP and VSP, and optimize the water quality of the WDN. Other works were focused on optimizing the operation of PS with improving the reliability of the system. For example, Hao Wang et al. [41] used particle swarm optimization to minimize the operation of the PS and minimize the number of switches of the pumps in an drainage system. Alternatively, Carpitella Silva et al. [42] optimized energy consumption of a PS and minimized the required pressure service in a water network using genetic algorithms and multi-criteria analysis.

Up to now, the limitation in most of pump scheduling methodologies consider a fixed efficiency of the frequency drive in VSP. In some cases, they neglected the efficiency of frequency drive. The first part of this work is to develop a methodology that improves the classical control systems strategies in terms of consumption energy. The purpose of this methodology is to face the limitations of pump scheduling problems by determining the optimal number of FSP and VSP, the total number of pumps in the station. Sometimes in a optimization of WDN could be necessary to redefine the number of pumps in a PS. Another purpose of this methodology is to consider the efficiency of the frequency drive in VSP in the optimization process. The mathematical formulation for model the operation of PS is explained in the chapter 3 of this document.

2.5. Pumping station design

The process of selecting pump model and the number of them for a PS is difficult to establish because these variables represent several solutions for a classic PS design according to the operational requirements of the network. The PS must satisfy the critical conditions of the network, the maximum flow (Q_{max}) and the maximum required head (H_{max}). The definition of the pump model and the number of pumps depends to the criteria or experience of the designer. The scheme of the head curve of the PS and the set-point curve is showed in Figure 5. The variation of the pump efficiency and the pumping head with flow and the different operating constraints conditioned both variables the pump model and the number of pumps. There are two classic approaches of determining these variables. The first approach consists firstly of selecting a pump model that deliver the maximum required head (H_{max}) of the network. Once the model is set, the number of pumps is obtained by dividing the maximum flow (Q_{max}) by the flow a single pump of the model (Q_{b1}), which would deliver at the maximum head (H_{max}). The second approach is based on first fixing the number of pumps and then determining the pump model. Once the number of pumps is fixed, the maximum flow (Q_{max}) is divided by the number of pumps. This obtained flow and the maximum required head (H_{max}) are the operating conditions the selected pump model must meet. In summary, there is no bi-univocal relationship between these two variables (model and number of pumps). It means that a pump model corresponds a unique number of pumps in a classic PS design. However, a fixed number of pumps could lead different pump models in the PS design.

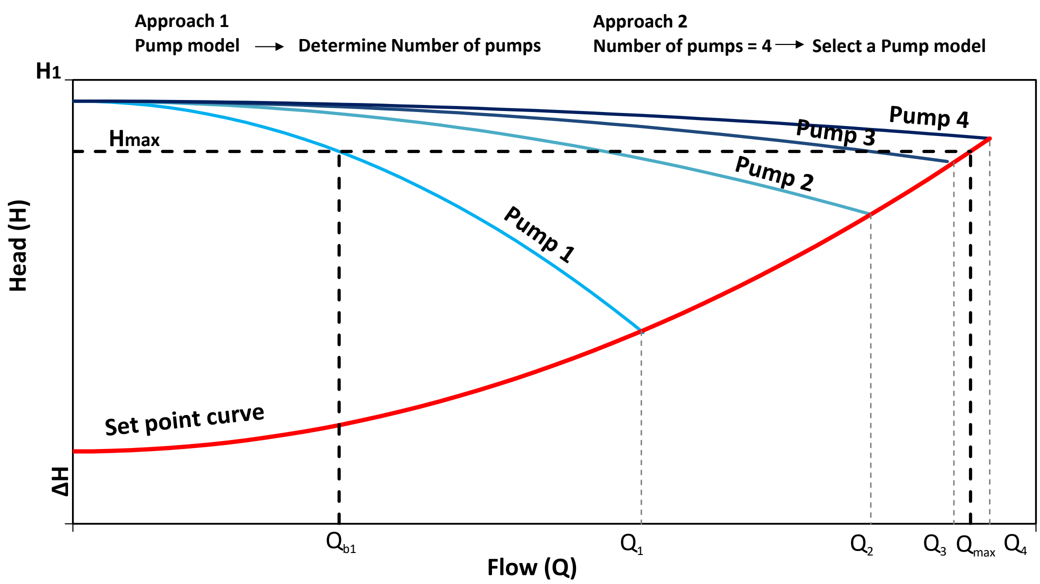


Figure 5. Scheme of the head pumping curve of the PS and the set-point curve

A classic PS design consists of determining the pump model, the number of pumps, the control system configuration that minimize the LCC of the project. In fact, most of the researchers related with PS for WDN are focused on developing methodologies to optimize economic aspects, specifically with investment, maintenance, and operational costs. For example, Ostfeld [43] developed a multi-objective methodology based on genetic algorithm to optimize capital, operational and treatment costs for a PS design. In a similar way, Nault et al. [44] implemented a methodology to evaluate the life cycle cost, the net present value, and the CO_2 emissions of the PS analyzing different scenarios of control and operation conditions. Alternatively, Walski and Creaco [45] analyzed different configurations of pumping including FSP and VSP of different size and different operation conditions of the network to select the best configuration based on the capital and operational costs. In addition, Leon-Celi et al. developed a methodology based on the set-point curve to optimize the operational and water production costs in a WDN for a PS design. In parallel, Diao et al. [46] analyzed the impacts of a WDN in terms of LCC with different consumption flow scenarios, such as uniform demand pattern and spatial variation of the demand. Martin-Candilejo et al. [47] proposed an economic method of design for a WDN through optimization of infrastructure and operational costs. Finally, Gutierrez-Bahamondez et al. [48] developed a methodology of a PS design that select the most suitable pump model based on the minimization of capital and operational costs. In addition, this methodology includes the optimal flow distribution for multiple PS in the WDN.

However, economic factors are not the only aspect to be considered in engineering projects, such as PS design. In a PS there is several aspects to consider for it design. For example, the location, feasibility of implementing the PS, the flexibility of operation, and complexity of installation. These aspects are related with the pump model and the number of them in the station. In fact, one of the essential parts of PS installation are electrical requirements. There are many electrical requirements to be considered, such as the electrical panels, the electrical protections for the pump, the layout of the electrical conduits, the power supply of all the measurement and control elements. Hence, the greater electrical requirements, the greater complexity of installation of the control system. In addition, a PS is monitored by Supervisory, Control and Data Acquisition (SCADA) system [49]. SCADA systems are difficult to put in practice with complex pump scheduling and control configurations due to the different feature sets, connectivity, programming, technical support of the various components and cybersecurity issues. In fact, several authors such as Salomons et. al. [50] and Manteigas et. al. [51] aims to develop simple and practical controller methodologies that are feasibly and practical for real-time pump scheduling in a PS. In short, the increased complexity of the PS control system carries with it a whole range of potential hidden costs that are difficult to determine in the PS budget. Therefore, there is the necessity to include technical criteria in addition to economic criteria in engineering design projects as stated Naval and Justa [52]; Liu et al. [53].

In addition, another aspect that is important to consider in PS design are environmental criteria and its environmental impact on the implementation of WDN. This aspect has become sensible in WDN due to the climate change issues in the last two decades. It is important to evaluate environmental aspects in the operation of PS to reach sustainable development goals in WDN [54]. In fact, several research have been developed methodologies to optimize and improve environmental indicators, such as GHG emission by PS and the ratio of the delivered head and the required head in WDN [55, 56, 57]. Hence, it is important to consider environmental aspects in addition to technical and economic criteria in the design process of a PS.

In summary, a proper PS design should consider together technical, economic, and environmental criteria. In this way, a multicriteria decision making methodology is a suitable approach to solve this problem, especially with criteria that have opposite interests as it happens with a PS design.

2.6. Multicriteria decision making

Multicriteria Decision Making (MCDM) is a process, where several alternatives for a goal are evaluated in terms of different criteria to make the ultimate decision to solve the problem. For example, in a PS design, the ideal solution should be a pump model that satisfy the operational conditions of the network with minimum required space for the installation, and the minimum investment, maintenance, and operation cost. At the same time, the ultimate solution should have the simplest pumping configuration and the least environmental impact caused by the implementation and operation of the PS. However, it is not possible to satisfy in the same form all criteria in the design process. In this way, all the potential solutions have to be assessed in term of the criteria considered in the PS design. These evaluations allow to obtain a rating of solutions in every criterion. There are several methods or approaches of MCDM problem, and they depend basically on the type of information received from decision maker and particular features of the information. In general, there are numerous of MCDM methods, but the most common used MCDM methods used in engineering problems are Technic for Order Preference by Similarity to Ideal Solution (TOPSIS), Analytic Hierarchy Process (AHP) and Analytical Network Process (ANP).

The TOPSIS method was developed by Hwang and Yoon [58]. This method consists of determining the ideal and the worst solution for the problem. In this way, the idea of this approach is that the selected alternative should be nearest to the ideal solution and farthest to the worst solution. This method evaluates the alternatives in every criterion and the set of alternatives are compared together identifying weights for each criterion by a group of experts. The normalized scores of the alternatives for each criterion are calculated as the geometric distance between each alternative and the ideal alternative. Finally, the alternatives are ranked according to the obtained distance in order to choose the most suitable alternative with respect to the problem goal.

The AHP method was developed by Saaty [16]. This method is structured in a multi-level hierarchical form. It starts defining the goal, followed by the criteria, sub-criteria and finished with the alternatives. One of the relevant data of this method is a set of pairwise comparisons of the criteria. These comparisons are judged by a group of experts. The idea of this approach is to determine the importance weight of the decision criteria and sub-criteria, and the assessment of the alternatives in terms of each criterion. These assessments allow to rank the alternatives with respect to the problem goal. The AHP method has been widely used in Hydraulic Engineering projects. The AHP allow to solve the uncertainty of aspects, such as technical, economic, social, environmental criteria that could arise in this kind of projects. For example, this multicriteria decision method has been applied to determine the priority strategies to implement in different systems. For example, Raminelli and Costa [59] apply the AHP to determine the better strategies for water supply system management between leak detection and correction, rational use of water, and replace old water mains. In a similar way, Taillander et al. [60] developed a tool based on the AHP method to select the adequate management strategy for sewer system considering technical, social, economic and environmental criteria. In addition, Ward et al. [61] used the AHP method and spatial analysis for determine the suitable water harvesting sites for water management in Cambodia.

The ANP is a MCDM developed by Saaty [62], is an updated of the AHP method and it is based on a generalized form of the AHP. On the other hand, the AHP method considers that each element of the hierarchy level is independent of all the others. In this way, the criteria and sub-criteria are considered independent one to another. In a similar way, the alternatives are considered independent of the criteria and one another. Therefore, the AHP method does not allow to determine the interdependent relationship of the criteria. The main idea of the ANP method is to analyze the interdependent relationship of the criteria and alternatives forming a network structure. As a result, the ANP is a feasible MCDM, specially in uncertain and dynamic environment.

The most widely MCDM method used in engineering projects under uncertainty scenarios to make the best decision in the problem is the AHP method. Consequently, the AHP was chosen to design a PS. As first approach of the PS design, the decision criteria considered in the AHP method are technical and economic criteria with their respective sub-criteria. The methodology and formulation of this first approach is developed in the fourth chapter of this document. As second approach for a PS design, environmental criteria were included in the AHP method in addition to the technical and economic criteria. The development of the methodology of this second approach is explained in the fifth chapter of this document.

2.7. Conclusions of the state of the art

In summary, one of the gaps identified in PS design for WDN in the state of the art is the optimization of operation of PS control systems are constrained with the number of pumps. The number of pumps in an arbitrary parameter that is established according to the experience of the designer. Therefore, this constraint does not allow a proper optimization of consumed energy in PS. In addition, the efficiency of frequency drive in VSP has not been considered in pump scheduling. Hence, this neglected aspect leads to inaccuracies in the operation optimization of PS. Therefore, it is important to develop a methodology of optimization of PS control systems that allow redefine a number of pumps in a PS combining the operation of FSP and VSP in the PS. This methodology consists of determining the optimal number of FSP and/or VSP for any flow. This optimization of control system allows to redefine the total number of pumps in the PS. In addition, the development of a mathematical expression that allows to estimate the efficiency of frequency drive in the optimization process.

Another gap to consider related with PS design is that the design solution is focused only on minimizing economic aspects such as, investment, operational and maintenance cost. Important aspects to consider in a PS design such as, technical criteria are usually neglected in the design process to search the most suitable solution for the PS. In the last two decades, environmental aspects have became an important factor in WDN projects. A classic PS design usually considers only the yearly average demand pattern for the design. In this way, the variability of demand should be considered in the design of a PS to improve the reliability of the design.

Chapter 3. Optimization of control system operation in a pumping station

The first stage of this work is to develop a standardized methodology to optimize the operation of PS control systems. The optimization of control systems is oriented to pumping configurations with the combination of FSP and VSP with PC and FC respectively. The main objective of this methodology is to determine the optimal number of FSP and VSP for any flow range, so the consumed energy of the PS be the optimal. In addition, the objective of this process is to redefine the total number of pumps in a technical and precise form. In this way, this proposed methodology was presented in a technical article and published in Water Journal MPDI. The reference of this paper is:

> Briceño-León, C. X., Iglesias-Rey, P. L., Martinez-Solano, F. J., Mora-Melia, D., & Fuertes-Miquel, V. S. "Use of fixed and variable speed pumps in water distribution networks with different control strategies". Water, vol. 13, no. 4, pp. 479, 2021.

This paper discusses the classical approach for control systems in PS with a novel approach in the operation of control systems in a PS. This methodology consists of expressing the pumping head, the pump's efficiency and the set-point curve in dimensionless form. These dimensionless terms of the pump model and set-point curve are related with the best efficient point (BEP). These curves are the principal basis of the optimization of PS control systems. The main objective is to standardize a methodology to optimize the operation of control system for any pump model and any set-point curve. A special contribution of this work is to develop an expression that allows to estimate the efficiency of a frequency drive when a VSP changes its rotational speed. In summary, the objective of this methodology is to determine the optimal number of FSP and VSP for any flow rate in a time slot, so the consumed energy be minimum in that flow. In addition, this methodology aims to redefine the total number of pumps in the PS according to the performed optimization. Finally, this paper presented a case study to compare the energy consumption of the classic control system configurations in PS and the proposed optimization in control systems of PS.

3.1. Introduction

PS operation play a significant role in energy consumption in urban water networks. Besides, the electricity consumed by pump stations corresponds the 20% of the total electricity demanded in the world. Almost 95% of energy consumption in water networks is related to pumping energy costs and the 90% of the total cost of the pumps cycle life is related to operational cost [18]. In fact, the European policies on climate and energy [63] stablished as goal to save at least 27% of consumed energy for 2030 in order to mitigate climate change problems.

These previously antecedents could incentivize researches, such as Casasso et al. [64] and Candilejo et al. [65] to develop strategies to improve energy efficiency in water infrastructure that includes PS. The Environmental Protection Agency (EPA) [4] defined several measures to save energy in PS, such as reduce pressure service, manage pressure service, maximize efficiency of the system, adequate pump and control modes selections. In addition, pumping system sizing, piping layout and the head pressure demands are principal factors to improve PS efficiency. Changing pumping operational mode used to be the most common strategy to achieved consumed energy optimization [66]. Besides, implementing Variable Frequency Drives (VFD) and automatic control modes on PSs are other methods to optimize operational costs [49].

Most of investigations about pumping optimization in water supply systems focused on pump scheduling optimization with FSP to minimize the operation costs. A pump scheduling optimization is a process that starts with a pump model and with a determined number of pumps that are previously set. Then, this problem consists of selecting a number of pumps in a PS to be operated and determining the current state of the pumps (switch on/off) in every interval of time. This set of pumps in operation must satisfy objectives, such as to minimize the amount of electric energy and the requirements of demands of the water network [4].

In last three decades, there have been developed some mathematical methods to solve pump scheduling problems including linear programming [19] [67], nonlinear programming [22] [68] and dynamin programming [23] [69]. The problem of these mathematical methods is that they are computationally slow. Later, it has been developed more powerful methods to solve pump scheduling optimization that highlight metaheuristic method (evolutive algorithms). For example, Lopez-Ibañez et al [26] represent a new form of pump scheduling basing on time controlled triggers and using ACO, where the objective is to minimize electricity cost. Magalhaes-Costa et al [27] established a general optimization routine for any water distribution systems that is integrated to EPANET [70] using a Branch and Bound algorithm. De Paola et al. [71] developed a modified Harmony search multi-objective optimization in the operation of PSs to optimize the energy consumption in water networks. In addition, Wang H. et al [41] used particle swarm optimization (PSO) in a drainage PS optimization. Besides, Mohsen et al. [72] used a non-dominated sorting genetic algorithm in a multi objective optimization tool to minimize electricity cost and pollution emission of PSs in water networks. Finally, goal programming is another method that it has been highlighted in the last years for pumping operation optimization. Abdallah and Kapelan [38] developed an iterative extended lexicographic goal programming for fast FSP scheduling optimization in order to minimize consumption energy.

In the last twenty years the use of VSP have been developed and the benefits of these pumps in energy terms comparing with FSP have been demonstrated in different applications such as, water supply networks or ground water pumping [29] [30]. Even though of these benefits, pumping scheduling methods are more common with FSP. The principal reason is associated with the increasing of complexity of the pump scheduling problem. In fact, the optimization of VSP depends of discretization of VSP speeds [6]. Another important aspect is to find the optimal number of running pumps. Therefore, it increases the number of decision variables, the computation time and it could leads in the problem of suboptimal solution [73].

Several literatures of VSP scheduling used metaheuristic methods including GA [33] [74]. Furthermore, another optimization methods are highlighted, such as ACO [34] or PSO [24]. In order to improve computational time, Rao and Salmons [75] combined ANN with GA. Then, Abdallah and Kapelan [40] developed a fast VSP scheduling method through an improved goal programming algorithm to optimize the energy cost in a computationally efficient manner.

Another alternative to optimize PS in energy terms is to use control systems in order that a PS operates according to the requirements of flow and head of the water network and do not consume excess of energy by the pumps. In this way, Lamaddalena and Khila [28] developed a methodology to regulate pumping systems in an irrigation network to save energy consumption. In that methodology they used FSP and VSP to adapt the pumping system to the head system curve. The head system curve that was used in these previous works can be defined as the minimum head required to satisfy the flow demand in the consumption nodes as these demands varies in space and time. However, this concept is quite complex to apply in water networks because there are many head systems as demand consume varies. In a similar way, Nowak et al. [76] presented an optimization process using VSP with different constraints in operational controls. There could be different pumping configuration with FSP and VSP for PS in water networks. However, when using more FSPs than the minimum required in the system generates significant benefits in energy costs because pumps improve their efficiency as it was demonstrated by Walsky and Creaco [45]. Later, Candilejo et al. [65] [47] improved a methodology to estimate pump's performance for a proper design of a PS in order to reduce operational costs and then create a methodology for the optimal design of a water pumping system with variable flow rates.

On the other hand, León-Celi et al. [77] [78] developed a methodology that optimized the flow rate of multiple pump stations and also the energy consumption in closed water networks. A simpler concept (set-point curve) was used in this methodology and it is defined as the minimum head required at the exit of the PS to guarantee the flow demand and maintaining the minimum pressure required at the critical consumption node at every time step [8]. Thus, as a difference of the head system curve, the set-point curve has only one curve for every pump station. However, this methodology does not consider the selection of pump models. In fact, the energy was computed only with theorical values. Also, the efficiency of pump stations was assumed with a constant value.

A problem of optimization of PS is that the process is based with a fixed model of pump and a set number of pumps. Therefore, the optimization of consumed energy is limited to the model of pump and the number of pumps that were previously set. Another problem is that it has not been deepen in a PS design. There is not a clear criterion to select the most suitable pump model and determine the total number of pumps. In fact, a PS is usually designed in maximum situations (maximum demand flow and maximum pressure service). However, a PS rarely operates in these conditions. Hence, a control system allows that the operation of a PS be adapted to the requirements of the network. Even though, the pumping configurations of regulation modes are usually limited to the number of pumps that were previously set and it has not been evaluated other pumping configurations that could be more optimal in energy terms.

On the other hand, a problem of previous works related with VSP is that they assumed a constant efficiency regardless of changes in the rotational speed of the pump. In fact, this efficiency is affected by rotational speed and by the frequency inverter's performance. Consequently, the calculated energy of VSP are lower than the real energy used and it derivates to an inaccuracy of operational costs [79]. Simpson and Marchi [80] evaluated the approximation of affinity lows to estimate the efficiency of a VSP and they conclude that the BEP of the efficiency using the affinity laws has a deviation in relation to the real BEP. Even though, there are expressions that reduce this inaccuracy such as Sarbu and Borza expression [81]. Later, Coelho and Andrade-Campos [82] developed an expression to correct the deviation of the BEP of the affinity laws.

A VFD can be defined as an electrical device that converts the wave power from the power supply into the variable frequency power and sent to the motor. Also, its performance is the relation between the input power of the motor and the input power of the frequency inverter [83]. Several works have realized laboratory tests to measure the efficiency of VFD device such as Europump and the Hydraulic Institute [83] and Aranto [84]. These tests consist of measuring the efficiencies of VFD with different percentages of the motor load where the electrical frequency is changed from a minimum to a maximum value (50 Hz in Europe).

In this way, one of the novelties of this present work is to develop a new methodology that determines the most suitable energetically number of pumps in a PS design. In addition, this work will determine the optimal number of FSP and VSP and the pumping configuration, so the consumed energy be the minimal in the regulation mode of the PS. Evidently, the selection of the pump model will be the one with the lowest operational and investment cost. Nonetheless, the objective of this work is to solve what is the number of pump and the most suitable regulation mode for a pump model. Furthermore, another novelty of this work is to consider some important aspects on VSP such as, the effect that produces on the global efficiency the rotational speed changes and its influence over the performance of a frequency inverter. Accordingly, this work will develop an expression to estimate the performance of a frequency and this expression is adjusted to the experimental results on previous literature.

Basically, this work is not exactly a pump scheduling optimization. In fact, this is a new methodology of PS design which the main objective is to calculate the total number of pumps, so the consumed energy be minimum. In addition, this work determines the optimal operational combination of FSP and VSP for every flow rate of the network on a control system. This methodology begins since a set pump model and the set-point curve of a network. To achieve this objective, this work will develop a methodology based on the operation of a pumping control system and some important concepts such as: the pumping curve, the efficiency curve and the set-point curve. It is important to mention that this work is focused in determine the optimal number of pumps but not in select the most adequate pump model.

3.2. Methods

3.2.1. Methodology of pumping control system

A pumping system is usually designed for the maximum requirements of the network, so it is considered the maximum demand flow (Q_{max}) and the maximum total dynamic head required (H_{max}) to supply the requirements of demand flow and pressure for the network. The total dynamic head is defined as the total equivalent head to be pumped and it includes, the suction head, the static head, the head losses produced by the friction in the piping system and the required pressure of the nodes. Even though, there are several forms to select the necessary number of pumps in a PS. The most common hypotheses are: One hypothesis is to set a number of pumps and from this fixed value it is selected the pump model. The second hypothesis is to set a pump model according to the maximum requirements of the network and then calculate the number pumps (*b*). It is calculated by the following expression that is the relation between the maximum demand flow of the system (Q_{max}) and the flow that one pump could supply with the total dynamic head when the demand flow is Q_{max} or in other words the maximum dynamic head required ($Q_{,hmax}$).

$$N_{pumps} = int(\frac{Q_{max}}{Q_{b,hmax}}) \tag{1}$$

The term *int* in equation (1) indicates that N_{pumps} is the next higher integer of the value obtained in this expression. In this way, we named classic method to the second hypothesis, when it is set a pump model according to the maximum requirements of the network and then is calculated the number of pumps.

In order to optimize the energy in a pumping system, the pumping curve has to be as close as possible to the set-point curve and make sure that the efficiency of the pump operates near to the BEP. This statement is achieved by different configurations of control systems, combining FSPs and VSPs and combining different control modes (flow and pressure).

Control system makes that operational points of the pump (*Q, H*) match with the set-point curve of the network. The pressure and flow of the system are constantly measured with their respective controls and then these values are sent to a PLC. These values are compared with the variables of the set-point curve, and it orders the pumps to change the rotational speed of the VSP in order the pumps operate at the same points of the set-point curve. A classic control system has two ways of operation: pressure and flow control. Pressure control system aims to maintain a constant head pressure at the exit of the pump station through a pressure switch that sends signals to a PLC and this device order the pump station to maintain the set head pressure. On the other way, flow control system presumes to measure instantly the head pressure and the flow at the exit of the PS whose measures are sent to a PLC. This PLC order the pump station to operate at the correspondent rotational speed (*N*) so that it follows the set-point curve. This work will only analyze the operation of flow control system. Even though, the pressure control systems operate in a similar way.

In the pumping control system of the classic method, the total number of pumps (*b*) determines the number of flow operational ranges. These ranges are defined by the terms ($Q_{b1}, Q_{bi}, ..., Q_{bn}$), where the term Q_{bi} is the maximum flow that can be supplied when there are *i* pumps in operation if the control system pretends that the head added by the pump be the same at the required head of the set-point curve. In other words, Q_{bi} is the intersection between the set point curve and the head curve of *i* pumps. In this way, the term *i* take values from *1* to *n*, where *n* is the total number of pumps of PS (Figure 6). The term H_{max} is referred to the total dynamic head when the demand flow is maximum (Q_{max}).

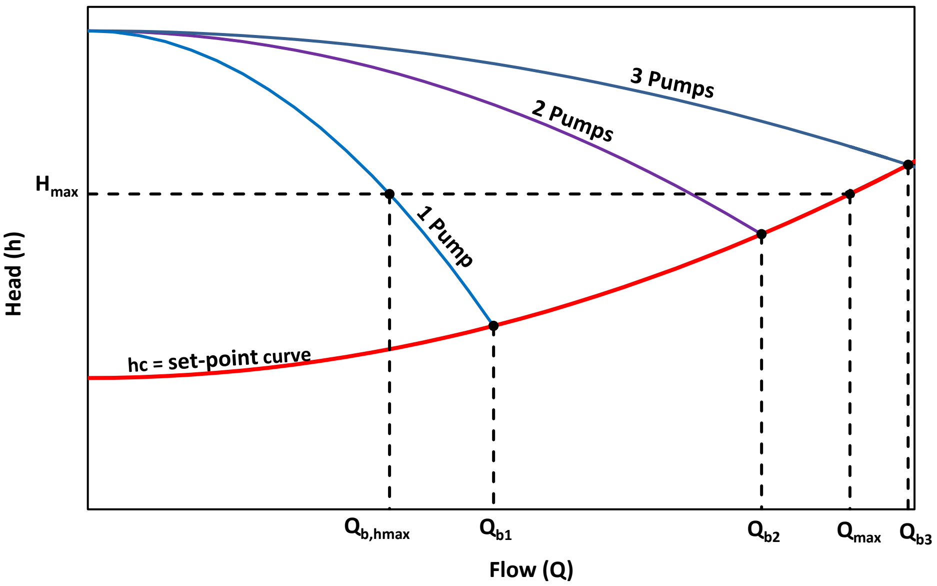


Figure 6. Scheme of a classic operational control system.

In the classic method, when demand flow (*Q*) is in the range ($0 < Q < Q_{b1}$), one pump supplies the flow demand at *N* rotational speed to follow the set-point curve. Where, *N* could have values from ($0 < N < N_0$) and N_0 corresponds to the nominal rotational speed. On the other hand, when the flow (*Q*) is in the second range ($Q_{b1} < Q < Q_{b2}$), one pump operates at 100% of nominal speed (N_0) and the second pump operates at a correspondent (*N)* rotational speed so that follows the set-point curve. Another alternative is that the two pumps operate at a same correspondent (*N*) rotational speed following the set-point curve. When the flow (*Q*) is in the range ($Q_{b2} < Q < Q_{b3}$), two pumps work at 100% of nominal speed (N_0) and the third pump works at a (*N*) rotational speed following the set-point curve. Other alternatives of operation in this last range are: one pump works at 100% nominal speed (N_0) and two pump work at a same correspondent (*N*) rotational speed following the set-point curve or three pumps operates at a same correspondent (N) rotational speed that follow the set-point curve.

The idea of this proposed methodology of PS design is to determine the optimal number of pumps and the optimal pumping configuration of the control system in every flow rate to minimize the energy. This methodology starts with a set-point curve of the system that determines the conditions of flow and head (*Q, H*) required at the end of the pump and with a set pump model. Since the operational flow range of the classic method, it is tested different pumping configurations combining FSP and VSP and calculating the consumed energy in every configuration to determine the optimal number of FSP and VSP in operation. These configurations are determined by adding a pump to the minimum required number of pumps until get the minimum consumed energy. Finally, the results of energy of the different pumping configurations determines the optimal number of FSP and VSP in every flow rate.

In summary, the operational flow ranges and the number of required pumps of the control system of the classic method are used only as reference in this proposed methodology. In order that the methodology, be systematized for any pump model, the set-point curve and the characterized curves of the pump model are going to be expressed in a dimensionless for, where these terms are in relation to the BEP of the pump.

Before to describe the mathematical formulations and the process of this methodology, it is important to highlight several assumptions of this methodology. This methodology is adapted only to closed systems. However, this methodology could also be applied to elevated storage systems if it is used as reference the head and flow (*H, Q*) curves that could be supplied a pump. In addition, it is assumed that PS are configurated in parallel and equipped with pumps of the same characteristics. Another assumption is that the type of demand is for urban consumption and does not change through the time. Furthermore, it is assumed that the suction head of the pump is constant and does not change. It is important to mention that the main objective of this proposed control system is to determine the most suitable pumping configuration to obtain the optimal consumed energy. This work does not consider any kind of cost, including investment, operational, and maintenance costs in the process of this methodology. In future studies it could be considered these cost to this proposed methodology of PS design.

3.2.2. Mathematical formulation

The Total Dynamic Head curve of a pump (H) and the efficiency curve of a pump (η) are in function of the flow (Q). When a pump rotates with different rotation speeds, the total dynamic head curve and the efficiency curve are affected by the rotational speed that is defined by the term (α). This term is the relation between the real rotational speed of the pump (N) and the nominal speed (N_0). Taking as reference the affinity laws, both curves are expressed as the following expressions.

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

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

$$\alpha = \frac{N}{N_0} \tag{4}$$

The terms H_1, *A, B, E and F* in the previous equations are coefficients that characterized the pump and the term n is the number of pumps that conforms the pumping system.

The hydraulic power represents the energy of the pump when supply some flow with a certain head pressure. It is directly proportional to the specific weight of the water (γ), the flow rate (Q) and the total dynamic head (H). Even though the efficiency of the electrical motor could be between 90% and 95%, it is assumed that the mechanical power on the shaft (P_a) is equal to the electrical power consumed by the motor-pump group (*P*). This power includes the hydraulic power and the power losses on the transmission of the shaft. Therefore, the efficiency of a pump is defined as the relation between of the hydraulic power and the shaft power. The relation between the consumed power of a pump (*P*), the mechanical torque (*M*) and the rotational speed of the shaft (ω) are expressed in the following equation:

$$P = \frac{\gamma \cdot Q \cdot H}{\eta} = M \cdot \omega = P_a \tag{5}$$

The methodology presented is based on expressing the equations of a pump in a dimensionless way, taking the BEP of the pump as a reference. Therefore, the reduced terms including total dynamic head (*h*), flow (*q*), efficiency (ϑ), mechanical torque (β) and power (π) are obtained by the relation between the values of these variables and the values of the BEP.

$$h = \frac{H}{H_0}\ ;\ q = \frac{Q}{Q_0}\ ;\ \theta = \frac{\eta}{\eta_0}\ ;\ \beta = \frac{M}{M_0}\ ;\pi = \frac{P}{P_0}\ ;\ \alpha = \frac{N}{N_0} \tag{6}$$

Taking as reference the affinity laws and the previous described terms, the head pressure curve and the efficiency curve in a dimensionless form are expressed as the following equations.

$$h = h_1\alpha^2 - \alpha^{(2-B)} \cdot a \cdot \left(\frac{q}{n}\right)^B \tag{7}$$

$$h_1 = \frac{H_1}{H_0}\ ; a = \frac{A \cdot Q_0^B}{H_0} \tag{8}$$

$$\theta = e \cdot \frac{q}{\alpha \cdot n} - f\ \cdot \left(\frac{q}{\alpha \cdot n}\right)^2 \tag{9}$$

$$e = \frac{E \cdot Q_o}{\eta_0}\ ; f = \frac{F \cdot Q_o^2}{\eta_0} \tag{10}$$

$$\pi = \frac{q \cdot h}{\theta} = \beta \cdot \alpha \tag{11}$$

Before to analyse a pumping control system, is important to define the set-point curve. This curve is referred to the demand flow (*Q*) and the total dynamic head required (H_c) to satisfy the minimum required pressure of the user's demand at the critical node. The set-point curve is defined as the following expression.

$$H_c = \Delta H + R \cdot Q^c \tag{12}$$

The term ΔH refers to the static head that is defined as the difference of elevations between the axis suction of the pump and the critical node and adding the minimum required pressure of the critical node. The term *R* is a constant value because the type of demand does not change through the time, and it is associated to the energy losses in the system and is defined as the resistance of the flow presented in the pipelines. Finally, the term *c* is an exponent that depends on the characteristic of the system. The terms *R* and *c* are obtained by a regression adjustment from the points (H_c, *Q*) of the set-point curve to the expression (12). Taking as reference the dimensionless terms in a pumping system, the dimensionless form of the set-point curve leads to

$$h_c = \lambda_1 + r \cdot q^c \tag{13}$$

where the term λ_1 is defined as the relation between the static head (ΔH) and the nominal head of the pump (H_0); and the term r is associated with energy losses R and the nominal point of the flow and head of the pump (Q_0, H_0).

$$\lambda_1 = \frac{\Delta H}{H_0} \; ; \; r = \frac{R \cdot Q_0^c}{H_0} \tag{14}$$

In order to design a pumping control system is important to determine the rotational speed (α) of the pump so the pumping system follow the set-point curve. This type of control system we named flow control system, and it is focused on this work. However, if the control system aims to maintain a constant head pressure in the pump station (pressure control system) the process is similar. This rotational speed is calculated in an iterative form by setting values of rotational speed on the pumping curve equation (7) and the set-point curve (13) until the head pressure be the same on both equations.

In order to estimate the efficiency of a pump using a VFD, the affinity laws are used in the equation of the efficiency curve. As it was mentioned previously in the introduction, the affinity laws present an incongruence to calculate the efficiency [80]. Even though, Coelho and Andrade-Campos [82] proposed an expression that corrects the inaccuracy of the affinity laws. This expression (15) related the real efficiency or corrected efficiency (η_2) when the rotational speed of a pump is (N_2) and the estimated efficiency (η_1) when the rotational speed is (N_1). From equation (15) a correction factor $f(\alpha)$ is defined in equation (16). This factor corrects the efficiency of the pump estimated by the affinity laws.

$$\frac{\eta_2}{\eta_1} = 1 - \left(1 - \frac{N_2}{N_1}\right)^3 \tag{15}$$

$$f_{(\alpha)} = \frac{\eta_2}{\eta_1} = 1 - (1 - \alpha)^3 \tag{16}$$

On the other hand, the reduced mechanical torque (β) could have values greater than the unit in some cases. In a VSP, a reduced mechanical torque (β_v) is defined by the relation between VSP's mechanical torque (M) and the maximum torque of the pump (M_{max}). Thus, β_v is expressed as:

$$\beta_v = \frac{M}{M_{máx}} \tag{17}$$

Also, the mechanical torque of the pump β and the torque of the VSP could be related through the following expression:

$$\beta_v = \frac{\beta \cdot M_0}{M_{máx}} = \frac{\beta}{\beta_{max}} \tag{18}$$

Another, important aspect to consider in the energetic analysis of VSP is the decrease of the efficiency system because of the frequency inverter performance. As it was mentioned in the introduction section, there are several works such as, Europump & the Hydraulic Institute (2004) that analyse energy losses in the VFD device relating rotational speed and mechanical torque.

They developed experimental essays of different frequency inverters, evaluating the performance with different mechanical torque and different rotational speeds. The aim of this methodology is to develop an expression that best adjusted to the experimental essays of Europump & the Hydraulic institute [83]. As a result, the expression that best adjusted to the performance essays is:

$$\eta_v = \eta_{v,0} \cdot (\beta_v^{k_1} - k_2 \cdot (1-\alpha)^{k_3}) \tag{19}$$

In this previous equation, η_v is the performance of VFD. This value is determined by the mechanical torque of the VSP (β_v) and the rotational speed (α). The coefficients that best fit the efficiency curve of frequency inverters essays realized by Europump & the Hydraulic Institute [83] have been obtained by regression adjustment from experimental tests. These values are $k_1 = 0.025$, $k_2 = 0.16$ and $k_3 = 2.71$. The figure 2 shows the adjustment of the developed expression by regression technics with the experimental essays of the VFD. Where the horizontal axis represents the rotational speed (α) and the vertical axis represent the reduced efficiency of the VFD (ϑ_v). The different type of lines represents the adjustment curve of the efficiency of VFD for different reduced mechanical torque (β) and the points represents the experimental essays obtained from Europump & the Hydraulic institute [83].

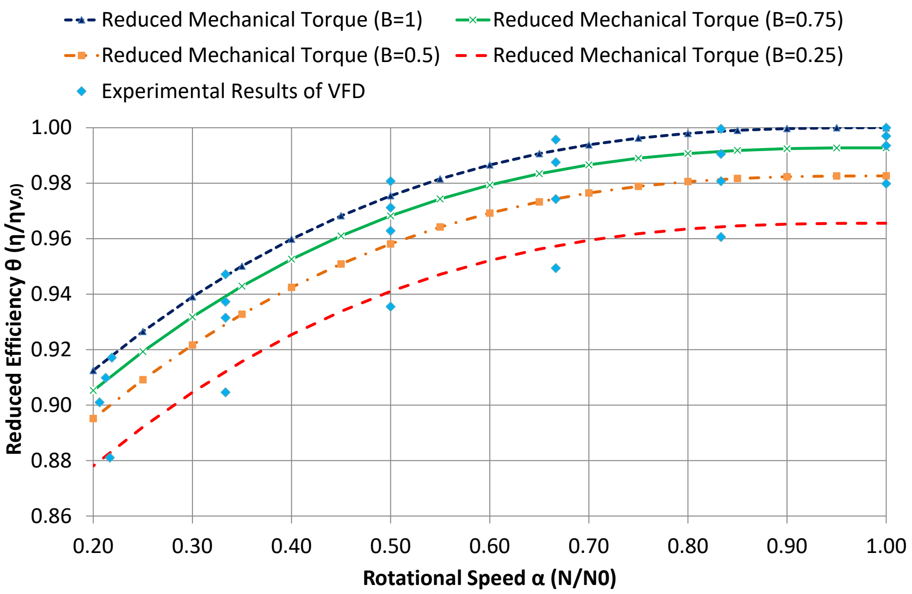


Figure 7. Adjustment of the efficiency of VFD with experimental essays

The performance of the frequency inverter in a reduced form is expressed as the following expression:

$$\theta_v = \frac{\eta_v}{\eta_{v,o}} = \beta_v^{k_1} - k_2 \cdot (1-\alpha)^{k_3} \tag{20}$$

Finally, the global efficiency of the pumping system (η_c) and its reduced form (ϑ_c) should be defined considering the correction of the inaccuracy of the estimated efficiency and the performance of the frequency inverter. Mathematically, they can be expressed as:

$$\eta_c = \eta \cdot f_{(\alpha)} \cdot \eta_v \tag{21}$$

$$\theta_c = \theta \cdot f_{(\alpha)} \cdot \theta_v \cdot \eta_{v,o} \tag{22}$$

The total consumed energy of a pumping system is expressed as the following equation:

$$\pi_T = \frac{q \cdot h}{\theta_c} = \beta \cdot \alpha \tag{23}$$

This last expression allows evaluating the consumed energy in dimensionless form for the different alternatives of pumping configuration for every flow range. Finally, this analysis will determine the optimal number of FSP and VSP in operation that is the objective of the methodology.

3.2.3. Process of the optimization methodology

As it was previously explained in the mathematical formulations, the terms of the characteristic curves of the pump and the set-point curve are expressed in dimensionless form that are in relation of the BEP of the pump. In this way, the flow of the optimization analysis of the pumping system is expressed in a reduced form (q) that is the relation between the supplied flow and the nominal flow of the pump (Q/Q_0). In the same way, the total consumed energy is expressed in a reduced form (π_T) that is the relation between the consumed power of the pump and the nominal power of the pumps (P/P_0). In order to explain how the total operational range (q_{min}<q<q_{max}) is expressed in this methodology, the following Table 1 shows some examples of the limits of the operational range that are: minimum demand flow (Q_{min}) and maximum demand flow (Q_{max}) and its equivalency in reduced terms (q_{min} and q_{max}) with different pump models.

Table 1. Examples of flow representation of the system with the proposed method

Pump Model Q_0 (l/s)	(Q_{min})	(Q_{max})	q_{min}	q_{max}
100	20	200	0.2	2
50	20	200	0.4	4
40	20	200	0.5	5
20	20	200	1	10

This optimization process starts with a set pump model of the PS and the requirements of (Q, H) of system (the set-point curve) and a set flow range ($q_{min} < q < q_{max}$). It is important to remind that this process is focused with the control system that allows the PS follows the set-point curve (flow control system). With these data, it is determined the minimum required number of pumps of the PS according to the classical method stablished. It is obtained by the relation between the flow of the system and the flow that one pump supply with the maximum total dynamic head required ($Q_{max}/Q_{b,hmax}$).

Once it is obtained the total number of pumps, it is determined the flow operational range of the pumping system. It is important to remind that the total number of pumps (N_{pumps}) determines the same number of operational ranges in the classic method. In this way, every operational range is set by the term *i,* where this term varies from 1 to N_{pumps} and every term of *i* determines the number of pumps in operation in every flow operational range. For example, if the number of pumps is three pumps, there are three operational ranges. In the first, second and third operational range there are one pump, two pumps and three pumps in operation respectively. In summary, this proposed methodology takes as reference the operational range of the classical method to analyze the optimal number of pumps and pumping configuration in every flow rate.

The next step is to set the number of pumps in study to the minimum required number of pumps. Since this point, it will be determined all the possible pumping configurations in operation with FSP and VSP. For example, in the first range of operation the only possibility of operation is 1 VSP. Conversely is not possible evaluate 1 FSP because it exceeds the requirements of the systems and could not follow the set-point curve. In the second range the possibilities are: 2 VSPs or 1 FSP with 1 VSP. Whereas, in the third range the possibilities are 3 VSPs or 1 FSP with 2 VSP or 2 FSP with 1 VSP. Then it will be evaluated the energy for every pumping combination in every flow rate and it is determined the minimum consumed energy.

Once it is analyzed the consumed energy with the number of pumps in study, it will be incremented in a unit pump the current number of pumps in study. With this increment of number of pumps, another time it is determined all the pumping combinations and evaluated the consumed energy in every flow rate. Then, it is the determined the minimum consumed energy.

If the minimum consumed energy with the current number of pumps is not incremented with respect of the last number of pumps, another time it is incremented in a unit pump the current number of pumps and the process is repeated. Nevertheless, if the minimum consumed energy of this increment of pumps is incremented with respect to the last number of pumps, the process is stopped, and the optimal number of pumps is the last number of pumps in study.

The next Figure 8 shows an example with a set flow how the consumed energy evolve as different pumping combinations are evaluated. As an example, it is assumed that the calculated number of pumps for a set pump model is three pumps, so there are three operational ranges. This Figure 8 shows different pumping combinations for the second range ($q_{b1} < q < q_{b2}$). For example, with a reduce flow ($q = 2.2$) is in the second range and the minimum required of pumps is 2 pumps and the possible combinations are 2 VSP or 1 FSP with 1 VSP. Then it is added 3 and 4 pumps in this flow and the possible combination that are evaluated are: 0 FSP + 2 VSP, 1 FSP + 1 VSP, 0 FSP + 3 VSP, 1 FSP + 2VSP and 0 FSP + 4 VSP. There are more pumping combinations for 4 pumps, such as 1 FSP + 3 VSP. However, this combination is not necessary to be evaluated because the combination 1 FSP+2 VSP is not the optimal and it is inferred that the combination

1 FSP-2 VSP will consume more energy. In summary, it is observed in the Figure 8 that the optimal pumping combination in energy terms for a flow ($q = 2$) is 0 FSP + 3 VSP.

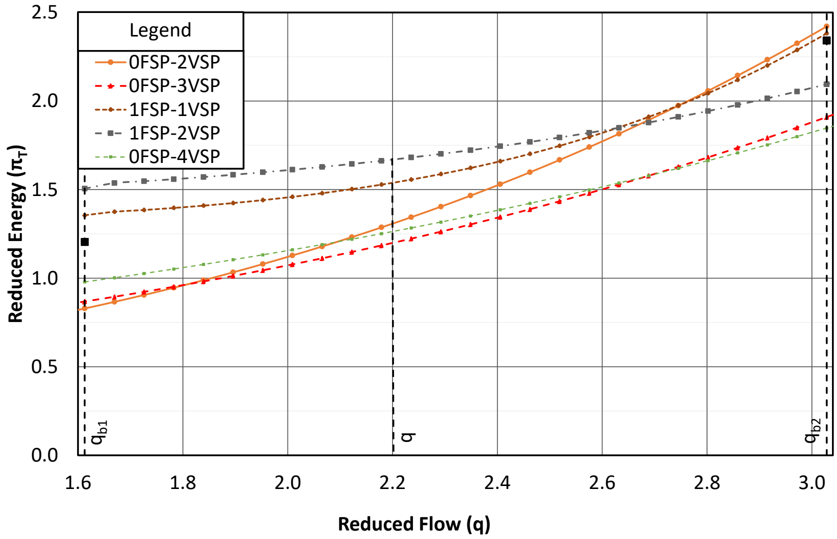


Figure 8, Example of how the consumed energy evolves with different pumping combinations with a set flow

3.3. Case studies

This paper considered two study cases to apply the methodology. The first case is TF Network, and the second case is E1 Network In order to design the pump station is necessary to set a pump model that supply the requirements of the network. The objective of this work is to determine the most suitable control system in energy terms, but this work does not approach in the selection of the pump model. Therefore, TF network and E1 network are not focused on the pump model selection. These case studies are only focused to analyze the optimal control system that could be obtained from a certain model pump. In this way, the pump models will be set in both case studies and then the optimal operational mode will be determined.

3.3.1. TF network

The information of TF Network are obtained from Leon Celi's work [11]. This network is composed by 4 PS and these PS are directly pumped to the consumers. The suction of the pump and the axis of the pump have the same level. Hence the suction head is 0. This study only obtained the values of the set point curve and the flow rates supplied from every supply source. In order to explain the process of the proposed method, it has selected the PS-4 of TF network as example. For the other PS of TF network the process is the same that it is going to explain in PS-4. The flow rates obtained in PS-4 vary 6.80 l/s (Q_{min}) to 33.50 l/s (Q_{max}) and the average demand flow (Q_m) is 17.2 l/s. Since several possible solutions of pump models for the pump station, it has been set a pump model to apply in the methodology. The characteristics of the pump model and the set-point curve in dimensional and dimensionless form are described by Tables 2 and 3.

Table 2. Characteristic terms of the pumping curve

Pumping Curve			
Characteristic Terms		**Reduced Terms**	
H_1 (m)	102.75	h_1	1.33
A $\frac{m}{(l/s)^2}$	0.2290	a	0.33
B	2	B	2
E	0.1228	e	1
F	$5.8 \cdot 10^{-3}$	f	2
Q_o (l/s)	10.59	q_o	1
H_o (m)	77.06	h_o	1
Q_{bmax} (l/s)	21.18	q_{bmax}	2
η_o (%)	65	θ	1
Q_{max} (l/s)	33.50	q_{max}	3.16
$Q_{b,hmax}$ (l/s)	11.27	$q_{h,max}$	1.06

Table 3. Characteristic terms of the set-point curve

Set-point Curve			
Characteristic Terms		**Reduced Terms**	
ΔH (m)	28.18	λ	0.3657
R $\frac{m}{(l/s)^2}$	4.05E-2	r	0.0589
c	2	c	2
H_{max} (m)	73.63	h_{max}	0.95

The minimum number of pumps required for this model pump in a classic system are three pumps. The operational ranges in a classic system are: $0 < q < q_{b1}$; $q_{b1} < q < q_{b2}$; and $q_{b2} < q < q_{max}$. These ranges of the classic system are used as reference to develop the proposed methodology.

3.3.2. E1 Network

The E1 network is conformed with one PS and three consumption nodes. This PS is directly pumped to the consumers. The suction of the pump and the axis of the pump have the same level. Hence the suction head is 0. The average demand flow is Q_m = 246 l/s and the maximum demand flow is Q_{max} = 312 l/s. This network has been chosen with two different objectives. The first one is to demonstrate that the application of the proposed methodology is valid regardless of the network considered. Furthermore, this is a methodology focused solely on the requirements of the PS. The second objective is to show how the selection of the pump model for a certain PS is associated with the definition of a different control system in each case. For this reason, in this network, three different models of pumps have been analysed and compared. These models were selected so that the required number of pumps in the classic system were three pumps. The parameters of the characteristic curves of these three pump models are described in Table 4. The behaviour of the E1 network from the PS point of view is defined by its setpoint curve. The parameters of the setpoint curve for this case are shown in Table 5.

Table 4. Characteristic values of each pump model

Pump Model	**A**	**B**	**C**
H_1 (m)	61.67	49.33	42.67
A $\frac{m}{(l/s)^2}$	0.0024	0.001	0.0008
B	2	2	2
E	$2.05 \cdot 10^{-2}$	$1.24 \cdot 10^{-2}$	$1.32 \cdot 10^{-2}$
F	$1.28 \cdot 10^{-4}$	$5.50 \cdot 10^{-5}$	$5.70 \cdot 10^{-5}$
Q_0 (l/s)	80	112.5	115
H_0 (m)	47	37	32
Q_{bmax} (l/s)	160	225	230
η_0 (%)	82	70	76
Q_{max} (l/s)	312	312	312
$Q_{b,hmax}$ (l/s)	113.39	136.43	119.26

Table 5. Setpoint curve of the pumping station of the E1 network

Parameter	**Value**
ΔH (m)	20.00
R $(m/(l/s)^2)$	$1.15 \cdot 10^{-4}$

3.4. Results and discussions

3.4.1. TF network results

The different alternatives of pumping configurations that are evaluated in reduced energy terms are the result of adding a pump to the minimum required number of pumps in every operational range of the classic system until get the optimal pumping configurations in energy terms. When the consumed energy of the current pumping configuration increase with respect of the last pumping configuration, it is not necessary to evaluate another configuration adding a pump because is implicit that the consumed energy of this configuration will be greater than the other configurations. Therefore, there are seven different pumping configurations evaluated that included:

1. Zero FSP with One VSP (0 FSP+ 1 VSP)
2. Zero FSP with Two VSP (0 FSP+ 2 VSP)
3. Zero FSP with Three VSP (0 FSP+ 3 VSP)
4. One FSP with One VSP (1 FSP+ 1 VSP)
5. One FSP with Two VSPs (1 FSP+ 2 VSP)
6. Zero FSP with Four VSPs (0 FSP+ 4 VSP)
7. Two FSPs with One VSP (2 FSP+ 1VSP).

These configurations evaluated in energy terms are represented in Figure 9.

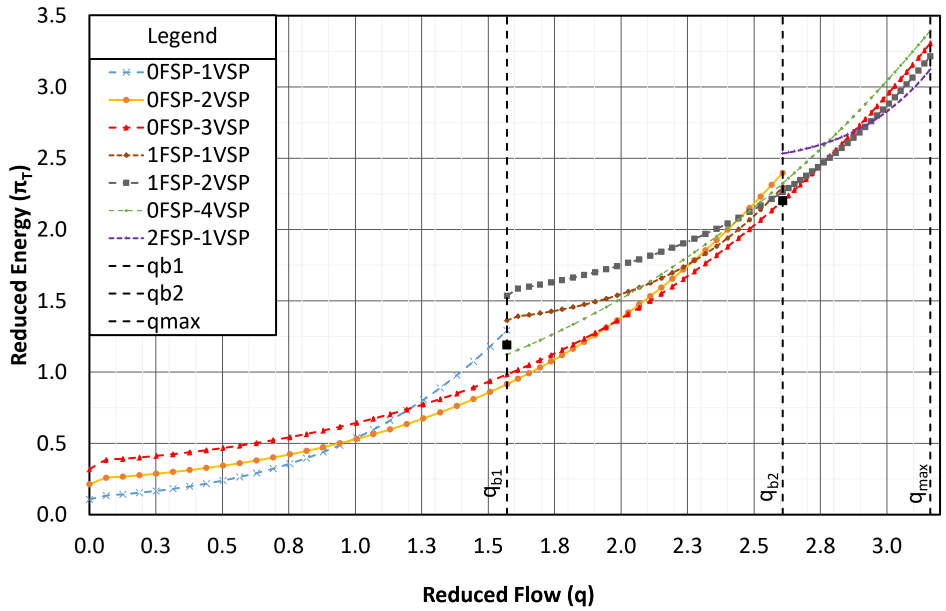


Figure 9. Consumed energy (πT) for different pumping configurations (TF Network)

The broken vertical lines in Figure 9 represent the limit flows of the operational ranges in the classy system. These limit flows in reduced terms are: q_{b1} = 1.57, q_{b2} = 2.61, and q_{max} = 3.16. Horizontal axis of Figure 9 represents the reduced flow rate (q) of the PS, whose values are from ($0 < q < q_{max}$). Vertical axis represents the reduced consumption power (π_T) of pumping configurations. These terms (q *and* π_T) are related to the BEP of the pump (Q_0 *and* P_0). The notation of the legends is defined as (n FSP + m VSP), where the terms *n* and *m* are the number of FSP and VSP respectively. Every legend illustrates the reduced power curve of the different pumping configurations.

There are some important points to highlight in the generated energy graph. There are jumps of energy when the pumping configuration change from zero FSP with one VSP (0 FSP + 1 VSP) to one FSP with one and two VSPs in operation (1 FSP + 1 VSP and 1 FSP + 2 VSP). Another energy jump is produced when the configuration changes from zero FSPs with two VSP (0 FSP + 2 VSP) to two FSPs with one VSP (2 FSP + 1 VSP). These jumps are produced because when a pump starts to work ($q = 0$), the consumed energy of a pump is not zero and the mechanical torque consume energy even though the efficiency of the pump is zero.

In the first range of the classic system ($0 < q < q_{b1}$), the configuration zero FSP with one VSP (0 FSP + 1 VSP) starts to be the optimal configuration until the range $0 < q < 1.01$. After this range the optimal configuration is zero FSP with two VSP (0 FSP+2 VSP) until the end of the first range ($1.01 < q < q_{b1}$). In the second classic range ($q_{b1} < q < q_{b2}$), the configuration 0 FSP + 2 VSP continues to be the optimal until the range $q_{b1} < q < 1.99$. Then the optimal configuration is 0 FSP+3 VSPs until the end of the second range ($1.99 < q < q_{b2}$). Finally, at the beginning of the third classic range $q_{b2} < q < q_{max}$, the configuration 0 FSP + 3 VSP continues to be the optimal configuration until the range $q_{b2} < q < 2.92$. At this point, the optimal configuration change to 1 FSP + 2 VSP the reduce flow reaches the value of 3.03. Finally, if this reduced flow continues growing, the optimal configuration change to 2 FSP + 1 VSP until the maximum demand flow (*3.03 < q <* q_{max}).

Is important to mention that is not necessary to continue increasing the number of pumps. For example, when the flow is q_{max}, the configuration 0 FSP + 4 VSP is not the optimal. If it continues to increase the number of pumps of pumps to 5 pumps, all the combinations of 5 pumps will increase the consumed energy. In fact, it is not necessary to evaluate other combinations of 4 pumps, such as 1 FSP + 3 VSP, 2 FSP + 2 VSP or 3 FSP + 1 VSP because it is inferred that the consumed energy of these combinations will be greater than the optimal configuration in this q_{max} that is 1 FSP + 2 VSP.

3.4.2. TF network discussion

The Table 6 shows a resume of the optimal number of FSP and VSP in operation for every flow range, and Figure 10 represents the number of operating pumps (N_{pumps}) in relation to the demand flow rate (q). As it can see in this figure, the shape of the graphic of N_{pumps} has several steps. Every step represents the limit range of the number of pumps in operation and the vertical lines in the figure represents the flow limits of the operational ranges in the classic system. Even though Figure 10 shows three steps but, the proposed system has five different operational ranges or pumping configuration because in the range of three pumps there are changes on pumping configuration. For example, in this range the configuration change from 0 FSP + 3 VSP to 1 FSP + 2 VSP and finally to 2 FSP + 1 VSP.

In the last Figure 9 can be appreciate when the demand flow (q) is close to the limit operational flow (q_{max}), the configurations that combines FSP and VSP tend to get better results in energy terms than configurations using only VSP. Therefore, the performance of the frequency inverter affects in a significant form the global efficiency of VSP, so these pumps consume more energy than FSP.

Table 6. Resume of the optimal pumping configuration

	Optimal pumping configuration		
Flow range	**No. FSP**	**No. VSP**	**No. pumps**
0 < q < 1.01	0	1	1
1.01 < q < 1.99	0	2	2
1.99 < q < 2.92	0	3	3
2.92 < q < 3.03	1	2	3
3.03 < q < 3.16	2	1	3

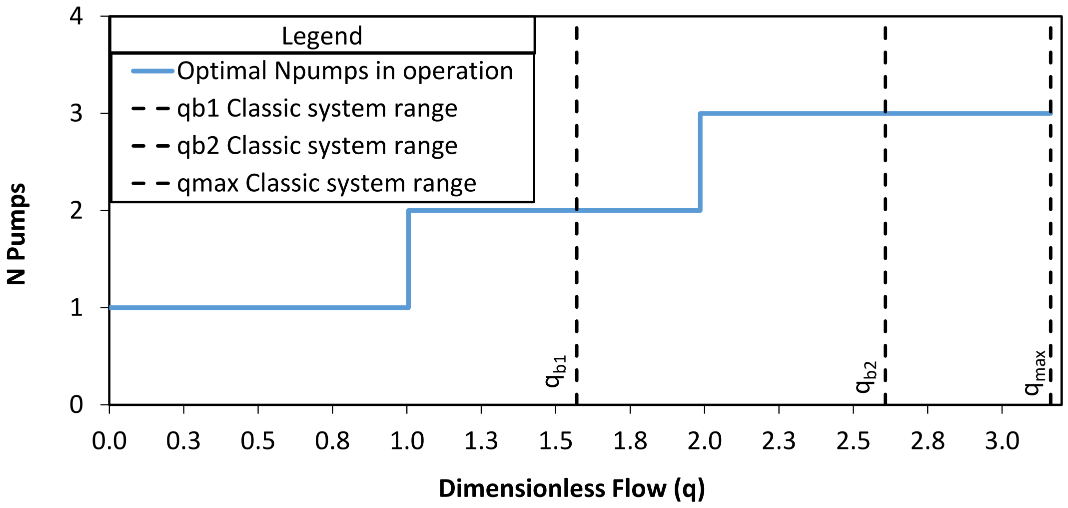


Figure 10. Optimal Number of pumps

Therefore, both systems (classic and proposed) have different operational ranges but have the same total number of pumps requires for the design of the PS. Besides, the limits of the flow ranges are not the same in both systems. For example, the changes of number of pumps in operation from one to two pumps and from two to three pumps take place before than the classic system. Therefore, the operational mode of this proposed system is different than the classic system and leads to energy savings.

In summary, in the first case study (TF Network) the total number of pumps is three pumps that is the same as classic system. However, there are more changes of pumping configurations than the classic method. In fact, there are 5 different optimal pumping configurations throughout the range study ($0 < q < q_{max}$), while the classic method has three different pumping configurations in the range study.

3.4.3. E1 network results

The methodology proposed in this work performs the energy analysis using reduced variables. For this reason, Tables 7 and 8 shows the dimensionless values of both the characteristic parameters of the pumps and the characteristic values of the set-point curve. It should be noted that the three pump models have the same dimensionless shape of their head and efficiency curves. Therefore, their values in reduced variables are the same. The reduced values of the characteristic curves of the pumps are: $h_1 = 1.33$, $a = 0.33$, $b = 2$, $e = 1$, $f = 2$ and $q_{b.max} = 2$. Obviously, there are values that are different depending on the pump model. The maximum flow to supply is fixed. However, the value of the maximum reduced flow (q_{max}) will be different in each model since the reduced variables are defined based on the BEP. Likewise, the reduced flow supplied by each pump model will also be different when the head is equal to the maximum required by the setpoint curve ($q_{b,hmax}$).

Table 7. Reduced Values of the different pump models

Pump Model	A	B	C
q_{max}	3.90	2.77	2.71
$q_{b,hmax}$	1.42	1.21	1.04

Table 8. Reduced values of the set-point curve for each pump model

Pump Model	A	B	C
λ	0.42	0.54	0.62
r	0.015	0.039	0.047
h_{cmax}	0.66	0.84	0.97

In order to present the application of the methodology, Figure 11 shows an example of the results in the case of using Model A. The horizontal axis is represented the dimensionless flow (q) of the total rage ($0<q<q_{max}$). Whereas, the vertical axis represents the dimensionless total consumption power (π_T) of the pumping configurations. These terms (q *and* π_T) are related to the BEP of the pump (Q_0 *and* P_0). The evaluation of the consumed energy for each pumping flow can be observed with different control configurations. These different control settings are determined by the number of FSP and VSP. In the case of FSP, the pumps that are running rotate at their nominal speed, while the VSP adjust their rotation speed in such a way that the operating point is adjusted to the setpoint curve. As it can see in Figure 11, there are nine different curves of reduced energy of the different pumping configurations evaluated for the pump model A. There are three limit operational flows in the classic system represented by vertical broken lines in the figure 6. These flow limits are: q_{b1} = 1.61, q_{b2} = 3.02 and q_{max} = *3.16.*

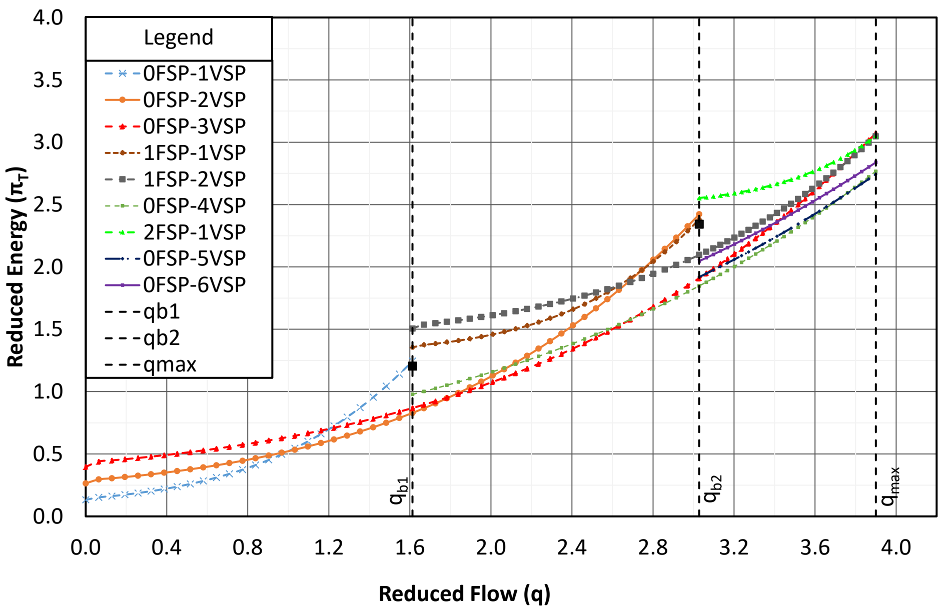


Figure 11. Consumed energy (πT) for different pumping configurations (Model A)

3.4.4. E1 network discussion

The optimal numbers of FSPs and VSPs obtained in every flow rate for the three different pump models analysed are defined by the Table 9. This table illustrates the results obtained with each model have different configuration control system.

Table 9. Optimal number of FSD and VSD pumps for different pump models

Model A			Model B			Model C		
Flow range	FSP	VSP	Flow range	FSP	VSP	Flow range	FSP	VSP
0 < q < 1.03	0	1	0 < q < 1.17	0	1	0 < q < 1.25	0	1
1.03 < q < 1.84	0	2	1.17 < q < 2.15	0	2	1.25 < q < 2.10	0	2
1.84 < q < 2.75	0	3	2.15 < q < q_{max}	0	3	2.10 < q < 2.33	1	1
2.75 < q < 3.76	0	4				2.33 < q < 2.59	0	3
3.76 < q < q_{max}	0	5				2.59 < q < q_{max}	1	2

The proposed configuration system mode for the second and third pump model is similar to the classic system because the total optimal number of pumps are three pumps as it is established in the classic system. Whereas, in the first pump model the optimal number of pumps are five pumps that are more than the minimum required of the classic system. Another important point to highlight is the optimal head (H_0) of the first model pump that is further away to the maximum head of the set-point curve (H_{cmax}) than the optimal head (H_0) of the second and third model, where H_0 is close to H_{cmax}. The optimal number of pumps in every flow range of the three different model pumps can be visualized in Figure 12. Because of the three model pumps have different BEPs and the reduced flow rate is in relation of the nominal flow (Q_0), the maximum operating limit (q_{max}) of the three model pumps have different values.

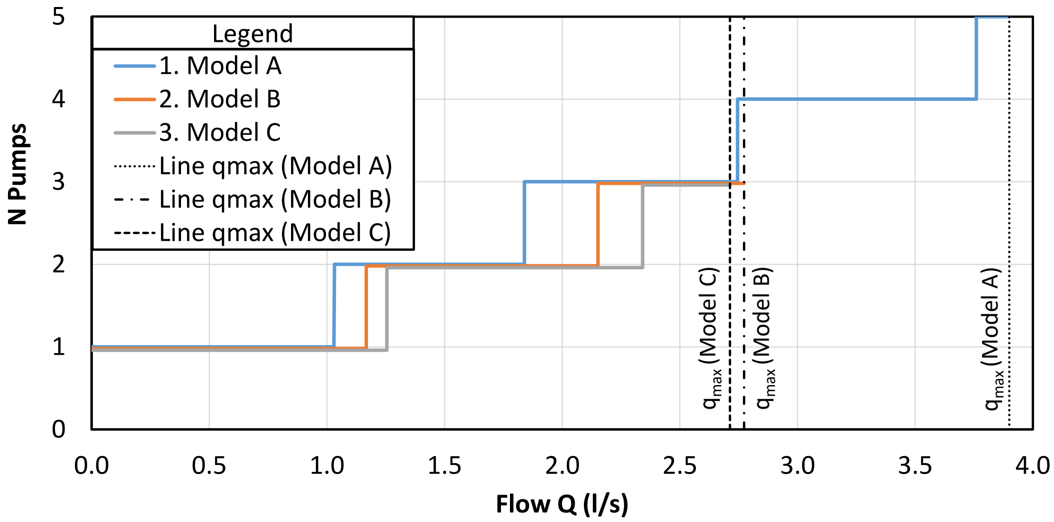


Figure 12. Comparison of optimal number of pumps for the different pump models (E1 Network)

Even though, that the total number of pumps of the optimal configuration of pump A model has more pumps than model B and C, the optimal configuration of model A consumes less energy in all flow rates than the others pump models. It is corroborated in the Figure 13. This figure compares the consumed energy of the optimal pumping configurations of the three model pumps analysed. It is important to mention that the consumed energy (P_T) and flow rate (Q) have to be represented dimensional form to compare the consumed energy of the optimal configuration of the three model pumps in a better way. Since the flow rates in dimensional form (Q) are the same for the three model pumps, but the flow rate in a dimensionless form (q) are different for the three pumps because the variable (q) is in function of the BEP and the three pumps have different BEP.

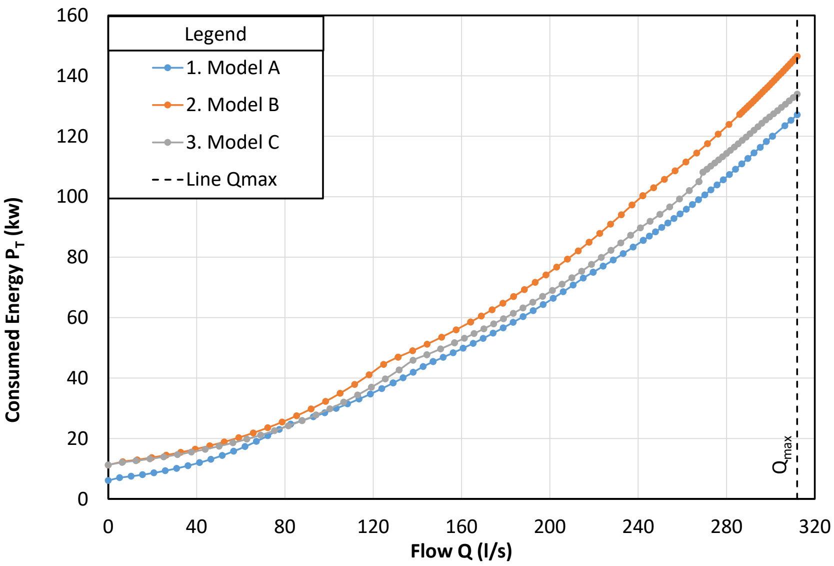


Figure 13. Comparison of consumed energy of different pump models configurations (E1 Network)

In summary, E1 network was analyzed using both systems and three different pumps. One model pump of the three studied it was obtained that the total number of pumps in the proposed system was greater than the classic system and also gets an energy saving in comparison with the classic system.

3.5. Conclusions

Much of the scientific research on pump scheduling takes, as starting point a number of pumps previously set according to the classic system operation. This assumption could lead to not achieving the optimal result in terms of energy consumed in the PS because it has not been optimally designed. Another limitation presented by some studies on the operation of PSs is they do not consider the effect of the performance of the frequency inverters on the global efficiency of PS when a VSP changes its rotational speed. In the best case it is assumed a constant efficiency of frequency inverter on the global efficiency. This may generate inaccuracy to determine the consumed energy of these pumps and it affects the PS global energy consumed. Therefore, the propose of this present work is to discuss the classic system operation determining the optimal number of pumps for every flow rate so that the consumed energy be optimal. Another contribution of this work is to consider that the efficiency of the frequency inverters of the VSP varies depending on the load. In this way, the determination of the global energy optimum takes into consideration the efficiency of these devices.

The discussion about the classic operating system of a PS is relevant since different operating rules lead to lower energy consumption. Besides, it is important to analyse the optimal number of pumps for every flow rate because it determines the total number of pumps in an optimally PS design.

This study has accomplished to develop a methodology that analyse how the pumping curve and the set-point curve influence the determination of the optimal number of FSP and VSP for each flow rate. The main idea of this methodology was to express the set-point curve and the pumping curve in a dimensionless form in relation of the BEP of the pump so that the methodology be more systematized to analyse different case studies. In this way, several pumping configurations are added and evaluated in energy terms to obtain the configuration with the minimum consumed energy.

The results obtained in both study cases has allowed to conclude that the performance of frequency inverter has a great influence in the global efficiency of a VSP, especially when the demand flow is close to the limits of the classic operational ranges (q_{b2}, q_{b3}, q_{max}). In fact, there could be cases where the consumed energy on VSP is higher than FSP. Therefore, a combination of FSP and VSP consume lower energy than a configuration only with VSP.

The number of FSP and VSP in operation cannot be inferred in a simple form as commonly do in the classic system. It requires a deep analysis on the control system, where the optimal number of pumps depends on several factors such as: the BEP of the pump, the energy losses on the set point curve and how far or close is the optimal head of the pump to the maximum head of the set point curve. For example, the optimal configuration of the pump of TF network and the second and third model pump of E1 network resulted that the total optimal number of pumps are the same to the minimum required pumps in the classic system. Even though, the optimal number of pumps in the first model pump of E1 network are more than the minimum required in the classic system.

Furthermore, the minimum required of pumps of a pumping system is not necessary the best option in energy terms. In fact, the first pump model of E1 network has an optimal number of pumps greater than the second and third pump model, and at the same time this first pump model is the best option in energy use. In summary, the total number of pumps associated to a pump model in a PS is not necessary a decisive factor to determine the best alternative in energy terms, but it requires a deep analysis in the control pumping system configuration.

One limitation of this proposed methodology is that the set-point curve expression adapted to closed networks. However, the general procedure of this methodology is similar to networks with storage system. Another limitation is that the pumping curve, pump efficiency curve and set-point curve were adjusted in exponential expressions. Even though, this methodology is valid to be applied in any case study of PS designs. Furthermore, the expression of frequency inverter efficiency was adjusted according to experimental works that were previously mentioned in the methodology section. However, this expression is still valid to be considered on the analysis of PS operation.

Future research will be to develop a methodology to select the most suitable pump model for a PS design including this new proposed control system operation. Besides, it will be considered investment cost, operational cost and maintenance cost in order to design appropriately a PS.

Chapter 4. Design of PS considering technical and economic aspects based on the AHP

The second phase of this thesis is the development of a PS design methodology considering technical and economic criteria in a comprehensive form. The objective of this phase is to select the most suitable pump model and pumping configuration for a PS design based on a MCDA. The criteria considered in this first PS design approach are technical (e.g., number of pumps, complexity of the control system) and economic (e.g., investment, operational and maintenance costs). In this way, this proposed methodology of PS design was presented in a technical paper and published by Water Journal of MPDI. The reference of this paper is:

> Briceño-León, C. X., Sanchez-Ferrer, D. S., Iglesias-Rey, P. L., Martinez-Solano, F. J., & Mora-Melia, D. "Methodology for Pumping Station Design Based on Analytic Hierarchy Process (AHP)." Water, vol. 13, no. 20, pp. 2886, 2021.

This paper developed a general methodology for PS design considering multiple decision criteria (i.e., technical and economic) based on the AHP method. The decision criteria of the AHP method are constructed in a hierarchy form. In this way, the fist level criteria are Technical and Economic criteria. The second level criteria or sub-criteria are the number of pumps and the complexity of PS control system, investment cost, operational cost, and maintenance cost. An important aspect of this method is that the priorities of the criteria and sub-criteria are obtained by the evaluation of a group of experts. In addition, these obtained priorities were weighted with their consistency. The purpose of considering the consistency index to assess the priorities of the criteria is to improve the reliability of evaluation in the methodology.

This proposed methodology of PS design consists of three stages. The first stage is related with the required data for the design of PS, such as database of pump models, the set-point curve of the network, the demand pattern, and data base of purchase and installation costs of the elements in a PS. The second stage consists of determining the feasibly pump models according to the conditions of the WDN. Then, the number of pumps of every feasible pump model is determined. In addition, every feasible pump model were combined with the feasible control system configurations. In this way, several possible solutions are obtained for the PS design. In every possible solution were evaluated in every one of the five sub-criteria considered for the design. In the third stage, these solutions are subjected to a Pareto Front. In this phase the dominated solutions are discarded, while the dominant solutions are considered as potential solutions for the PS. These potential solutions are scored in every one of the sub-criteria to obtain the overall score of the potential solutions based on the AHP. Finally, the solution with the highest score is chosen as the ultimate solution in the PS.

This paper presented several case studies to apply the development of this methodology. The case studies show the ultimate solution in every PS and the overall ranking of the potential solutions with their respective score in every one of the criteria. In addition, this approach of PS design was compared with a classic PS design (i.e., LCC minimization) to analyze the effect of considering technical criteria in the design process.

4.1. Introduction

PS are fundamental elements in water distribution systems and represent one of the largest components on the water networks operation's operation budget. In fact, approximately 85% of energy consumption in water networks are from PS operation [85]. The total costs in water network designs are mainly composed by capital costs and operational costs. Capital costs are associated with investment and installation costs, while operational costs are associated with energy consumed and network maintenance costs [86].

Usually, PS designs are focused to minimize operational costs and satisfying the requirements of the total dynamic head (*H*) and demand flow (*Q*) of the water network. The total dynamic head is the head required for the pump to supply the flow to the system nodes with the required pressure. This head includes the suction head, static head, head losses produced by piping system and the required pressure by consumption nodes. The first step for a PS design is selecting the pump model from the maximum network requirements (H_{max}, Q_{max}). Next, the control mode of the PS is established. For example, several research have carried out to optimize energy costs in PS through mathematical pump scheduling models. The main mathematical methods applied to solve these problems are: linear programming [87], no lineal programming [68], dynamic programming [23]. These pump scheduling problems start from a fixed pump model and a fixed number of pumps and consist of finding the optimal values of decision variable. In this case, the decision variables are the state of the pumps (on/off) at each time interval to minimize the power consumption of the PS. These methods were used to optimize different types of pumping system: with one or several pumps, with or without storage tanks. One limitation of these methods is their computational efficiency since they require high computation time to find the optimal solution. Other algorithms with better computational efficiency in solving pumping scheduling problems are GA [88]. In addition, these algorithms could have other decision variables, such as the rotational speed of the pumps in each every time interval [34].

Other works have developed different PS design strategies using multi-objective algorithms. These works optimized energy consumption and other important aspects, such as water storage and water network resilience. For example, Abdallah and Kapelan [38, 40] developed an iterative methodology to optimize the energy consumed by FSP and variable speed pumps VSP. They also considered the minimization of maintenance costs by relating these to the switching frequency of the pumps. In a similar way, Luna et al. [39] improved the energy efficiency of a PS in a water distribution system by optimizing the pump operation schedule and considering aspects, such as the water storage risk. Alternatively, Carpitella Silva et al [42] optimized energy consumption of a PS and minimized the required pressure service in a water network using genetic algorithms and multi-criteria analysis. The limitations of these works are: the PS were previously designed, they do not consider the selection of a suitable pump model, and they do not study the efficiency of the PS control system.

On the other hand, León-Celi et al. [77, 78] delved into the operation of PS. They developed a methodology to optimize operational water production costs using the concept of set-point curve and considering the pump operation math always this curve. In this way, the PS consumes the minimum required energy to satisfy the head and demands requirements at the network consumption nodes. In a similar way, Briceño-Leon et al. [89] developed a methodology that determines the optimal number of pumps and their control mode in order to minimize the energy consumption of the PS.

Moreover, there are other research of PS systems that aims to analyze and minimized economic aspects including investment, maintenance, and operational costs. For instance, Mahar and Singh [90] developed an optimization model for pumping system designs minimizing the total annual cost of the network. The costs considered in this work were piping system cost, pumping unit cost, maintenance, and operational costs. Piping and pumping unit costs were based on expressions developed by Bhave [91]. In a similar way, Nault et al. [44] implemented a methodology to evaluate the life cycle cost, the net present value of PS, but also they considered CO_2 emissions analyzing different scenarios, such as installing a flow regulator valve and implementing VSP in the PS. Alternatively, Walski and Creaco [45] compared the total annualized cost of PS including capital costs and operational costs for different pumping configurations including FSP and VSP. The capital costs were determined as described by Walski [92]. These configurations are analyzed with different scenarios of demand flow and total dynamic head required. Then, Diao et al. [46] analyzed the impacts that a design and operation of a water distribution system could have with different flow design scenarios, such as uniform demand pattern and spatial-variant pattern cand considering LCC. Finally, Martin-Candilejo et al. [47] proposed a methodology to design a water supply system efficiently through optimizing construction and operation costs when there is a variation of the type of demand. This methodology was based on an equivalent flow rate and equivalent volume to optimize the computational calculation process.

The problem of these previous research work is that they do not develop a methodology to select a suitable pump model for the PS. In fact, most of these researches set a pump model and set the number of pumps in arbitrary form. Designers of water pumping systems are usually focused to analyze operational cost, capital cost or LCC and satisfy the requirement of the network. However, the analysis costs in an engineering project design could be complex to assess because it intervenes other variables, such as life cycle, interest rate, and amortization factor. Other important aspects such as technical factors including the number of pumps, the control system mode, and the complexity of operation are not deeply studied or analyzed in a PS design. These parameters are set according to the criterion or experience of the designer. Besides, these aspects could give different alternatives of design in a PS system and could have opposite interest with economic factors. Therefore, it is imperative that stakeholders of the design use a multicriteria decision analysis to select the most suitable alternative of pump model in the pumping system. In summary, a proper design of PSs is important to consider economic aspects, such as capital and operational costs, but also it is important to contemplate technical aspects including the number of pumps and the complexity of the control system operation.

A multi-criteria decision analysis is used to select the best alternative from different options in a make decision problem. This analysis consists on evaluating several possible alternatives to solve a problem considering different criteria that could have opposite interests [93]. The most common multi-criteria analysis is the AHP developed by Saaty [15, 94].

The AHP method has been widely used in business, industrial, government and management fields [95]. This method has also been applied in civil engineering fields to face decision making problems. For example, Ahmed et al. [96] use the AHP method for a design of high performance concrete mixtures., Al-barqawi and Zayed [97] demonstrated that a rehabilitation plan for water networks could assess their condition based on the AHP method. Aschilean et al. [98] scientifically solved the selection of the type of pipe rehabilitation technology in a water distribution system. Furthermore, Karleuska et al [99] developed a methodology to establish priorities in implementing irrigation plans in different areas using the AHP method. The criteria used in this work were: environmental protection, water-related, social, economic and time aspects. In order to determine the coherence of the ranked criteria, they were analyzed through a consistency index (CI) developed by Saaty [100]. This analysis provides better reliability to implement irrigation plans. In addition, another example where AHP was used in an engineering analysis is a method to determine the resilience of water surface suitability developed by Ward et al. [61]. This model helps to guide future water infrastructure projects to improve climate resiliency of a studied region.

This proposed work aims to demonstrate that a PS of water network can also be designed through a multi-criteria analysis (AHP method) and not only based on economic aspects to decide the most optimal solution. The main contribution of this methodology of PS design is to deep the analysis of the design evaluating the importance priority of technical aspects (the number of pumps and the complexity of operation of the system) and economic aspects (investment, operational, and maintenance costs). The definition of these aspects, especially with technical aspects are not absolute and depend on the criteria of the stakeholder of the PS design.

In general, most of the previous works of pumping station aims to minimize energy consumption or optimize the total LCC. In addition, these optimizations are based on a set pump model and a fixed number of pumps. These last aspects lack a deep analysis of how to assess them. Therefore, the proposed methodology uses the AHP method is to define the importance priority of the aspects considered in the PS design (technical and economic factors). Finally, this methodology allows determining the most suitable solution in the PS according to the assessment of the importance priority of the considered criteria.

4.2. Materials and methods

4.2.1. Problem statement

The process of selecting pumps for a pumping station is difficult. Apart from other aspects, the first step consists of determining the design point. The pumping station must provide the maximum required flow (Q_{max}) and the corresponding maximum head (H_{max}). At this point, two different variables must be considered: model of the pump and number of them. The variation of the pump efficiency with flow and the different operating conditions conditioned both the pump model and the number of pumps.

The traditional approach of pumping station design starts selecting the pump model. Once the model is established, the number of pumps is obtained by dividing the maximum required flow (Q_{max}) by the flow a single pump (Q_{b1}) would deliver at the maximum head H_{max}. Hence, if the pump model is known, the design of the PS would be completely defined. However, there is no bi-univocal relationship between these two variables (model and number of pumps). In some occasions, the number of pumps is initially fixed. In this latter case, there will be several models that can be installed in the PS. The selection will depend on other factors as expected efficiency, required automation and other operating conditions. The method presented in this work is aimed to select the best combination of number of pumps and pump model according to different criteria. These criteria will be assessed using the AHP.

León-Celi et al. [78] defined the setpoint curve as a theoretical curve that points out the minimum energy required on source points (storages and pumping stations) to meet the minimum pressure required in each demand in the network. As consequence, the consumed energy in PSs will reduce as the pumping curve is as close as possible to the setpoint curve. A suitable control system allows the operational points of the pumps to be close to their optimal operating points. The control system is based on the combination of FSP and VSP, and on measurements of pressure and flow. These configurations of control are regulated according to network demands. In the general case of having both FSP and VSP, FSP supplies the highest demanded flow at the head of the setpoint curve while VSP supplies the remaining flow to adjust to the setpoint curve. In addition, this pump operates at the correspondent rotational speed following the setpoint curve [101]. Depending on the type of pumps and the controlled variables it is possible to define up to seven different control systems. Detailed information of them can be found in the Appendix section.

The impact of the number of pumps in the design of the PS is important. Usually, this parameter is arbitrarily established but some elements of the PS are defined from this criterion. The proposed methodology intends to minimize this impact. In this way, different pump models from a database are evaluated. Then, pump models that best fit the network conditions are evaluated with different control system strategies. Together with the technical aspects, other important aspects such as investment, operational, and maintenance costs are considered to select the most suitable pump model in the design. Hence, both technical and economic aspects are evaluated in this method.

In summary, this methodology considers two levels of criteria. Technical and economic factors are considered as first-level criteria. Technical factors are divided into two sub-criteria: the number of pumps and the complexity of the control system. On the other hand, economic factors are divided into three sub-criteria: investment, operational, and maintenance costs. In general, all these five aspects or sub-criteria are considered as second-level criteria. A rating of alternatives is established for each criterion. It means an absolute measurement of the alternatives in each criterion. The assessment of every alternative is compared with a set ideal assessment value. This ideal value is the best assessment value in each criterion [102].

Therefore, the main objectives of this methodology are determining the importance weight in every criterion and sub-criteria and an overall rating of the alternatives to select the most suitable pump model in the PS design.

4.2.2. Required data for pumping station design

To design a pumping station, some information should be provided. It is not part of this work to discuss the origin of these data and they are assumed as known. Next, a brief description of the assumptions is presented. The hypothesis is related to the needed information to design a PS. These data are:

1. Basic scheme of a PS
2. Set-point curve of the network
3. Demand patterns
4. Parameters of the pumping curve
5. Electric tariffs
6. Database of costs of the elements in a PS
7. Different configurations of the control system

This methodology is focused only on PSs that are directly injected into the network and with pumps coupled in parallel. Also, it is considered the suction head of the PS is zero. It is assumed the number of pumps in the PS are of the same characteristic. In addition, the control system operation is based on conventional PS operation (explained in chapter 3).

1. Basic scheme of a PS: Iglesias-Rey et al. [103] proposed a basic scheme of a PS (Figure 14). This scheme includes a backup pump to guarantee the reliability of the PS. The scheme is defined by three characteristic lengths (L_1, L_2 and L_3). These lengths are considered proportional to the nominal diameter of the pipelines (DN_i) through a factor fn_i as shown in equation (24). It was also assumed that the diameter DN_i was calculated from the maximum required flow (Q_{max}) and a maximum design velocity of 2 m/s.

$$L_i = fn_i \cdot DN_i \tag{24}$$

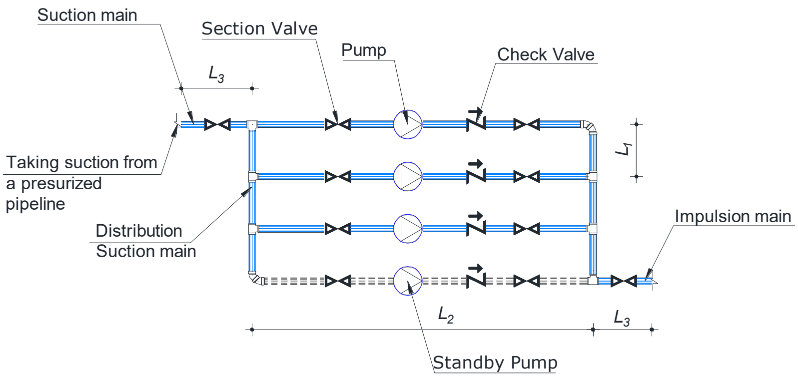


Figure 14. The basic scheme of a PS

2. Set point curve of the network: The setpoint curve represents the total dynamic head required (H_c) for each required demand flow (Q) of the network to satisfy consumption nodes. This curve is defined as the total dynamic head needed by the pump station to supply the demand flow and maintaining the minimum pressure required at the critical consumption node of the network [77]. Usually, the setpoint curve can be written as in equation (25):

$$H_c = \Delta H + R \cdot Q^c \tag{25}$$

In this equation, the term ΔH refers to the static head adding the minimum required pressure of the consumption nodes, R is associated with the energy losses in the system and c is an exponent that depends on the characteristics of the system. The terms R and c can be obtained from a regression adjustment of values of the setpoint head (H_c) and its corresponding demand (Q, H_c).

3. Demand patterns: Demand patterns correspond to the variation of consumed flow in a period (day hour, weekday, year season).

4. Parameters of the pumping curve: To select a pump, it is accepted that there is a list of available commercial pumps. Each pump model is defined by the BEP, that is, nominal rotational speed (N_0), nominal flow (Q_0), nominal head (H_0), nominal efficiency (η_0) and the parameters used to describe the curves of the pump (H-Q and η-Q). Relation among these variables are used as follows.

$$H_b = H_1\alpha^2 - \alpha^{(2-B)}A \cdot \left(\frac{Q}{b}\right)^B \tag{26}$$

$$\eta = E \cdot \frac{Q}{\alpha \cdot b} - F \cdot \left(\frac{Q}{\alpha \cdot b}\right)^2 \tag{27}$$

$$\alpha = \frac{N}{N_0} \tag{28}$$

$$P_{T,t} = \sum_{i=1}^{n} \frac{\gamma \cdot Q_{FSP,i} \cdot H_{b,i}}{\eta_{FSP,i}} + \sum_{j=1}^{m} \frac{\gamma \cdot Q_{VSP,j} \cdot H_{b,i}}{\eta_{VSP,j}} \tag{29}$$

$$E_T = \sum_{i=1}^{h_T} P_{T,i} \cdot h_i \tag{30}$$

In equations (26), (27)and (28), the terms H_1, A, B, E and F are coefficients that characterized the pump; the term b is the total number of pumps of the PS; and the term α is the relation between the current rotational speed (N) and the nominal rotation speed (N_0). In equation (29), the term $P_{T,i}$ is the total consumed power by the PS in every period t; γ is the specific gravity of the water; $Q_{FSP,i}$ is the flow of every FSP; $Q_{VSP,j}$ is the flow of every VSP, $H_{b,i}$ the head of pump i; and n and m are the number of FSPs and VSPs respectively. Finally, in equation (30) the term E_T is the total consumed energy by the PS in a day, h_t is the period duration and h_T are the 24 hours in a day.

5. Electric tariffs: Electric tariffs are managed by companies that provide energy service to the users. These tariffs could be different in a period of a day, year, season or could not have any kind of variation. This work contemplates three different electric tariff hours: peak hours, off-peak hours and plain hours, and two seasons: summer and winter.

6. Database of costs of the elements in a PS: In addition, every element of a PS, such as pumps, pipes, valves, control elements and other accessories has a database with its commercial costs including the installation costs.

7. Configurations of control system: Seven different modes of control systems have been used in this work based on two aspects. The PS may content FSP, VSP or a combination of both. Besides, measurements devices may supply readings for pressure only (PC), flow (FC), or with NC [101]. Table 10 described the required equipment of every control system. For a detailed description of these control systems, reader can find *t* The operational modes of these seven configurations of control system are detailed in the appendix section of this document.

Once the information for PS designs is obtained, the parameters of characteristic elements for every pump model (the total number of pumps (*b*), number of FSP (*n*), number of VSP (*m*), and the regulation mode) must be defined.

Every pump model of the database is considered, but only those models that meet the requirements of the water network are selected for evaluation. In this way, if the maximum head of the pump (H_1) is higher than the maximum total dynamic head of the set-point curve ($H_{c,max}$), the pump model is suitable for selection. Otherwise, the pump model is not viable, and it is discarded. Then, it is defined the total number of pumps (b_i) of every viable pump model needed to satisfy the maximum demand flow (Q_{max}). As a result, several alternatives with different pump models and number of pumps are selected for further evaluation using the AHP. The criteria used in the AHP is described in detail below.

4.2.3. Definition of the techno-economical criteria

The classic design of PS is carried out in three stages: site, pump selection and final design. The initial part (site) includes the analysis of the PS needs and the determination of head and design flow requirements. The second includes the calculation of the system curve (set point curve), and the selection of the pumps that best approximate this curve. The third includes the design of the infrastructure, the electrical installation and the installation of the control system and the selection of its components.

The PS design problem could initially be evaluated from an economic point of view. However, it is extremely complex to economically value all the elements involved in a PS project. There are many factors that are not usually considered such as civil works, electrical installation, the environmental impact on the surroundings or the space required for the project development. Thus, some authors (Jayanthi and Ravishankar [14]; Murugaperumal & Raj [104]; Vilotijevic et al. [105]; Naval & Justa [52]; Liu et al. [53]) define the need for a technical-economic approach to the design of facilities of this type.

This work focuses on considering two fundamental technical aspects: the size of the PS and the complexity of the control system. Three economic aspects are also considered: investment costs, operating costs and maintenance costs. The need for each of these is justified below.

Some US Army Corps [13] guidelines for PS design define the configuration and space required for a PS are determined by the distances between the different equipment and the space requirements of facilities such as access for personnel or the minimum space required for maintenance. This fact, together with the need to consider aspects such as civil works costs, electrical installation costs or the environmental impact of the work, led to the selection of the number of pumps as one of the technical criteria used in the proposed methodology. Moreover, the number of pumps is directly related to a large part of the equipment required in a PS and not defined in the diagram in Figure 14: the air valves or drains required for filling and emptying the installation, the air release valves that eliminate accumulated air bubbles and the structural elements for fastening the elements.

One of the essential parts of a PS project is the design of the electrical requirements. There are many electrical requirements to be considered: the electrical panels, the electrical protections associated with each pump, the layout of the electrical conduits, the power supply of all the measurement and control elements and their corresponding protection systems. The greater the complexity of the control system, the higher these costs are.

In addition, the current trend is for most of the PS to be monitored by some kind of SCADA system [49]. SCADA systems are a rapidly evolving field with increasing complexity due to the need for communication. The cost-functionality ratio in these systems is progressively increasing. SCADA systems are built over time and can become complex due to the different feature sets, connectivity, programming, and technical support of the various components. In short, there are several hidden costs associated with the complexity of the control system and SCADA. These include the difficulty of maintaining and troubleshooting; the need for increased skills and training needs of operators, maintainers, engineers, and programmers; multiple vendor support contracts; ongoing difficulties in trying to get incompatible equipment to communicate with each other; protocol adaptation needs; and even cybersecurity issues. In short, the increased complexity of the PS regulatory system carries with it a whole range of potential hidden costs that are not directly reflected in the PS budget. For this reason, this has been one of the technical criteria selected in the proposed methodology.

On the other hand, in relation to the economic aspects, it must be considered that investment, maintenance and operating costs have different time bases. There are economic approaches to be able to add up all these concepts. For example, the use of the amortization factor makes it possible to reduce investments to annual costs, using for this purpose the life cycle period of equipment and an interest rate. The first can be different according to the criteria used by the designer. The second can vary significantly over time. Thus, the result of the application of this technique will depend on the selected parameters. That is, different values of the amortization period and interest may generate different solutions to the problem. An alternative solution to this would be to treat each cost as a different criterion and define the weight of each criterion in the final solution. This is the purpose of the methodology used in this study, which considers three separate economic criteria.

In short, the criteria for PS design are organized into two levels. The first level classifies criteria depending on its nature: technical factors and economic factors. Every factor or criteria are divided into several sub-criteria of the same type. For instance, technical factors (TF) include:

the number of pumps (C1) and the complexity of control system (C2). The economic factors (EF) are: investment (C3), operational (C4) and maintenance costs (C5). The criteria and sub-criteria are assessed by a group of experts to determine the importance of each criterion and sub-criteria through a pairwise comparison. The importance of the criteria will allow the alternatives to be ranked from the best to the worst.

The number of pumps is a design parameter that is defined for every pump model. This criterion is assessed in a quantitative form, and it is ranked better as the PS has a lesser number of pumps.

The complexity of the regulation mode is a parameter that evaluates how complex is the operation of the control system. This criterion is evaluated according to the number of the required equipment in the control system. In this way, the complexity is ranked better as it is required a lesser number of devices in the system. This criterion is established through scales. Table 10 shows the required number of elements in every regulation mode.

Table 10. Required equipment or device for different control systems

	Control System	Frequency inverter	Pressure Switches	Pressure transducer	Flowmeter	PLC	No. regulation equipment
1.0	With NC						0
2.1	FSP with PC		X				1
2.2	FSP with FC				X	X	2
3.1	VSP with PC	X		X		X	3
3.2	VSP with FC	X		X	X	X	4
4.1	FSP and VSP with PC	X		X		X	3
4.2	FSP and VSP with FC	X		X	X	X	4

On the other hand, economic factors are related to the costs to carry out the design and operation of the PS. In this aspect, investment costs include the provision and installation of the required elements of the PS. The cost of implementation and installation of the pumps are obtained by a database of unit costs of every pump model. The costs of pipes, valves, control elements and other accessories are determined through mathematical expressions based in existing projects. These expressions are detailed in the appendix section of this work. These elements and accessories of the PS were shown in Figure 14.

Operational costs are related to the energy consumption of the PS. The energy consumption is determined by the consumed power of pumps and this consumed power is computed according to the operational points (H, Q) and the efficiency (η) of the pumps for every time interval as described in equations (26) to (30). Finally, daily energy cost is determined with the consumed power and electric tariff for every time interval (h) and this daily energy cost is extrapolated to annual consumption energy to determine the annual operational cost.

Maintenance costs are determined according to a preventive maintenance program. This program establishes the maintenance activities and the frequency of implementation of these activities for PS. The costs of every maintenance activity and their frequency of implementation are obtained from a database. Finally, it is obtained the annual cost of maintenance for the PS. The maintenance activities are associated with preventive maintenance of every device within the PS.

In summary, economic factors are assessed in a quantitative form and are ranked positively as these costs reduce. The formulations to evaluate investment, operational and maintenance costs of the alternatives are detailed in the appendix section of this document.

4.2.4. Methodology of analytic hierarchy process (AHP)

The AHP method requires to define the required data of the PS: the setpoint curve, demand pattern, pump database, unit cost database, basic scheme of PS and electric tariff. For every feasible pump model, the number of pumps (*b*) can be defined. Then, the number of FSPs and VSPs (*n, m*) defines different configurations of control system (c_i) for the viable pump models. The criteria of technical and economic factors of the solutions generated by the pump models and different configuration of control modes are evaluated. After the assessment, all these alternatives can be classified in dominant and dominated solutions thorough Pareto front. The dominant solutions continue in this process, while the dominated solutions are discarded. The AHP method follows a hierarchy construction. It is established by the objective to reach criteria and sub-criteria for the PS and finally by the alternatives to evaluate. The judgments of the group of experts determine the importance weight of the criteria of technical and economic factors in the PS. Then, the dominated solutions are assessed using these weighted criteria. Finally, the most suitable pump model alternative is selected according to the obtained rating of the alternatives. The following flowchart (Figure 15) describes the process of the proposed methodology applying the AHP method.

Once it is defined the hierarchy construction, it was surveyed a group of 70 different experts on PS design. There are seven different group of experts: academic, commercial, construction, consultancy, management, operation and direction. This group of experts judges how important is a criterion over another criterion through pairwise comparisons of first-level criteria (factors) and second-level criteria (sub-criteria of the factors).

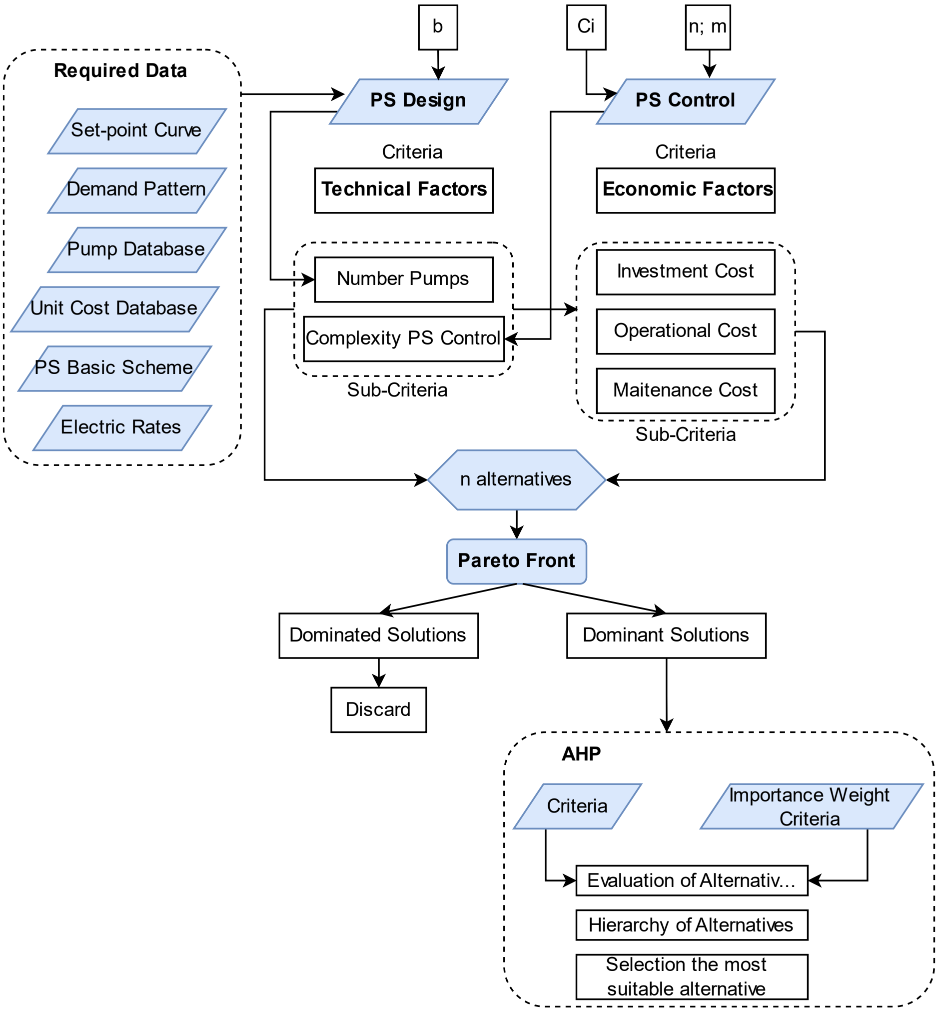


Figure 15. Flowchart of the proposed methodology

The pairwise comparisons of the criteria are realized by a numeric scale established by Saaty [94]. This scale is established by the numbers (1, 3, 5, 7, 9) where the number 1 represents the same importance of one criterion over another and the number 9 represents the maximum importance of one criterion over another. In this way, it is constructed a quadratic matrix of (n_c x n_c), where n_c is the total number of criteria. The criteria are placed in rows and columns of the matrix in order to form a pairwise comparison of the criteria. Hence, this matrix is formed by values of the comparisons of every criterion over another (a_{ij}). The sub-terms *i* and *j* represent each criterion placed in rows and columns respectively. These pairwise comparisons are reciprocal with each other. For example, the reciprocal pairwise comparison of a_{ij} (a_{ji}) is defined as the inverse, that is, $1/a_{ij}$. The priority vector of every criterion and sub-criterion is usually obtained through arithmetic mean with the values of pairwise criteria comparisons as defined by the AHP. In addition, this work proposes to consider the consistency of the comparison values of every group of experts to obtain the final importance weight of the criteria. Therefore, the final importance weight of the criteria is determined thorough a geometric weighting of the priority vector of the criteria with the consistency of the obtained comparison by the group of experts. These values are obtained in a dimensionless way by the following expressions.

$$a_{ij} \cdot a_{ji} = 1 \tag{31}$$

$$Na_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n_c} a_{ij\ (columns)}} \tag{32}$$

$$C_i = \frac{\sum_{i=1}^{n_c} Na_{,ij}}{n_c} \tag{33}$$

In equation (31) a_{ij} are pairwise comparisons of a criterion over another. In equation (32), the terms Na_{ij} are normalized values of a_{ij} concerning the summation of values in each column matrix. Finally, the term C_i in equation (33) is the importance weight vector or priority of each criterion for each group of experts. The sub-index *i* represents every criterion for each group of experts and n_c is the number of criteria.

One of the conditions to use the AHP method is that the pairwise comparison matrix *W* of (n_c x n_c) done by the group of experts should be consistent. This matrix is consistent if satisfies the following expression:

$$\overline{V_i} = W \cdot C_i = \lambda_{max} \cdot C_i \tag{34}$$

$$\lambda_{max} = max\left(\frac{\overline{V_i}}{\overline{C_i}}\right) \tag{35}$$

Where, $\overline{V_i}$ is the final vector of the product between the matrix of comparisons (*W*) and the importance weight vector of the criteria C_i, the term λ_{max} represents the maximum quotient between the relation of the final vector ($\overline{V_i}$) and the importance weight vector of the criteria (C_i).

The pairwise comparisons are considered consistent if the consistency ratio (*CR*) is below 1. This ratio is the relation between the consistency index (*CI*) and random consistency index (*RI*) that is obtained according to the size of the pairwise matrix (*A*) of (n_c x n_c). The term *CI* measures the consistency of the comparisons done by the group of experts [102]. These terms of consistency are calculated by the following expressions:

$$CR = \frac{CI}{RI} \tag{36}$$

$$CI = \frac{\lambda_{max} - n_c}{n_c - 1} \tag{37}$$

$$RI = \frac{1.98 \cdot (n_c - 2)}{n_c} \tag{38}$$

One of the contributions of this methodology is to avoid that a pairwise comparison realized be discarded because it is inconsistent. This a problem that has not been solved yet by the AHP method. Hence, the proposal consists of a geometric weighting of the priority of the criteria for each group of experts with the inverse of consistence ratio (*CR*) of every group. In this way, the importance weight of every criterion for each group of experts considering the consistency of the pairwise comparison realized by the experts ($CP_{i,j}$) is obtained the equation (39), where the sub-index *j* represents every group of experts.

$$CP_{i,j} = C_i^{1/CR_j} \tag{39}$$

Finally, the general importance weight of all groups of experts of every criterion is obtained as a geometric mean, as described in equations (40) and (41).

$$CP_{i,GM} = \prod_{j=1}^{n_e} CP_{i,j}^{\sum_{j=1}^{n_e} 1/CR_j} \tag{40}$$

$$CP_{0,i} = \frac{CP_{0,i,GM}}{\sum_{i=1}^{n_c} CP_{0,i,GM}} \tag{41}$$

In the previous equations $CP_{i,GM}$ is the geometric mean of the importance weight considering the consistency of every criterion. It is defined as the product of the importance weight considering the consistency of all group of experts with an exponent of the summation of the inverse of consistency ratio of all group of experts. The term n_e is the number of groups of experts. Finally, the term $CP_{0,i}$ is the general importance weight or priority considering the consistency of every criterion.

This methodology aims to generalize the obtained importance weight of criteria for the design of a PS and it might be always applied in any pumping system. Therefore, there is no need to survey a group of experts each time a PS is designed.

Once the overall priority of every criterion and sub-criterion has been defined, the alternatives for each sub-criterion of the technical and economic factors are evaluated. It is important to mention that it is necessary to establish the type of assessment of every criterion. In this way, the number of pumps is a quantitative assessment and is considered a positive assessment as lesser is the number of pumps. In the same way, operational and maintenance costs are quantitative assessments and are expressed in annual costs, while investment cost is quantitative, but it is expressed as the total cost to install the PS and the control system. The assessment of these criteria is considered positively as less are the annual costs of investment, operation, and maintenance.

However, the complexity of the control system is assessed differently through ratings. This criterion is assessed through a pairwise comparison of the different configurations of control. It is compared how complex is a control system with respect to another. Then, the complexity priority of every configuration of control (Cc_i) is obtained as the AHP method establishes in equation (33). The sub-term *i* represents the type of regulation mode. The maximum value of the complexity priority (ca_i) is the regulation mode with the least complexity of operating. Finally, it is determined the rating of priority of every regulation mode as is shown in the following expression.

$$Rc_i = \frac{Cc_i}{Cc_{i,(max)}} \tag{42}$$

The rating (Rc_i) is obtained as the relation between the complexity assessment of every regulation mode and an established ideal value that is the maximum complexity priority of the regulation modes $Cc_{i,(max)}$. This obtained rating could have values from 1 to 0, where 1 is the regulation mode with the best complexity assessment and 0 is the regulation mode with the worst complexity assessment. Table 11 shows a matrix of the pairwise comparations of the regulation modes, the complexity priority and the rating of every regulation mode.

Table 11. Regulation modes rating

Regulation mode (*i*)	1	2.1	2.2	3.1	3.2	4.1	4.2	Complexity Assessment (Cc_i)	Rating (R_i)
1.0	1	3	5	7	9	7	9	0.43	1.00
2.1	1/3	1	3	5	7	5	7	0.24	0.57
2.2	1/5	1/3	1	3	5	3	5	0.14	0.32
3.1	1/7	1/5	1/3	1	3	1	3	0.07	0.15
3.2	1/9	1/7	1/5	1/3	1	1/3	1	0.03	0.07
4.1	1/7	1/5	1/3	1	3	1	3	0.07	0.15
4.2	1/9	1/7	1/5	1/3	1	1/3	1	0.03	0.07

Then, the assessment of the alternatives in every criterion ($A_{i,j}$) is normalized concerning the maximum and minimum assessment of the alternatives in every sub-criterion ($A_{i(\max),\mathrm{j}}, A_{i(\min),j}$) as it is shown in expression (43). The sub-index *i* express the alternative number and *j* expresses the criteria number (From C1 to C5). The assessment of the alternatives ($A_{i,j}$) corresponds to the obtained values of the number of pumps, complexity, investment, operational and maintenance costs of the alternatives. The best assessment of the criteria (number of pumps, complexity, investment, operational and maintenance cost) is the lowest value of all alternatives. In contrast, the worst assessment of the criteria is the highest value of all alternatives. Then, the overall normalized assessment of every alternative (ONA_i) is obtained through the product of the normalized assessment of the alternatives and the overall priority of every criterion as showed in the equation (44).

$$NA_{i,j} = 1 - \frac{A_{i,j} - A_{i(\min),j}}{A_{i(\max),\mathrm{j}} - A_{i(\min),j}} \tag{43}$$

$$ONA_i = \sum_{j=1}^{n_c} NA_{i,j} \cdot C_j \tag{44}$$

In equation (44) the overall normalized assessment of every alternative (ONA_i) is the summation of the product of normalized assessment of every alternative for each criterion ($NA_{i,j}$) with the priority of every criterion (C_j), the sub-index *j* takes values from 1 to n_c, where n_c is the total number of criteria considered in the PS design ($n_c = 5$).

Then, it is obtained the distributive priority of the overall normalized assessment of each alternative (PA_i) to finally determine the total rating of every alternative (TR_i) as it is described in the following expressions.

$$PA_i = \frac{ONA_i}{\sum_{i=1}^{n} ONA_i} \tag{45}$$

$$OR_i = \frac{PA_i}{PA_{i,(\max)}} \tag{46}$$

The distributive priority of the overall normalized assessment of each alternative (*PA_i*) in equation (45) expresses the relation between the overall normalized assessment of each alternative (*ONA_i*) and the summation of the normalized assessment of the total number of alternatives. The sub-index *i* is the number of the alternative that takes values from 1 to *n* and *n* is the total number of evaluated alternatives. Finally, the total rating of every alternative (*TR_i*) is the relation between the distributive priority of the overall normalized assessment of every alternative (*PA_i*) and the maximum value of distributive priority of the overall normalized assessment of every alternative (*$PA_{i,(max)}$*). The values obtained for *OR_i* range from 1 to 0, where 1 is the best assessment of the alternative and 0 is the worst.

In this way, it is obtained the hierarchy of the alternatives through a unique rating of alternatives (*TR_i*) and finally, it is determined the pump model alternative with the best assessment. In other words, it is obtained the most suitable pump model alternative for a PS design considering technical factors (number of pumps and complexity of the control system) and economic factors (investment, operational and maintenance costs).

4.3. Case studies

This work presents two networks of case studies to show the effectiveness and application of the developed methodology. These networks are TF Network and CAT Network obtained from Leon-Celi's work [11]. Both networks have four PS. In order to show how to apply the methodology in a PS design, it was analyzed the PS1 and PS2 of TF Network and the PS2 and PS3 of CAT Network. Nevertheless, the AHP method could also be applied for the other PSs of these networks and the process would be the same. In summary, there are four different PSs as case studies to apply this methodology. The objective of this work is to select the most suitable pump model for the PSs to be designed considering aspects, such as the number of pumps, operation control complexity, investment cost, maintenance cost and operational cost. Where, these aspects are grouped in technical and economic factors.

It is important to mention that this methodology begins as datum with 67 pump models with their respective characteristics of the pumping curves (*Q, H*) and (*Q, η*) and their commercial costs. Furthermore, this work is provided by a database of the cost of the pipelines, valves, minor accessories, elements of the control system in the PSs and the maintenance activities costs including their respective installation cost. For this case study, it is considered that the maximum number of pumps in a PS is 10 pumps. Another important data is the set-point curve of the PSs and the demand pattern of the network.

These case studies have different electric tariff hours in every season (winter and summer). The electric tariff of peak, off-peak and plain hours for every season are shown in Table 12. Besides, it is considered that the summer season starts from March 28 to October 25 and the winter season starts from October 26 to March 27. Therefore, in summer there are 211 summer days and 155 winter days.

Table 12. Electric tariff for different time zones

		Time zones			
		Summer season		Winter Season	
Type of hours	**Electric Tariff**	**From**	**To**	**From**	**To**
Off-peak hours	0.069	0	8	0	8
Peak hours	0.095	11	15	18	21
Plain hours	0.088	9	10	8	18
		16	23	21	23

The mean flow (Q_m), the minimum flow (Q_{min}) and maximum flow (Q_{max}) of the different PSs are showed in Table 13.

Table 13. Demand flows for the different PSs

	TF-PS1	**TF-PS2**	**CAT-PS2**	**CAT-PS3**
Q_m (l/s)	35.00	24.44	18.00	37.00
Q_{min} (l/s)	12.30	8.60	6.30	13.00
Q_{max} (l/s)	70.00	48.88	36.00	74.00

The demand pattern is the same for all PSs since the characteristic of consume and demand are similar in both networks. The minimum demand pattern is 0.35 times the mean flow and the maximum demand pattern is 2 times the mean flow. The demand patterns for the 24 hours of a day are presented in Figure 16.

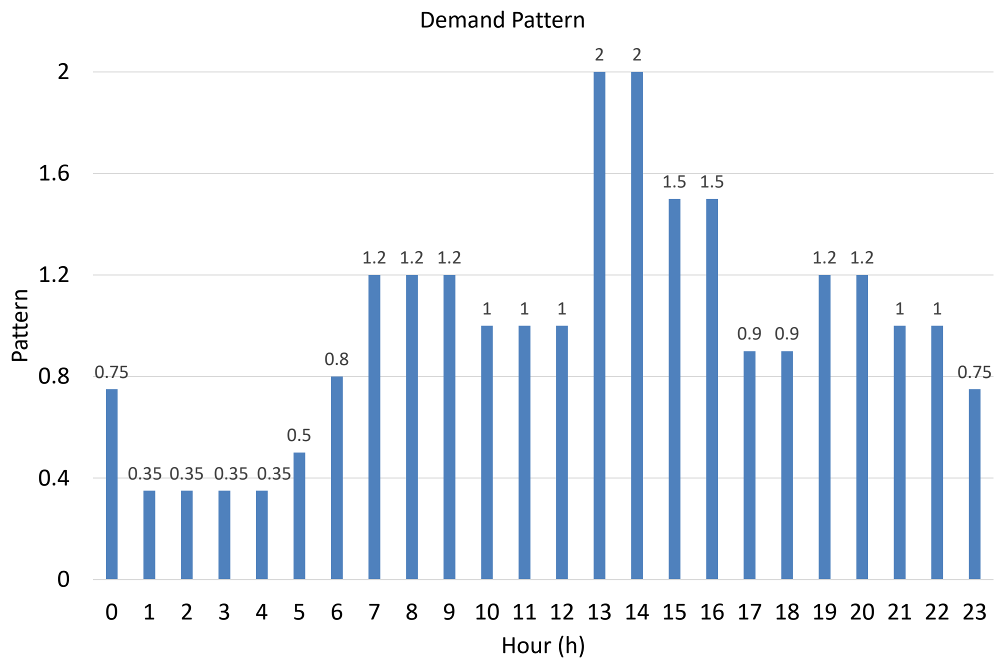


Figure 16. Demand Pattern for TF-Network and CAT-Network

The parameters of the set-point curve (ΔH and R) of every PS are detailed in the following Table 14.

Table 14. Set-Point curve parameters for every PS

Data	TF-PS1	TF-PS2	CAT-PS2	CAT-PS3
ΔH	25.00	28.00	25.00	22.00
R	0.0020	0.0059	0.0106	0.0015

4.4. Results

It was surveyed 70 different experts on PS design. The number of experts in every group were: academic (22), commercial (3), construction (4), consultancy (19), management (12), operation (2) and direction (8). Table 15 shows the priorities of the criteria and sub-criteria in a PS design for the seven different group of experts. In addition, this table shows the overall priority of every criterion and sub-criterion.

Table 15. Overall priority and priority of every criterion for every expert group

	Overall	Academic	Commercial	Constructor	Consultancy	Management	Operation	Direction
TF	0.33	0.38	0.09	0.25	0.34	0.36	0.70	0.48
EF	0.67	0.62	0.91	0.75	0.66	0.64	0.30	0.52
C1	0.20	0.26	0.04	0.18	0.15	0.20	0.43	0.36
C2	0.13	0.13	0.06	0.07	0.19	0.15	0.27	0.12
C3	0.14	0.15	0.32	0.12	0.15	0.11	0.06	0.09
C4	0.31	0.29	0.44	0.31	0.29	0.31	0.11	0.25
C5	0.21	0.17	0.15	0.32	0.22	0.22	0.12	0.18

The commercial, operation and direction group present major differences in the obtained priorities of technical and economic factors than the other groups taking as reference the overall priorities. In general, economic factors have more importance weight than technical factors, except for operation group. The criterion C4 (Operational Cost) is the criterion with the most importance weight, the second and third place are between maintenance cost (C5) and the number of pumps (C1) in almost all the group of experts.

The PS design process begins by defining the viable pump models. It means the pump models whose head pressure at null flow (H_1) is higher than the maximum required head pressure (H_{max}). In contrast, the pump models that are not viable are eliminated. This process is the first selection filter. These viable pump models with the combination of different regulation modes generate several solutions. These solutions are evaluated with the different criteria of PS design: technical factors (number of pumps and complexity) and economic factors (investment, operational and maintenance costs) and go through the second selection filter the Pareto front. This second filter selection reduces in a significant way the number of solutions. Finally, it is obtained the overall rating of these solutions according to the assessment of the criteria.

Table 16 shows a summary of viable the number of pump models in every PS and their respective total number solutions. This number is obtained by the combination of all possible configurations of control system in every pump model. In addition, this table shows the number of pump models and their number of solutions once the Pareto front was applied. In the last column of the table evince the reduction rate of solutions of the Pareto front in every PS.

Table 16. Number of viable pumps and solutions numbers for every PS

	Viable Solutions		Pareto Front (Final viable solutions)		
	No. Models	**No. Solutions**	**No. Models**	**No. Solutions**	**% Reduction Solutions**
TF-PS1	43	471	12	49	89.60 %
TF-PS2	39	359	14	40	88.86 %
CAT-PS2	45	357	15	30	91.60 %
CAT-PS3	45	490	7	31	93.67 %

In TF-PS1 has 12 different final pump models viable that have been analyzed. The bests alternatives for each pump model are summarized with the assessment and rating of every criterion are shown in Tables 17 and 18 respectively. The best pump model alternative is the model B30 with three pump units and with a regulation mode 2.1 (FSP with PC). The assessment of the criteria: number of pumps, investment, operational and maintenance costs are close to the best value of these assessments, where the rating values of these criteria are over 0.70. The next best pump model is B65 with three pumps and with a regulation model 1.0 (NC). This alternative has a better rating of complexity criterion than the best model (B30). Also, the assessment and rating of the number of pumps and maintenance cost are similar to the best alternative model (B30). Nonetheless, the assessment of operational cost criterion is more expensive than the best alternative (B30). It makes the overall rating value of the pump model (B65) is less than the best model (B30) because the operation cost has the greatest importance weight of all criteria. On the other hand, the pump model B33 with two pumps and with a regulation mode 3.2 (VSP pumps with FC) is the alternative with the least number of pumps and is the alternative with the best assessment of the number of pumps criterion of all alternatives. Besides, the assessment of the criteria: investment, operational and maintenance costs are close to the best value assessment of these criteria with rating values over 0.78. However, the rating of the complexity of the model B33 is the worst of all alternatives and it affects the overall rating of this alternative.

Table 17. Assessment of the criteria for each alternative (TF-PS1)

Priory weight of Factors		Technical Factors (0.33)				Economic Factors (0.67)		
Priority Weight of Criteria		C1 (0.20)			C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)
Hierarchy	**Model**	**b**	**m**	**n**	**Control system**	**Investment cost (€)**	**Operational cost (€/year)**	**Maintenance cost (€/year)**
1	B30	3	3	0	2.1	77,091.61 €	18,094.16 €	1,040.11 €
2	B65	3	3	0	1.0	100,767.32 €	21,387.13 €	1,136.44 €
3	B61	3	3	0	2.1	109,645.45 €	15,351.70 €	1,148.58 €
8	B33	2	0	2	3.2	76,896.63 €	16,099.10 €	1,018.72 €
12	B31	3	2	1	4.1	81,049.03 €	14,910.76 €	1,107.24 €
15	B59	4	4	0	1.0	120,430.57 €	18,320.99 €	1,420.55 €
22	B66	3	0	3	3.2	126,266.96 €	10,723.13 €	1,318.83 €
24	B28	4	4	0	2.2	98,748.70 €	13,046.24 €	1,407.69 €
37	B58	5	5	0	2.2	145,699.82 €	11,328.55 €	1,787.40 €
38	B27	6	6	0	2.2	134,865.79 €	11,963.36 €	1,960.90 €
39	B57	8	8	0	2.2	205,690.01 €	11,123.06 €	2,617.86 €
40	B49	10	10	0	2.2	243,678.07 €	9,936.37 €	3,178.36 €

b: number of pumps; m: number of FSP; and n: number of VSP

Table 18. Rating of the criteria and overall rating for each alternative (TF-PS1)

Priory weight of Factors		Technical Factors (0.33)		Economic Factors (0.67)			
Priority Weight of Criteria		C1 (0.20)	C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)	
Hierarchy	**ID Model**	**Rating N. Pumps**	**Rating Complexity**	**Rating Investment cost**	**Rating Operational cost**	**Rating Maintenance cost**	**Overall Rating**
1	B30	0.88	0.57	0.95	0.71	0.93	1.00
2	B65	0.88	1.00	0.83	0.60	0.89	1.00
3	B61	0.88	0.57	0.79	0.80	0.89	1.00
8	B33	1.00	0.07	0.95	0.78	0.94	0.98
12	B31	0.88	0.15	0.93	0.82	0.90	0.96
15	B59	0.75	1.00	0.74	0.70	0.78	0.96
22	B66	0.88	0.07	0.71	0.95	0.82	0.94
24	B28	0.75	0.32	0.84	0.88	0.79	0.94
37	B58	0.63	0.32	0.61	0.93	0.64	0.85
38	B27	0.50	0.32	0.66	0.91	0.57	0.80
39	B57	0.25	0.32	0.31	0.94	0.31	0.62
40	B49	0.00	0.32	0.12	0.98	0.10	0.48

There are 14 different final pump models viable for the characteristics of TF-PS2. The summary of the best alternatives for each pump model with the assessment and rating of the criteria are visualized in Tables 19 and 20 respectively. The best solution is the pump model B32 that is equipped with two pump units and its regulation mode is 3.2 (VSP with FC). This alternative has the least number of pumps and one of the cheapest pump models. It makes that rating value of the criteria: the number of pumps, investment, operational and maintenance costs are over 0.8 and it means that are close to the best assessment value of the criteria, except with complexity criterion that the rating value is 0.07. Even though this pump model (B32) has one of the worst ratings in complexity criterion, it does not affect this alternative has the best overall rating. In fact, the complexity criterion has not higher importance weight for the PS design comparing with the other criteria, such as operational, maintenance costs and the number of pumps. There are other pump modes with excellent rating value. For example, the pump model B29 with three pumps and with a regulation mode 2.1 (FSP with PC) has an overall rating value of 0.99. The assessment of the criteria of this alternative is also close to the best assessment value of the criteria. In fact, the rating of investment cost criterion is better than the best pump model alternative B32. However, the regulation mode of this alternative makes to increment the operational cost comparing with the best alternative (B32). This pump model alternative (B29) has a rating value of 0.68, while the best pump model alternative (B32) has a rating value of 0.83. Therefore, the overall rating value of the pump model B29 is less than the best pump model (B32).

Table 19. Assessment of the criteria for each alternative (TF-PS2)

Priory weight of Factors		Technical Factors (0.33)				Economic Factors (0.67)		
Priority Weight of Criteria		C1 (0.20)			C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)
Hierarchy	**ID Model**	**b**	**n**	**m**	**Control system**	**Investment cost (€)**	**Operational cost (€/year)**	**Maintenance cost (€/year)**
1	B32	2	0	2	3.2	40,033.75 €	11,033.00 €	890.95 €
4	B29	3	3	0	2.1	36,392.86 €	14,103.42 €	1,022.96 €
9	B60	3	3	0	2.1	60,626.74 €	11,562.38 €	1,131.43 €
10	B30	3	0	3	3.2	45,312.38 €	9,220.70 €	1,193.21 €
11	B31	3	0	3	3.2	47,703.25 €	9,194.79 €	1,193.21 €
23	B63	3	2	1	4.1	77,860.25 €	10,228.48 €	1,198.55 €
24	B61	3	0	3	3.1	85,229.43 €	9,529.86 €	1,243.41 €
26	B52	4	4	0	1.0	66,574.52 €	16,032.72 €	1,388.39 €
28	B59	4	4	0	2.2	68,867.09 €	9,965.95 €	1,483.99 €
32	B62	4	2	2	4.1	84,374.22 €	9,472.57 €	1,490.08 €
36	B51	5	5	0	1.0	76,708.45 €	15,975.26 €	1,655.77 €
37	B58	5	5	0	2.2	79,132.91 €	9,269.51 €	1,751.38 €
39	B28	6	6	0	2.2	60,527.23 €	11,276.87 €	1,918.87 €
40	B50	7	7	0	2.2	87,848.31 €	9,047.27 €	2,303.30 €

b: number of pumps; m: number of FSP; n: number of VSP

Table 20. Rating of the criteria and overall rating for each alternative (TF-PS2)

Priory weight of Factors		Technical Factors (0.33)		Economic Factors (0.67)			
Priority Weight of Criteria		C1 (0.20)	C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)	
Hierarchy	**ID Model**	**Rating N. Pumps**	**Rating Complexity**	**Rating Investment cost**	**Rating Operational cost**	**Rating Maintenance cost**	**Final Rating**
1	B32	1.00	0.07	0.88	0.83	0.90	1.00
4	B29	0.80	0.57	0.94	0.68	0.81	0.99
9	B60	0.80	0.57	0.55	0.80	0.75	0.97
10	B30	0.80	0.07	0.80	0.92	0.71	0.97
11	B31	0.80	0.07	0.76	0.92	0.71	0.97
23	B63	0.80	0.15	0.27	0.87	0.70	0.94
24	B61	0.80	0.15	0.15	0.90	0.67	0.94
26	B52	0.60	1.00	0.45	0.58	0.58	0.92
28	B59	0.60	0.32	0.41	0.88	0.52	0.91
32	B62	0.60	0.15	0.16	0.91	0.52	0.91
36	B51	0.40	1.00	0.28	0.58	0.41	0.85
37	B58	0.40	0.32	0.25	0.92	0.35	0.85
39	B28	0.20	0.32	0.55	0.82	0.24	0.62
40	B50	0.00	0.32	0.10	0.93	0.00	0.48

Tables 21 and 22 show the best alternative for each pump model with the assessment and rating of the criteria respectively. In CAT-PS2, 15 different final pump models are viable to the characteristics of the network, where the best alternative is the pump model B29 with two pumps and with a regulation mode 2.1 (FSP with PC). This alternative has the best rating of the investment cost criterion and the other rating values of the other criteria of this alternative are over 0.76 that indicates that is close to the best assessment value of the criteria, except with the complexity criterion which rating value is only 0.57. In general, this pump model is the best alternative with a rating value of 1. There are other pump models with lesser number of pumps than the best pump model alternative (B29). For example, the pump model B33 with one pump and a regulation mode 3.2 (VSP with FC). The rating values of the criteria of this alternative are over 0.87, except with the complexity criterion with a rating value of 0.07. The rating of the criteria: number of pumps, operational and maintenance costs of the best pump model B33 are better than the best alternative pump model B29. In contrast, the rating of the criteria: investment cost and complexity of the pump model B33 are better than the best pump model alternative B29. The worst rating of the complexity criterion of the pump model B33 makes that its overall rating value be less than the best alternative (B29).

Table 21. Assessment of the criteria for each alternative (CAT-PS2)

Priory of Factors		Technical Factors (0.33)				Economic Factors (0.67)		
Priority of Criteria		C1 (0.20)			C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)
Hierarchy	**ID Model**	**b**	**m**	**n**	**Control system**	**Investment cost (€)**	**Operational cost (€/year)**	**Maintenance cost (€/year)**
1	B29	2	2	0	2.1	26,857.50 €	8,709.77 €	737.07 €
2	B33	1	0	1	3.2	36,172.84 €	7,584.03 €	601.57 €
3	B60	2	2	0	2.1	45,032.91 €	7,529.47 €	845.53 €
8	B30	2	0	2	3.2	33,929.54 €	6,267.96 €	890.95 €
11	B31	2	0	2	3.1	34,140.13 €	7,678.38 €	832.69 €
14	B61	2	0	2	3.1	62,754.16 €	6,476.45 €	941.16 €
15	B28	3	3	0	2.2	35,755.30 €	8,198.96 €	1,097.85 €
16	B58	3	3	0	1.0	52,068.90 €	10,959.26 €	1,110.71 €
21	B59	3	0	3	3.2	66,803.39 €	5,229.30 €	1,293.10 €
22	B62	3	0	3	3.1	73,330.86 €	6,405.97 €	1,234.83 €
23	B15	5	5	0	2.2	43,682.33 €	8,035.18 €	1,642.91 €
24	B50	5	5	0	2.2	66,086.69 €	6,721.67 €	1,751.38 €
25	B41	5	5	0	2.2	64,990.43 €	7,054.42 €	1,751.38 €
26	B40	6	6	0	2.2	68,421.27 €	6,627.74 €	2,027.34 €
27	B38	8	8	0	2.2	80,856.08 €	5,918.28 €	2,455.36 €

b: number of pumps; m: number of FSP; n: number of VSP

Table 22. Rating of the criteria and overall rating for each alternative (CAT-PS2)

Priory of Factors		Technical Factors (0.33)		Economic Factors (0.67)			
Priority of Criteria		C1 (0.20)	C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)	
Hierarchy	**ID Model**	**Rating N. Pumps**	**Rating Complexity**	**Rating Investment cost**	**Rating Operational cost**	**Rating Maintenance cost**	**Final Rating**
1	B29	0.86	0.57	1.00	0.76	0.88	1.00
2	B33	1.00	0.07	0.86	0.84	0.94	1.00
3	B60	0.86	0.57	0.73	0.84	0.83	1.00
8	B30	0.86	0.07	0.90	0.93	0.81	0.98
11	B31	0.86	0.15	0.89	0.83	0.84	0.97
14	B61	0.86	0.15	0.48	0.92	0.79	0.96
15	B28	0.71	0.32	0.87	0.80	0.72	0.96
16	B58	0.71	1.00	0.63	0.61	0.72	0.96
21	B59	0.71	0.07	0.42	1.00	0.64	0.94
22	B62	0.71	0.15	0.32	0.92	0.66	0.94
23	B15	0.43	0.32	0.75	0.81	0.49	0.94
24	B50	0.43	0.32	0.43	0.90	0.44	0.94
25	B41	0.43	0.32	0.45	0.88	0.44	0.93
26	B40	0.29	0.32	0.40	0.91	0.32	0.92
27	B38	0.00	0.32	0.22	0.95	0.13	0.92

On the other hand, there are 7 different final pump models viable for CAT-PS3. The assessment and rating of the criteria for each best alternative of every pump model are shown in Tables 23 and 24, respectively. The pump model with the best overall rating is the pump model B28 with three pumps and with a regulation mode 1.0 (with NC). The rating value of the criteria: number of pumps, investment and maintenance cost are over a value of 0.80 and the operational cost criterion has a rating value of 0.68. These values indicate that the assessment of these criteria is close to the best assessment value of these criteria. It makes that this alternative has the best overall rating. The other pump models have also well overall ratings with a value over 0.94. Nonetheless, it is important to highlight the pump model B30 with two pumps and with a regulation mode 3.1 (VSP with PC) has lesser number of pumps than the best pump model alternative (B28). In addition, this alternative (B30) has the best rating of the number of pumps criterion. Besides, the assessment of the criteria: investment, operational and maintenance costs are similar to the best alternative (B28). Even though, the rating value of the complexity criterion of this alternative (B30) is only 0.15. It indicates that is far to the best value in this criterion. Therefore, the overall rating of this alternative (B30) is 0.98 that is less than the best alternative (B28). There are other pump models, such as B58 with five pumps and with a regulation mode 2.2 (FSP with FC). This alternative has the best rating of operational cost criterion, but the excessive number of pumps makes that the assessment of the investment and maintenance costs be far to the best assessment values. Therefore, it affects the overall rating of this alternative (B58).

Table 23. Assessment of the criteria for each alternative (CAT-PS3)

Priory of Factors		**Technical Factors (0.33)**				**Economic Factors (0.67)**		
Priority of Criteria		C1 (0.20)			C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)
Hierarchy	**ID Model**	**b**	**m**	**n**	**Control system**	**Investment cost (€)**	**Operational cost (€/year)**	**Maintenance cost (€/year)**
1	B28	3	3	0	1.0	76,003.47 €	18,694.99 €	1,036.55 €
7	B33	2	0	2	3.1	78,954.39 €	18,257.10 €	973.32 €
10	B27	4	4	0	1.0	92,400.92 €	18,663.93 €	1,312.08 €
12	B61	3	0	3	3.1	125,959.65 €	11,041.80 €	1,269.14 €
14	B59	4	4	0	1.0	120,430.57 €	18,564.49 €	1,420.55 €
20	B58	5	5	0	2.2	145,699.82 €	11,276.69 €	1,787.40 €
24	B49	7	7	0	1.0	173,427.47 €	16,154.81 €	2,255.73 €

b: number of pumps; m: number of FSP; n: number of VSP

Table 24. Rating of the criteria and overall rating for each alternative (CAT-PS3)

Priory of Factors		Technical Factors (0.33)		Economic Factors (0.67)			
Priority of Criteria		C1 (0.20)	C2 (0.13)	C3 (0.14)	C4 (0.31)	C5 (0.21)	
Hierarchy	**ID Model**	**Rating N. Pumps**	**Rating Complexity**	**Rating Investment cost**	**Rating Operational cost**	**Rating Maintenance cost**	**Final Rating**
1	B28	0.80	1.00	0.97	0.68	0.90	1.00
7	B33	1.00	0.15	0.94	0.69	0.94	0.98
10	B27	0.60	1.00	0.83	0.68	0.73	0.97
12	B61	0.80	0.15	0.56	0.92	0.76	0.96
14	B59	0.60	1.00	0.60	0.68	0.67	0.96
20	B58	0.40	0.32	0.39	0.91	0.45	0.94
24	B49	0.00	1.00	0.17	0.76	0.16	0.94

4.5. Discussion

In order to show the differences of importance weight of criteria and sub-criteria for a PS design according to the judgment of different group of experts, these results are represented through radial charts. In this way, Figure 17 shows the differences of the criteria: technical and economic factors in each group of experts and the overall priority of technical and economic factors. The different group of experts are represented in every vertex of the polygon and the radio of the polygon represents the dimensionless importance weigh, where this measure is from the center of the polygon and finish in the vertices with values between 0 and 1. In this way, it is formed a polygon of every criterion according to the importance weight in each group of experts.

In Figure 17 there are some differences to establish the importance weight of the factors in each group of experts. In general, the group of experts give more importance to economic factors than technical factors except. However, the operation group gives more importance to technical factors. It can be visualized in Figure 17 that the importance weight of technical and economic factors for each group of experts are close the overall priorities of these factors except in the operation group. Economic factors have the most importance weight for the commercial group, where there is a great difference concerning the other groups.

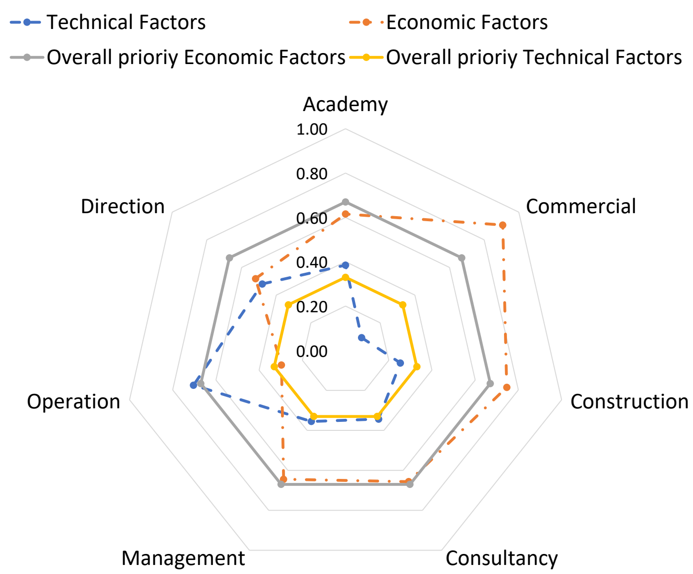


Figure 17. Importance weigh of factors of every group of experts

In contrast, Figure 18 shows the differences of the sub-criteria of each factor: number of pumps, complexity, investment, operational and maintenance costs in each group of experts. This Figure presents the priorities valuation of sub-criteria in every group of experts. As it is visualized, the most important sub-criteria by almost all group of experts are the sub-criteria C1 (number of pumps), C4 (Operational Costs) and C5 (Maintenance Costs). The C3 (Investment Costs) is the most important sub-criteria by the commercial group, but by the other groups this sub-criterion is less important. In general, it is observed a tendency to give more importance to the sub-criteria C1 and C5.

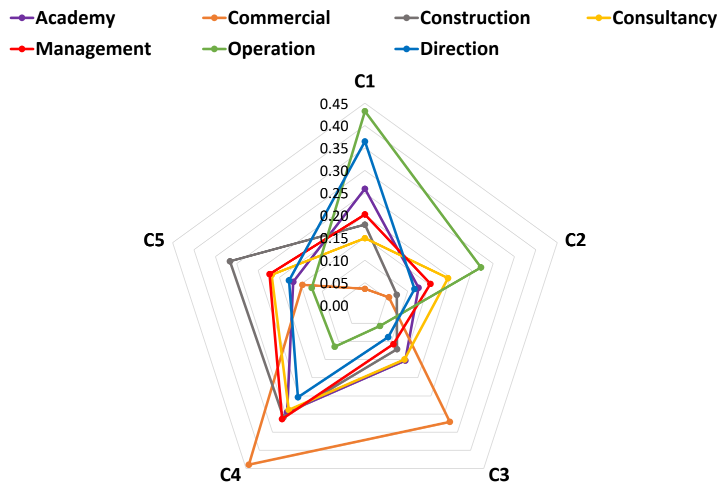


Figure 18. Importance weigh of criteria of every group of experts

In addition, is important to obtain the deviation of the priority of every group of experts concerning the overall priority. These deviations are expressed in a dimensionless way. This analysis allows determining how far or close is the assessment of the importance weight in every group of experts. It is formulated the following expressions.

$$CD_{,i,j} = \frac{\left|C_{i,j} - \widehat{C_\iota}\right|}{\widehat{C_\iota}} \tag{47}$$

$$D_j = \sum_{i=1}^{n} CD_{,i} \cdot \widehat{C_\iota} \tag{48}$$

The term $CD_{,i,j}$ in equation (47) is the deviation of the importance weigh of every criterion for each group of experts, the sub-terms *i* express the criteria number (From C1 to C5) and *j* expresses the group of experts and the term $\widehat{C_\iota}$ is the overall importance weigh of every criterion. The term D_j in equation (48) is the deviation of the priority of each group of experts. This term the summation of the product of the deviation of the priority of every criterion with the overall priority of every criterion. The term D_j represents the importance weight of the overall criteria for each group of experts concerning the overall importance weight.

Figure 19 shows a bar graph that represents the deviation of the importance weight for each group of experts concerning the overall importance weight. In the horizontal axis is represented every group of experts and on the vertical axis is the deviation of every group of experts. In summary, the commercial and operation sector are the groups with the most deviation concerning the overall importance weight with values of 1.08 and 1.49 respectively. Whereas the deviation of the other sectors: academy, construction, consultancy, management, and direction are not great differences. It means that the judgment of these group of experts to determine the importance of every criterion are similar, except with the commercial and operation group that the judgment of these sector is significantly different concerning the other sectors.

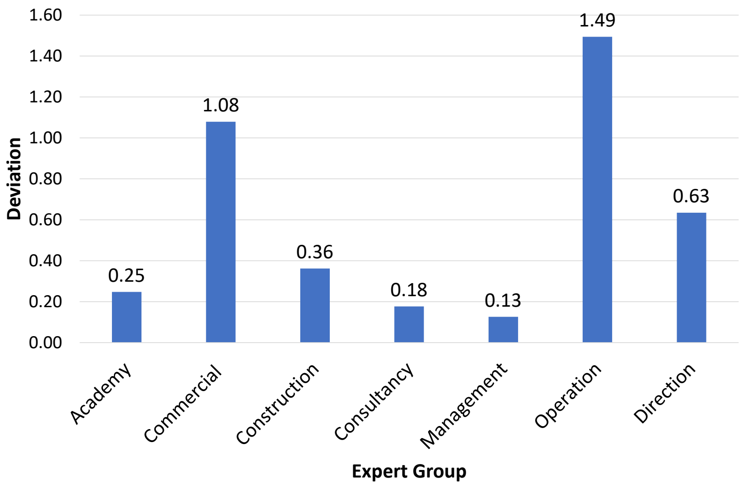


Figure 19. Deviation values of every expert group

On the other hand, the obtained results to determine the most suitable pump model in the four PSs as case studies could be summarized that the pump models with the least number of pumps tend to obtain the better overall ratings. This tendency could be explained that the number of pumps is directly proportional to other criteria, such as investment cost and maintenance costs. Hence, as less are the number of pumps the investment and maintenance costs decrease. On the contrary, as the complexity of the pumping system is assessed positively, the operational and maintenance costs decrease. However, the pump model with the least number of pumps is not necessary the most suitable pump model. For example, the most suitable pump models in the PSs TF-PS1, CAT-PS2 and CAT-PS3 are: B30 with 3 pumps and a regulation mode 2.1 (FSPs with flow control), B29 with 2 pumps a regulation mode 2.1 (FSP with FC) and B28 with 3 pumps and a regulation mode 1.0 (NC) respectively, but in these PSs there are other pump models with the least number of pumps that do not have the best overall rating. On the other hand, the most suitable pump model in PS TF-PS2 is the pump model with the least number of pumps B32 with 2 pumps and a regulation mode 3.1 (VSP with PC). Besides, is important to highlight that there is not a tendency that determines the most suitable pump model concerning the complexity of the pumping system. Therefore, there are different types of regulation modes in the most suitable pump model of the case studies because the complexity criterion has not great importance weigh in a PS design. On the other hand, there is a great tendency concerning the operational cost to determine the most suitable pump model. In this way, the pump models with better rating values in this criterion tend to get better overall ratings. However, it is not necessary that the pump model with the best rating in operational cost criterion is the most suitable pump model as it happens in the case studies analyzed.

In summary, although the priority analysis of the criteria in a PS design indicates that economic factors are more important than technical factors, the valuation of the economic factors of the alternatives depends on the valuation of the technical factors. In other words, economic factors (investment, operational and maintenance costs) are closely related to technical factors (number of pumps and complexity). The most relevant criteria for PS design are the number of pumps, operational maintenance costs. Nonetheless, complexity and investment cost could be relevant to determine the most suitable pump model in some cases when there are alternatives with similar ratings especially in the number of pumps, operational and maintenance costs.

In addition, this new proposal of PS design is compared with other conventional alternatives of design. This comparison is realized in one case study (TF-PS1) as an example to show the viability of the proposed work. The first alternative of conventional design is selecting the best solution according to the pump model with the minimum life cycle cost of all viable models. The life cycle cost is the summatory of investment, operational and maintenance annual costs. The second alternative of design is fixed the number of pumps according to the criteria of the designer. Then, select the pump model with the best efficient curve of the pump catalogue and with the minimum life cycle cost. The objective to compare conventional alternatives of PS design with this proposed methodology is to validate that a multi-criteria analysis is a viable method to design a Pumping system. Besides, The AHP method allows to assess or determine the priority in a design with important aspects, such as technical factors that includes number of pumps and the complexity of control mode and economic factors thar are investment, operational and maintenance costs. The conventional designs of PS are only based to satisfy the requirements of the system and obtained the minimum possible life cycle cost of the pumping system.

An annual interest rate (T_i) of 3% was assumed, and the cycle life (CL) of the equipment of PS are based according to the fabricator in order to determine the life cycle cost of the PS. The amortization factor (FA) is determined according to the equation (49) and this factor is affected to the investment cost to annualize it.

$$FA = \frac{T_i \cdot (1 + T_i)^{CL}}{(1 + T_i)^{CL}} \tag{49}$$

In the first alternative of conventional PS design, the number of pumps of the viable pump models were determined according to the classic method. The pump model is selected according that the pump model can delivered the maximum requirements of the system (Q_{max}, H_{max}). The number of pumps of the model is obtained by the relation of maximum demand flow (Q_{max}) and the flow that one pump (Q_{b1}) of the selected model deliver at the maximum head required of the system (H_{max}). Then, the number of pumps of every pump model were combined with all the different control mode obtaining several alternatives of solution. In every alternative is determined the life cycle cost and finally the best alternative is selected according to the minimum life cycle cost. The following Table 25 shows the best alternative of pump model (B28) with two FSP and VSP respectively and with a flow control mode. This table describe the respective number of pumps, control mode, investment, operational and maintenance annual cost of the best pump model. The summatory of these costs determine the cycle life cost of the most suitable alternative.

Table 25. Obtained results in (TF-PS1) in the first alternative of conventional design (analyzing life cycle costs)

Hierarchy	ID Model	*b*	m	n	Control system	Investment Cost (€/year)	Operational Cost (€/year)	Maintenance Cost (€/year)	Total Cost (€/year)
1	B28	4	2	2	4.2	7,021.77 €	10,259.15 €	1,472.04 €	18,754.75 €

Nomenclature: b: number of pumps; m: number of FSP; n: number of VSP

On the other hand, in the second alternative of conventional PS design, the number of pumps is fixed according to the relation of the maximum demand flow (Q_{max} = 70 l/s) and minimum demand flow (Q_{min} = 12.30 l/s) of the network. This relation gives as result 6 number of unit-pumps. Then, the relation of the maximum demand flow and the number of pumps (6 pumps) determines the supplied flow by each pump (Q_b = 11.66 l/s). This flow and the required head of the maximum demand flow of the system (H_{max} = 34.8 m) are the operational points to select the pump model with the best efficiency curve in the catalogue. In this case, the pump model selected is the model B27. Finally, the 6-unit pumps of the selected model are combined with different number of FSP and VSP and with every control mode configuration. These combinations determine several solutions. Then, the most suitable solution is selected according to minimum cycle life cost of all alternatives. In Table 26 is appreciate the most suitable alternative of control of the model B27 and the different parameters of this model: the pump model, the number of pumps, the control mode and the cycle life cost.

Table 26. Obtained results in (TF-PS1) in the second alternative of conventional design (fixing the number of pumps)

ID Model	b	m	n	Control Mode	Investment Cost (€/year)	Operational Cost (€/year)	Maintenance Cost (€/year)	Cycle Life Cost (€/year)
B27	6	2	4	4.2	8,741.36 €	10,707.82 €	2,025.25 €	21,474.43 €

As it can see in Tables 25 and 26, the two conventional alternatives of PS design give different pump model and number of pumps. These two alternatives of design used different criteria to set the number of pumps and the pump model. Moreover, these two designs have a common criterion that is the minimum life cycle cost to select the best solution. Hence, both designs use the same control mode 4.2 (FSP and VSP with FC) because this control mode follows the set-point curve and entails to optimize the operational cost life cycle cost. On the other hand, the best solution of TF-PS1 in the proposed methodology was the pump model B30 with 3 unit-pumps and with a control model 2.1 (FSP with PC). This solution uses lesser number of pumps than the conventional alternatives and its control mode is lesser complex than conventional designs. In addition, the best solution of design of this new methodology is not necessary the most economical solution in terms of life cycle cost. The principal difference of this proposal method compared with conventional methods is that this new method considers and assess technical aspects, such as number of pumps and complexity of control mode. In this case study, these aspects are determinant to select the best alternative in relation with other solutions that are more economics in terms of investment, operational and maintenance costs than the best solution as it can see in Tables 17 and 18. In contrast, conventional methods do not assess technical aspect and are only set to the criteria of the designer.

In brief, economic factors (investment, operational, maintenance costs) or life cycle cost are not the only form of analyze to select the most suitable solution in a pumping system. Technical aspects are also important to analyze in pumping system. For instance, how good could be having more or less number of pumps in a PS?, or How complex could be using pressure or control modes?. These questions are solved applying the AHP method. This methodology determines the importance priority in the design of the established criteria and sub-criteria in the PS design and it allows to rank the alternatives according to their final assessment to select the most suitable solution.

4.6. Conclusions

Most of the studies of PS are focused on optimizing the energy consumption or evaluating the total cost of the cycle of life of the system (investment, operational and maintenance costs). However, these researches are limited to pump models and the number of pumps that were previously set according to the criteria of the designer. In summary, there is not yet an approach of PS design that analyses subjective technical aspects, such as the most suitable number of unit pumps of the model or analyze the complexity of control system in order to select the most suitable solution. Hence, the idea of this work is to tackle these deficiencies of these previous studies. Therefore, the objective of this work is to define the assessment of these subjective aspects to select the most suitable pump model with its respective number of unit-pumps and control system in a PS design analyzing technical and economic factors. Aspects, such as the number of pumps and the complexity of operation are considered as technical factors, while other aspects, such as investment, operational and maintenance costs are considered as economic factors.

This work has been accomplished to apply an analysis of multicriteria decision, such as the AHP method to design a PS that includes selecting the most suitable pump model of different several alternatives from a base data. Besides, this methodology determined an importance weight of factors and criteria that could have in a PS design. In this way, different alternatives of pump model were evaluated with these criteria. From these evaluations and the importance weight of every factor and criteria are determined an overall rating of every alternative to determine the most suitable pump model for the PS design. This developed methodology was applied in different case studies of PSs, where it was obtained different results in every PS.

The overall importance weight of the factors and criteria to a PS design obtained in the analysis of the AHP method has concluded that economic factors are more determinant than technical factors to design a PS with an importance weight of 0.67 and 0.33 respectively. On the other hand, when it is analyzed the criteria, the most relevant criterion is the operational cost with a weight of 0.31 and followed by the criteria maintenance cost and the number of pumps with a weight of 0.21 and 0.20 respectively. The least relevant criteria are investment cost and the complexity of the system with a weight of 0.14 and 0.13 respectively. These obtained priorities of the factors and criteria are evidenced in the obtained results of the case studies to determine the most suitable pump model in a PS design.

The obtained results in the different case studies show that the alternatives of pump models with the least number of pumps tend to obtain better overall rating values. In one PS of the four case studies, the alternative of pump model with the least number of pumps is the best alternative. These results can be perceived because the number of pumps is directly related to the investment and maintenance costs, and it makes to be relevant in the overall rating. As there are lesser number of pumps in PS, the investment cost and maintenance cost decrease. Is important to mention that as less are the values of these criteria, these criteria are valued positivity, and the rating value is better. In fact, the number of pumps and maintenance cost are one of the most relevant criteria to design a PS with weights of 0.20 and 0.21 respectively. The most relevant criterion is operational cost with an importance weight value of 0.31, so is imperative that this alternative be also well ranked on the operational cost criterion to be the best alternative. There are other cases that a pump model that not necessarily has the least number of pumps but is the best option of all possible alternatives. This alternative is well ranked in other important criteria, such as operational cost and maintenance cost and these criteria could be also relevant to design a PS. There are other criteria, such as complexity and investment cost with less importance weight but it does not mean that these criteria are not important. A pump model with worse rating values of these criteria could be affected to be selected as the best alternative.

The results of pairwise comparison of the criteria realized by several group of experts could be subjective. Therefore, these results were weighted according to the consistency index ratio in order to mitigate the grade of subjectivity. However, the AHP method is valid to apply in a PS design when there are aspects with different interests. On the other hand, several costs that intervene in investment cost, such as the cost of the pump model units and other accessories that are equipped in a PS are obtained by a regression adjustment from a base data of commercial costs of these elements. Nevertheless, these approximations of costs do not affect the main objective of the work that is selecting the most suitable pump model in a PS design.

In the comparisons between conventional PS designs with the proposed methodology showed different solutions, especially in the aspects of number of pumps and complexity of the control system. Therefore, this proposed methodology displays the relevance when technical and economic factors are analyzed together, especially with the number of pumps and complexity of operation that are assessed positively or negatively according to the obtained results of the alternatives in these aspects. In summary, these comparisons demonstrate the utility of AHP method in typical engineering problems, such as PS design. Future research to deep this methodology of PS design is to consider aspects of Environmental factors. For example, CO2 emission by the pumps and the performance of the regulation mode. In addition, it could be included an analysis of annual interest rates on the investment costs. Another future research is to apply new optimal methodologies in pumping control mode systems and compare with the other configurations of control system that were analyzed in this work.

4.7. Appendix Section[1]

4.7.1. Control system

This work has contemplated seven different control systems and it is described these different configurations following.

1.0 With no control: This mode corresponds with the use of FSP that are in operation all the time. In addition, the flow supplying by the PS is constant thorough the time. This type of regulation does not have any kind control device.

2.1 Pressure control with FSP: This control mode operates switching on/off FSP and is based on measuring the total head of the system at the end of the PS with a pressure meter. This configuration works with a pressure switch that sends pressure signals to a system that orders the pumps to switch on/ off. These signals correspond to starting head and stopping head for every FSP. For example, if the PS is made up of three pumps, this regulation mode operates in the following way. The starting head of every FSP begins with determining the starting head of the last pump (*i* FSP), where *i* is the number of the FSP in operation. The intersection of the pumping curve of 2 FSP with the set-point curve determines the starting head of the last pump (H_{Ai}). Then, setting a head step (for example, $\Delta H = 5\ m$) it is obtained the starting head of the other FSPs. In this way, the starting head of 2 FSP (H_{A2}) is determined by ($H_{A2} = H_{Ai} + \Delta H$). The intersection between H_{A2} and the pumping curve of 1 FSP is the starting point of the 2 FSP. On the other hand, the stopping heads begin with the last FSP (H_{Pi}). This head is obtaining with the intersection of the flow of H_{Ai} in the 2 FSP with the pumping curve of the *i* FSP. In order to determine the stopping head of 2 FSP (H_{P2}) is obtained the head ($H_{Pi} + \Delta H$). The intersection of the flow of this head in 1 FSP with the pumping curve of the 2 FSP determines the stopping Head (H_{P2}). The following Figure 20 shows a scheme of an example of this regulation mode with three FSPs. In general, the necessary equipment of this regulation mode are the pressure meters and pressure switches.

[1] The published technical article presented in this chapter 4 includes an appendix section. This section is relevant for the development of this methodology. For instance, this appendix section is described as a sub-index in this chapter 4.

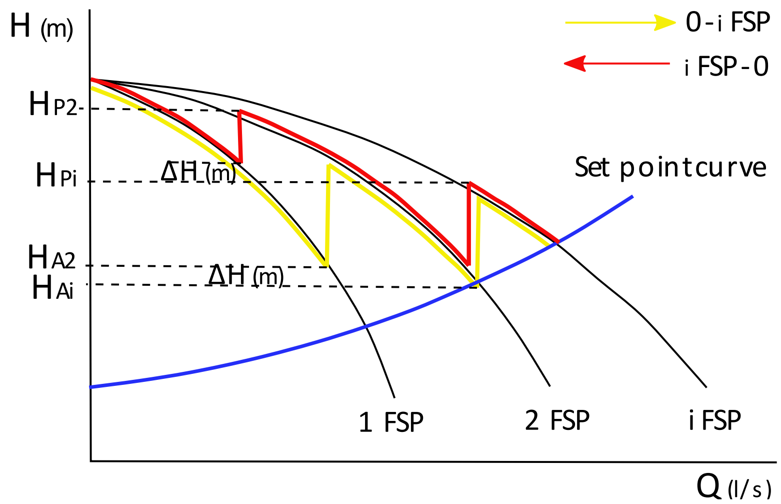


Figure 20. Pressure control with FSPs regulation mode

2.2- Flow control with FSP: This control system operates only with FSP and is based on measuring the flow at the end of the pumping station. The flow measured sends signals of switching on/off to the FSP through a PLC. This device identifies the set values of starting and stopping of the FSPs to order every FSP to switch on/off. The intersection of the set-point curve and the pumping curve of the i FSPs in operation defines the operational range of flow for the PS with their respective head that is defined by the terms Q_i and H_i. These terms represent the limit flow and limit head of the *i* FSPs in operation. In this way, when the demand flow (*Q*) is in the range ($0 < Q < Q_1$) is operating 1 FSP. When Q is in the range ($Q_1 < Q < Q_2$) the 2 FSP starts to operate and when *Q* is in the last range ($Q_2 < Q < Q_{max}$) the *i* FSP starts to operate. On the other hand, when the demand flow (*Q*) decreases, the *i* FSP stops when *Q* is near to the limits flow (Q_i). In the following Figure 21 it can be visualized the scheme of this regulation mode with 3 FSPs in the pumping station. The required equipment of this regulation mode are flow meters and a PLC.

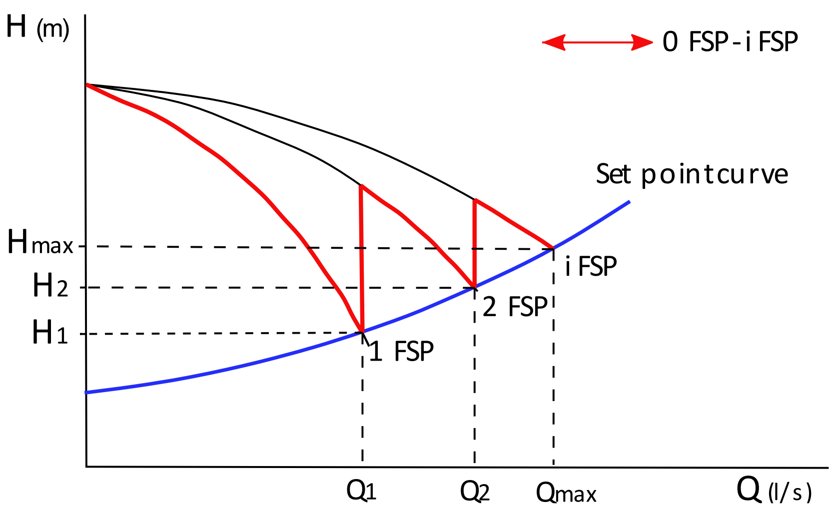


Figure 21. Flow control with FSPs regulation mode

3.1 Pressure control with VSP: In this control mode is necessary to incorporate a variable VFD in the pumps to allows the VSPs to change the rotational speed according to the demand flow (*Q*). This control mode consists of measuring the total head of the system at the end of the PS. A switched pressure sends the signals of starting and stopping of every VSP to a PLC concerning a fixed head value. Then, the PLC orders every pump to switch on/off and change the rotational speed (*N*) according to the flow and the set head value. The objective of this configuration is to maintain a fixed head in the PS regardless of the demand flow over time. This fixed head value is defined by the total dynamic head of the set-point curve at the maximum demand flow ($H_{c,max}$). The intersection of the fixed head ($H_{c,max}$) with the pumping curve of the *i* VSP determines the limit flows (Q_i) of the operational ranges of the *i* VSPs in operation. For example, if the PS has 3 VSPs and when *Q* is in the range ($0 < Q < Q_1$), 1 VSP pump operates with a correspondent rotational speed (*N*) to follow the fixed head. When *Q* is in the range ($Q_1 < Q < Q_2$), 2 VSP are in operation. One option is that the 2 VSPs operate at the same rotational speed (*N*) following the fixed head and the other option is that 1 VSP operates at the nominal rotational speed (N_0) and the other VSP operates at a rotational speed that follows the fixed head. When *Q* is in the rage ($Q_2 < Q < Q_{max}$), 3 VSPs are in operation, where 3 VSP could operate at the same rotational speed (N) following the fixed head. Another option is that 1 or 2 VSP operate at the nominal rotational speed (N_0) and the other VSPs operate at a correspondent rotational speed (*N*) following the fixed head. On the other hand, when *Q* decrease, the VSPs also decrease their rotational speed (*N*) following the fixed head and the i VSP switch off when *Q* is near to the limit flows (Q_i) of the operational ranges. The following Figure 22 shows a scheme of this regulation mode with 3 VSPs in the pumping station. The requirement equipment of this regulation mode are the variable frequency drives (VFDs), the pressure meters, the PLC, and the pressure switch.

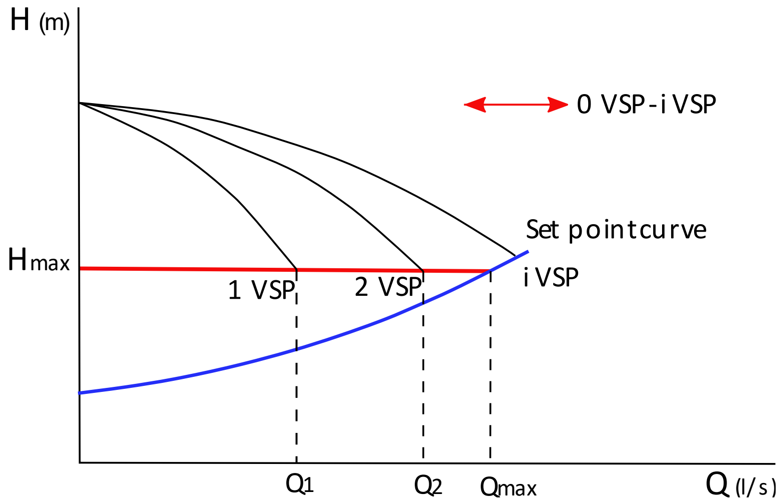


Figure 22. Pressure control with VSPs

3.2 Flow control with VSP: Similarly, to control mode (3.1), it is necessary to add a VFD into the pumps and could change their rotational speed concerning the requirements of the network. The objective of this control mode is that the operational points of the PS follow the set-point curve. It is based on measuring the flow and total head (*Q, H*) at the end of the PS. A pressure transducer sends the values of total head and flow to a PLC that orders to switch on/off or change the rotational speed of every pump concerning the values of (*Q, H*) of the set-point curve. The following Figure 23 shows an example of how this control mode operates. The intersection of the set-point curve and the pumping curve of the *i* pumps in operation determines the operational range of the flow in the PS. In the first range ($0 < Q < Q_1$), 1 VSP operates at a rotational speed (*N*) following the set-point curve. In the second range ($Q_1 < Q < Q_2$), 2 VSP operate at the same rotational speed (*N*) following the set-point curve or 1 VSP operates at the nominal rotational speed (N_0) and the other operates at a rotational speed (*N*) concerning the set-point curve. In the last range ($Q_2 < Q < Q_{max}$), 3 VSP operate at the same rotational speed (*N*) following the set-point curve. Another option could be that 1 or 2 VSP operate at the nominal rotational speed (N_0) and the other VSP operate at a correspondent rotational speed (*N*) concerning the set-point curve. On the other hand, when *Q* decrease, the VSP reduce their rotational speed following the set-point curve. When *Q* is near to the limit flows (Q_i) of the operational flows, the *i* VSP switches off to supply the necessary flow (*Q*) concerning the demand flow. The required equipment of this regulation mode are flow and pressure meters, VFD, pressure transducer, and the PLC.

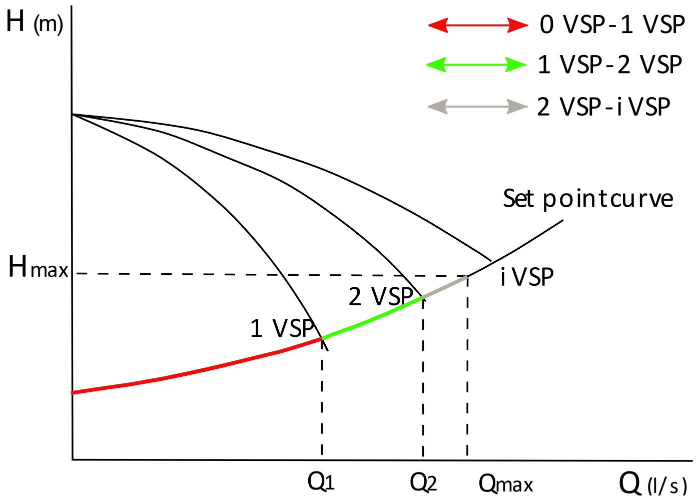


Figure 23. Flow control with VSPs

4.1 Pressure control with FSP and VSP: The objective of this regulation mode is that the pumping system maintains a fixed head value for every flow rate over time. This fixed head corresponds to the total maximum required head of the set-point curve ($H_{c,max}$). The operational mode of this type of control is similar to control mode (3.1) (Figure 9). The only difference between the regulation mode 3.1 is that the PS is combined by FSP and VSP. In this way, when demand flow (*Q*) is in the range ($0 < Q < Q_i$), only VSP is in operation with a rotational speed following the fixed head. When *Q* is in the range ($Q_i < Q < Q_{max}$), FSP supply the flow correspondent to Q_i and VSP supply the difference of the demand flow (*Q*) and the limit flow (Q_i) with their respective rotational speed to follow the fixed head. The VSP are always in operation and FSP are switched on/off concerning the demand flow.

4.2 Flow control with FSP and VSP: This control mode aims that the PS follows the set-point curve. The configuration and operational model are similar to the control mode (3.2) (Figure 10). The difference between this regulation mode with the control mode 3.1 is that it is combined FSP and VSP. In this way, VSPs supply small flows and FSPs supply great flows, where VSPs are always in operation. For example, VSPs supply the flow correspondent in the range ($0 < Q < Q_i$) or the difference of the demand flow (*Q*) and the limit flow (Q_i) with their respective rotational speed following the set-point curve. Whereas FSPs supply the flow correspondent to the limit flows (Q_i).

4.7.2. Economic factors

This criterion is the cost that includes in a PS design: Investment costs, maintenance costs and operational costs. This section describes the formulations to determine investment, maintenance costs and operational costs for each alternative of pump model.

Investment Costs

This intervenes in the cost of construction and installation of the infrastructure of the pumping station and the control pumping system. These costs are obtained from a database of the unit cost of installation of all the components in a PS design. Then the product of the quantity of each element of the PS with their respective unit costs determines the total investment cost in a PS design.

$$C_{Inv} = \left[(C_{PS} \cdot b) + \left(C_{pipe} \cdot L_T\right) + \left(\sum_{i}^{Acc_i} C_{Acc_i} \cdot N_{Acc_i} \right) + \left(\sum_{j}^{RM_j} C_{RM_j} \cdot N_{RM_j} \right) \right] \tag{50}$$

In equation (50), C_{Inv} is the investment cost of the PS expressed in annual form. The term C_{PS} correspond to the unit cost of every pump unit. This cost is obtained from a database of the commercial costs of the factories pump. The term b is the number of pumps in the PS. The term C_{pipe} is the unit cost of installation of pipelines and L_T is the total length of the pipelines. The term C_{ACCi} is the unit cost of installation cost of each accessory of the pumping station. These accessories include valves, elbow, or tee connectors. The term N_{ACCi} is the number of units of these accessories in the PS. The cost of the pipes and minor accessories of the PS are obtained by mathematical expressions. The terms of these expressions are detailed in table 17. The sub-term RM_j corresponds to every equipment of the control system of the PS. This equipment could be pressure switch, flow meters, transducer pressure, PLC or VFD concerning the type of the control mode in the PS. The term C_{RMj} is the unit cost of the installation of the equipment of the control system and the N_{RMj} is the number of every device of the control mode. The costs of the PLC, transducer pressure and pressure switch are obtained from a database of the commercial cost provided by the factory. In contrast, the cost of the flow meter and the VFD are obtained by mathematical expression, and it is detailed in Table 27. This table shows the function cost of different elements of a PS, the function variable of every equipment and the constant parameters of the function costs.

Table 27. Function cost of different elements in a PS

Element	C(X) (€)	X	C_1	C_2	C_3
Pipe	$C_{(X)} = C_1 + C_2 \cdot ND + C_3 \cdot ND^2$	*ND* (mm)	10.13	0.20	0.0005
Elbow connector	$C_{(X)} = c_1{}^{C_2 \cdot ND}$	*ND* (mm)	29.17	0.01	-
Tee connector	$C_{(X)} = c_1{}^{C_2 \cdot ND}$	*ND* (mm)	42.60	0.01	-
Section Valve	$C_{(X)} = C_1 + C_2 \cdot ND + C_3 \cdot ND^2$	*ND* (mm)	63.63	0.79	0.01
Check Valve	$C_{(X)} = C_1 + C_2 \cdot ND + C_3 \cdot ND^2$	*ND* (mm)	35.63	-0.14	0.01
Flow meter	$C_{(X)} = C_1 + C_2 \cdot D_{in} + C_3 \cdot D_{in}{}^2$	D_{in} (mm)	885.70	-9.22	0.06
Variable Frequency Drive	$C_{(X)} = C_1 + C_2 \cdot P + C_3 \cdot P^2$	*P* (KW)	168.19	116.08	-0.60

The term $C_{(X)}$ is the function cost of the elements of the PS, x is the variable of every function cost. These variables could be: the nominal diameter (*ND*) or the internal diameter (D_{in}) of these accessories, and the power (*P*) of the frequency drive. Finally, the terms C_1, C_2, and C_3 are constant parameters of every function cost.

Maintenance costs

These costs are related to the maintenance activities of the infrastructure of the PS, control system and their frequency of implementation. This cost is expressed in annual form, so the frequency of implementation is defined as the number of times to implement the maintenance activities in a year.

$$C_{Maint} = \left[\left(\sum_{i}^{APS_i} CU_{APSi} \cdot f_{APSi} \cdot b\right) + \left(CU_{pipe} \cdot f_{pipe} \cdot L_T\right) + \left(\sum_{j}^{Acc_j} CU_{Acc_j} \cdot f_{Acc_j} \cdot N_{Acc_j}\right) + \left(\sum_{k}^{RM_k} CU_{RM_k} \cdot f_{RM_k} \cdot N_{RM_k}\right)\right] \quad (51)$$

The term C_{Maint} is the annual maintenance cost of the PS. The term CUA_{PSi} is the unit cost of the maintenance activities of the pump and the sub-term *i* is every maintenance activity of the pump. The terms f_{APi} and *b* are the annual frequency of maintenance and the number of pumps in the PS, respectively. The term CU_{pipe} is the unit cost of the maintenance activity of the pipe. This cost is expressed in unit of length of the pipe (€/m). The terms f_{pipe} and L_T are the annual frequency of maintenance and the total length of the pipe, respectively. The term CU_{ACCj} is related to the unit cost of the maintenance activity of the accessories in the PS and the sub-term *j* is every one of these accessories (e.g., valves, elbow, and tee connectors). The terms f_{ACCj} and N_{ACCj} are the annual frequency of maintenance and the number of units of these accessories, respectively. Finally, CU_{RM_j} is the unit cost of maintenance of every equipment of the control mode in the PS. The sub-term *k* is every one of the equipment of the control mode (pressure switch, flow meter, transducer pressure, PLC, and VFD). The terms f_{RMk} and N_{RMk} are the annual frequency of maintenance and the number of units of these devices of control, respectively. It is important to mention that every maintenance activity of the PS and their frequency of implementation is based on the recommendation for the factory of these elements. The unit cost is obtained from a database of maintenance costs.

Operational cost

This cost is associated with the consumption energy by the PS in a year. This work considered two types of consumption energy in a year: Summer and Winter. Besides, every season has different energy tariffs concerning the type of hours that are: peak off-hours, rush hours and plain hours. The following expression determines the operational cost.

$$C_{Op} = Ns_{days} \cdot \sum_{i=1}^{h_T} P_{T,i} \cdot h_i \cdot C_{E,i} + Nw_{days} \cdot \sum_{j=1}^{h_T} P_{T,j} \cdot h_j \cdot C_{E,j} \quad (52)$$

The term C_{Op} is the operational cost of the PS in a year. The terms $P_{T,i}$ and $P_{T,j}$ corresponds to the consumed power of every hour in summer and winter, respectively. The terms h_i and h_j are the time interval in hours of summer and winter. $C_{E,i}$ and $C_{E,j}$ are the energy tariffs of every hour in summer and winter. The sub-terms *i* and *j* refer to every hour of a day in summer and winter and the term h_T are the 24 hours of the day.

Chapter 5. PS Design considering technical, environmental, and economic criteria based on the AHP method and demand variability

The third stage of this thesis is the development of a second approach of PS design. The idea of this methodology is to improve the first approach of PS design including (second phase of this thesis) environmental criteria in addition to technical and economic criteria. Another aim of this methodology is considering variability of demand in the design process. In addition, this PS approach pretends to include the operating optimization of PS control system in the design process. In this way, this methodology was presented in a technical paper in the Journal Water Resources Planning and Management of ASCE. The reference of the paper is:

> Briceño-León, C. X., Iglesias-Rey, P. L., Martinez-Solano, F. J., & Creaco E. "Integrating demand variability, and technical, environmental, and economic criteria in the design of pumping stations serving closed distribution networks." J. Water Resources Planning and Management, vol. 149, Issue 3, pp. 04023002, 2023.

This methodology of PS design considered in an integral way technical, economic, and environmental criteria based on the AHP. The technical criteria considered were size of the PS, flexibility of the PS operation, and complexity of the control system. The environmental criteria considered were MEI of the pump, GHG emissions, and efficiency of regulation. In short, this methodology is composed of 9 sub-criteria. A novelty to highlight of this work is the analysis of yearly demand variability in the design. While a single demand pattern is usually considered in a PS design, this proposed methodology considers a set of potential daily demand patterns and their respective probability of occurrence. The purpose of analyze the variability of demand in the operation in a PS design is that the design be more robust and reliable. In addition, this work considered the operating optimization of control systems in the PS during the design process. It Is important to mention that the control system strategies in this methodology were divided in 5 different strategies, while the control systems in the previous PS design approach were divided in 7 strategies. In this way, the control systems VSP with PC and FSP & VSP with PC were grouped in one control system strategy FSP and/or VSP with PC. Besides, the control systems VSP with FC and FSP & VSP with FC were grouped in the control system strategy FSP and/or VSP with FC. This optimization allows to define the number of pumps of the PS in a technically more adequate way. The original scale of the AHP sometimes can present problems of consistency in the evaluation the priorities in the criteria. Thus, this work proposed a modified scale of the original in the AHP in order that the obtained priorities the criteria be more consistence. In summary, the objective of this methodology is to select the most suitable solution in a PS design considering technical, environmental, and economic criteria in a comprehensive form and considering the variability of demand in the design. This methodology was programmed in visual basic application (VBA) for MS Excel in order to automate the calculation process to select the ultimate solution for the PS design.

This work presented two networks as case study to apply this methodology for PS design in the paper. Every PS was designed with different approaches including LCC minimization, considering technical and economic criteria, and considering technical, environmental, and economic criteria. In addition, it was compared the not consideration and consideration of the optimization of control system in the design process. Furthermore, it is compared the consideration of a single demand pattern and the variability of demand in the PS design. The obtained results allow to show the effects of considering the optimization of control system, technical criteria, environmental criteria and the variability of demand in a PS design.

5.1. Introduction

In the most recent century, the world population growth and economic development in urban settlements have caused increases and pattern variations in water consumption. Two of the seventeen SDG issued by The United Nations [3], 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 PS, which is typically performed in three stages for closed WDN.

A closed WDN is a network that is directly fed by one or various PS that take(s) water from the source(s) [45]. As water supply is guaranteed by the operation of pumps, this WDN configurations 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 [31].

The first stage of PS design for closed WDN 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 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 [106], as well as environmental benefits, such as the decrease in greenhouse gas (GHG) emission and leakage [31], [107].

Several studies have developed methodologies to optimize PS operation in the context of WDN design. For example, Lamaddalena and Khila [28] developed different control system configurations combining pressure and flow controls with FSP and Variable Speed Pumps VSP to optimize energy consumption in irrigation networks. Then, León-Celi et al. [78] optimized the energy consumption in water networks with multiple PS using the set-point curve concept. Similarly, Briceño-León et al. [89] 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 studies is that the optimization of the PS operation is performed after the pump model and the number of pumps in the installation were defined.

Other studies brought about significant improvements, such as minimization of energy, maintenance, and water treatment costs [38], [40]. Mahar and Singh [90] developed a methodology to optimize the total LCC (infrastructure, operational and maintenance costs) of PS. Then, Nault and Papa [44] improved the operational costs of PS considering environmental aspects, such as greenhouse gas emissions connected to pump operation. Similarly, Beygi et al. [55] optimized the total cost of water transportation systems and the reliability of the system based on the 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 [52]. In case studies, various levels of complexity can be found in the PS serving closed WDN, ranging between the (almost) total absence of control and the widespread use of flow and pressure control, frequency driver, and Programmer Logic Control (PLC) [108]. These control sytems allows PS to operate close to the set-point curve of the network in order to reduce energy consumption and leakage. 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 [49]. On the other hand, simple and robust control methodologies are sometimes preferred when pump scheduling is performed in real time to optimize pump operation [50], [51].

Another important aspect to consider in the design of PS is represented by environmental factors, such as the size of GHG emissions produced. In fact, previous works proved WDN management to be potentially harmful to the environment in our era of climate change [109, 110, 111]. However, to the best of our knowledge, only a limited number of works (e.g., Nault and Papa [44]) have so far tried to incorporate this aspect into PS design.

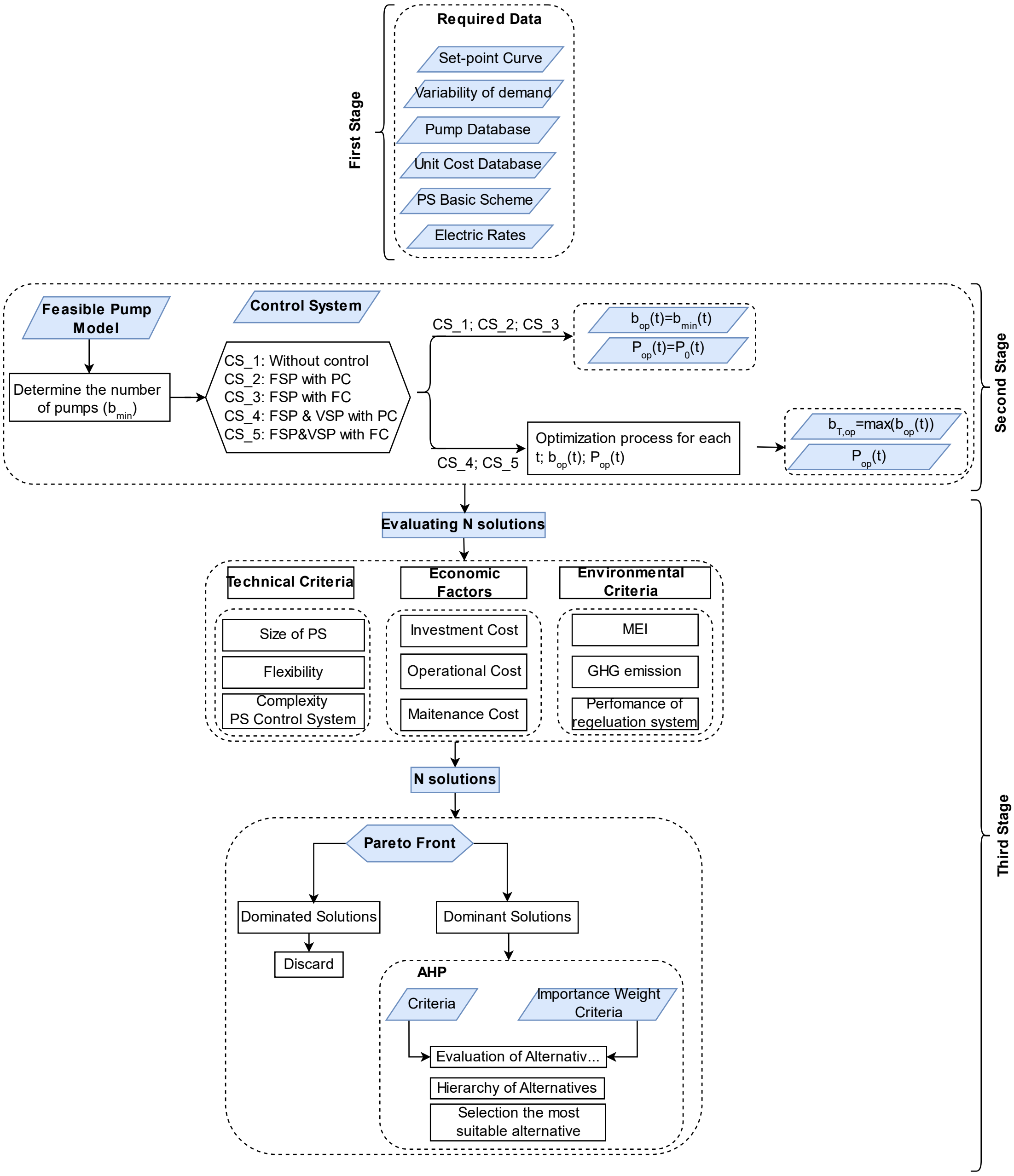
Though the studies just described have made significant contributions, the literature is still missing a comprehensive methodology integrating economic, technical, and environmental factors in the design of PS. A recent contribution to PS design was made by Briceño-Leon et al. [112], who integrated technical and economic criteria divided in 5 sub-criteria, i.e., number of pumps, complexity, investment, operational, and maintenance costs. However, they 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 the 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 the gap in research on PS serving closed WDN by combining pump control optimization according to various strategies and the AHP developed by Saaty [15, 94], Saaty and Sodenkamp [113] for the multi-criteria decision analysis [93] 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 [94]. In addition, this work considers of PS operation optimization in the design process to determine the number of pumps. Finally, it considers multiple daily demand patterns, each 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.

5.2. Methods

5.2.1. 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, 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. A flowchart of the proposed methodology is shown in Figure 24, 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 elements present in the flowchart.



b_{op}: optimal number of pumps; b_{min}: minimun number of pumps; b_T: total number of pumps; P_{op}: optimal power; P_0: Initial calculated power

Figure 24. Flowchart of the proposed methodology

5.2.2. First stage

The required data for PS design are described below.

<u>Pump model database</u>

Every pump model in a commercial catalog is defined by the best 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 Equations (53) to (59) characterize pump operation:

Head curve	$H = H_1\alpha^2 - \alpha^{(2-B)}A \cdot \left(\frac{Q}{b}\right)^B$	(53)
Efficiency curve	$\eta = E \cdot \frac{Q}{\alpha \cdot b} - F \cdot \left(\frac{Q}{\alpha \cdot b}\right)^2$	(54)
Rotational speed ratio	$\alpha = \frac{N}{N_0}$	(55)
Correction for pump efficiency	$\eta_c = 1 - (1-\alpha)^3 \cdot \eta$	(56)
Efficiency of the frequency drive	$\eta_v = \eta_{v,0} \cdot (\beta_v^{k_1} - k_2 \cdot (1-\alpha)^{k_3})$	(57)
Global efficiency	$\eta_S = \eta_c \cdot \eta_v$	(58)
Consumed power	$P_T = \frac{\gamma \cdot Q \cdot H_b}{\eta_S}$	(59)

The term H_1 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 operating VSP 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 Coelho and Andrade-Campos [82] formulation. The term η_v describes the efficiency of the frequency drive, as was developed by [89]. 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

The installation layout here is derived from the basic PS layout proposed by Briceño-León et al. [112] 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 25.

The size of the PS is defined basically by 3 types of lengths in the basic layout: the length of separation of each branch (L_1), the length of each branch (L_2), and the length upstream and downstream of the PS (L_3). 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 (L_1, L_2, or L_3).

$$L_i = f_i \cdot ND_i \tag{60}$$

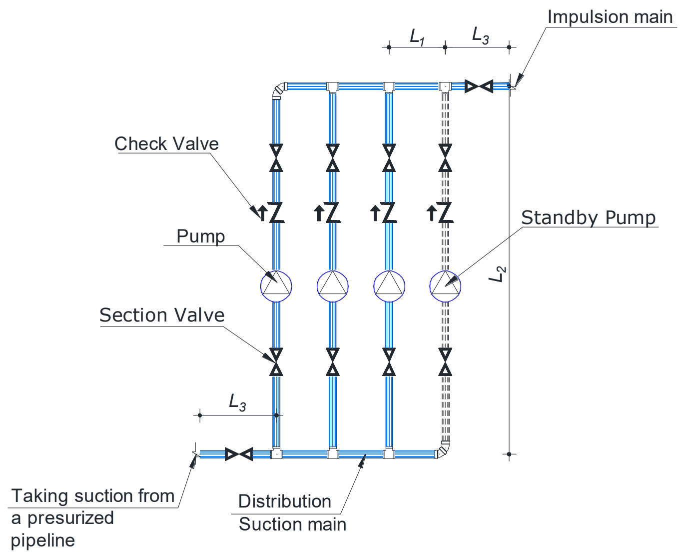


Figure 25. Basic layout of the Pumping Station

Set-point curve

The set point curve represents the required dynamic head (Hc) 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 in any time instant is replaced by a single constant value that is the minimun service pressure for consumption nodes. Therefore there is only one set-point curve for every PS [78]. This curve is expressed by the following equation:

$$H_c = \Delta H + R \cdot Q^C \tag{61}$$

The terms *ΔH*, *R,* and *c* are the static head of the PS including the minimum service pressure 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 (61) 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 [114] 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 26, 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 studies for PS design, this study 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, 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:

$$P_{rDP,j} = \begin{cases} \dfrac{P_{c,j+1}}{2} & j = 1 \\ P_{c,j+1} - P_{c,j-1} & 1 < j < N_p \\ \dfrac{1 - P_{c,j-1}}{2} & j = N_p \end{cases} \quad (62)$$

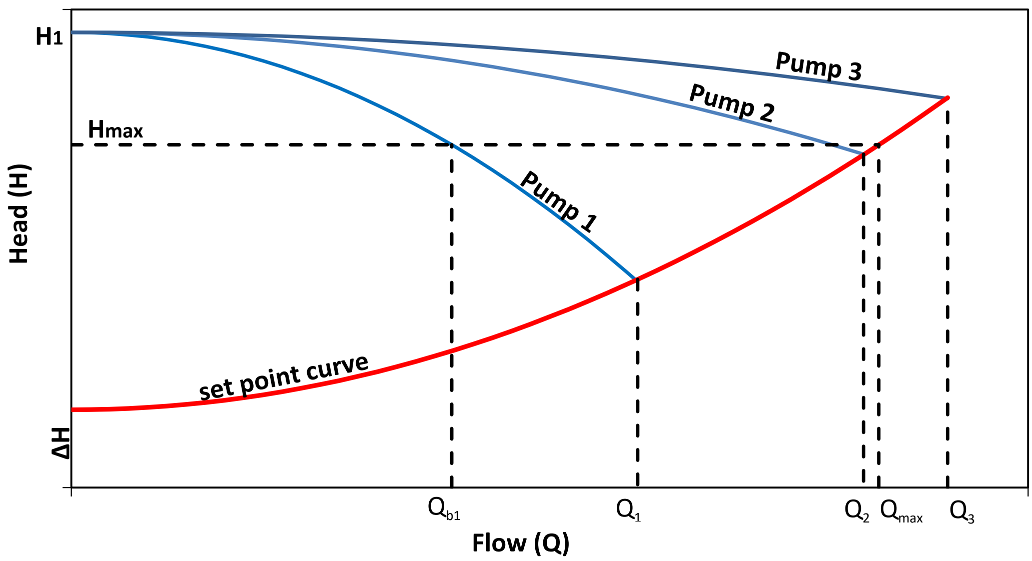


Figure 26. Set-point curve and Pump curves

The first and third expression in equation (62) are used to determine the probability of occurrence $P_{rDP,j}$ for the first and last scenarios of demand and correspond to the non-exceedance probability ($P_{c,j}$ = 0 and $P_{c,j}$ = 1.0). The second expression in equation (62) is used to determine the probability of occurrence of the other scenarios of demand with the non-exceedance probability values ($P_{c,j}$ = 0.05, 0.10, 0.15, …, 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. Though a single daily electricity tariff is assumed in the present work, variable daily tariffs are considered to differentiate the electricity price in peak hours, off-peak hours, and plain hours. Electricity tariffs can also be variable across the demand scenarios defined previously.

CO_2 emission factor

The CO_2 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: PC or Flow Control FC as described [112]. Specifically, five strategies of operation are considered for this methodology:

1. No control system
2. FSP with PC
3. FSP with FC
4. FSP and/or VSP with PC
5. FSP and/or VSP 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 PS operation, as it happens in strategies 3, 4 and 5. The elements required to implement the five different control strategies in the PS are defined in the following Table 28:

Table 28. Required elements in every Control System Strategy

	Control System	Frequency Inverter	Pressure Switches	Pressure Transducer	Flowmeter	PLC	Type of control elements
1	NC						0
2	FSP with PC		X				1
3	FSP with FC				X	X	2
4	FSP &/or VSP with PC	X		X		X	3
5	FSP &/or VSP with FC	X		X	X	X	4

PS unit cost database

This database contains the unit costs of the elements considered in a PS. This unit cost includes the purchase and installation of every element. The 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.

5.2.3. 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 25), the feasibility check for each pump model is that the maximum head (H_1) 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 passes the feasibility check, 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 construction of demand scenarios 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 VSP, with $b=m+n$, are the result of an optimization process for strategies 4 and 5 that will be explained subsequently.

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,…,N_t and d=1,…,N_d) is obtained to test the PS. In correspondence to each value $Q_{t,d}$, the value $H_{c,t,d}$ of the required head is obtained from equation (61). 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 equal 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_{rDP}, by means of the following formula:

$$E_{year} = 365 \times \sum_{d=1}^{N_d} P_{rDP,d} \left(\sum_{t=1}^{N_t} P_{T,t,d} \times \Delta t \right) \tag{63}$$

The number 365 in equation (63) is useful for determining the number of days of occurrence of every demand scenario in the year. 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 FSP and VSP in operation, and the optimal pump settings (on/off for FSP and rotational velocity for VSP) 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 VSP 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 to 3, the minimum number of pumps (b_{min}) is determined according the traditional approach of control system and correspond to 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_1). 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.

5.2.4. Third stage

Once the second stage of design yield a set of potential PS solutions, from 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

The economic criteria are given as:

1. **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 life cycle 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.

2. **Operational cost:** It relates to the yearly cost of electricity C_E (€) for pump operation. It is calculated with the following equation, which is similar to equation (63) and in which the tariff TE_t (€/KWh), that is, the unit cost of electricity at time t, appears:

$$C_{E,year} = 365 \times \sum_{d=1}^{N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} P_{T,t,d} \times \Delta t \times TE_t \right) \quad (64)$$

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

3. **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

The environmental criteria follow:

1. **Minimun efficiency index:** 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 [115] 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.

2. **Greenhouse gas 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 [116]. The formula for the assessment of the yearly GHG (Kg) differs from equation (65), due to the presence of EF (Kg/KWh) instead of TE_t (€/KWh):

$$GHG_{e,year} = 365 \times \sum_{d=1}^{N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} P_{T,t,d} \times \Delta t \times EF \right) \quad (65)$$

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

3. **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 an improvement of the PS performance in the environmentally friendly reduction of energy waste. 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:

$$\eta_{RS} = \frac{\sum_{d=1}^{j=N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} Q_{,d,t} \cdot \eta_{RS,d,t} \right)}{\sum_{d=1}^{j=N_d} Pr_{DP,d} \left(\sum_{t=1}^{N_t} Q_{,d,t} \right)} \quad (66)$$

A high score is assigned to this sub-criterion if the performance of regulation is high.

The ranking of the 5xN_{viable} dominant solutions obtained in the pareto front in the third 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 without an arbitrarily decision. 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. 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 group of experts as was shown by Briceño Leon et al. [112]. If *CR* <= 0.10, the comparison of sub-criteria is considered reasonable [117]. One contribution of this methodology is to obtain the general importance weight of every sub-criterion by determining the importance weight of every group of experts with their obtained CR.

The use of this methodology 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. [112]. Nevertheless, in this work, the assessment of the solutions in every criterion 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.

5.3. Applications

5.3.1. 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 annexes) were considered.

In PS design, a maximum number of b_{max} = 10 pumps inside the station was assumed as a constraint, and a single daily tariff distinguishing off-peak, peak, and plain hours was adopted for all networks (see Table 29).

Table 29. 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

Based on the demand patterns observed in two works in the scientific literature Alvisi and Franchini [118] , and Fiorillo [119] 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 and 1 respectively, feature a probability of occurrence P_{rDP} = 2.5%. The other scenarios, with probabilities of non-exceedance (P_c) equal to 0.05, 0.10,.., 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 (62). The demand pattern for TF1 and TF2 network is the same, whereas the demand pattern for CAT network is different. The Demand Scenarios for the CAT, TF1 and TF2 network are reported in Figure 27.

Table 30 provides 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. 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 30 shows that the most important sub-criterion in PS design is C8 (Operational costs) with a score of 0.19, followed by C3 (Control system complexity) 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.

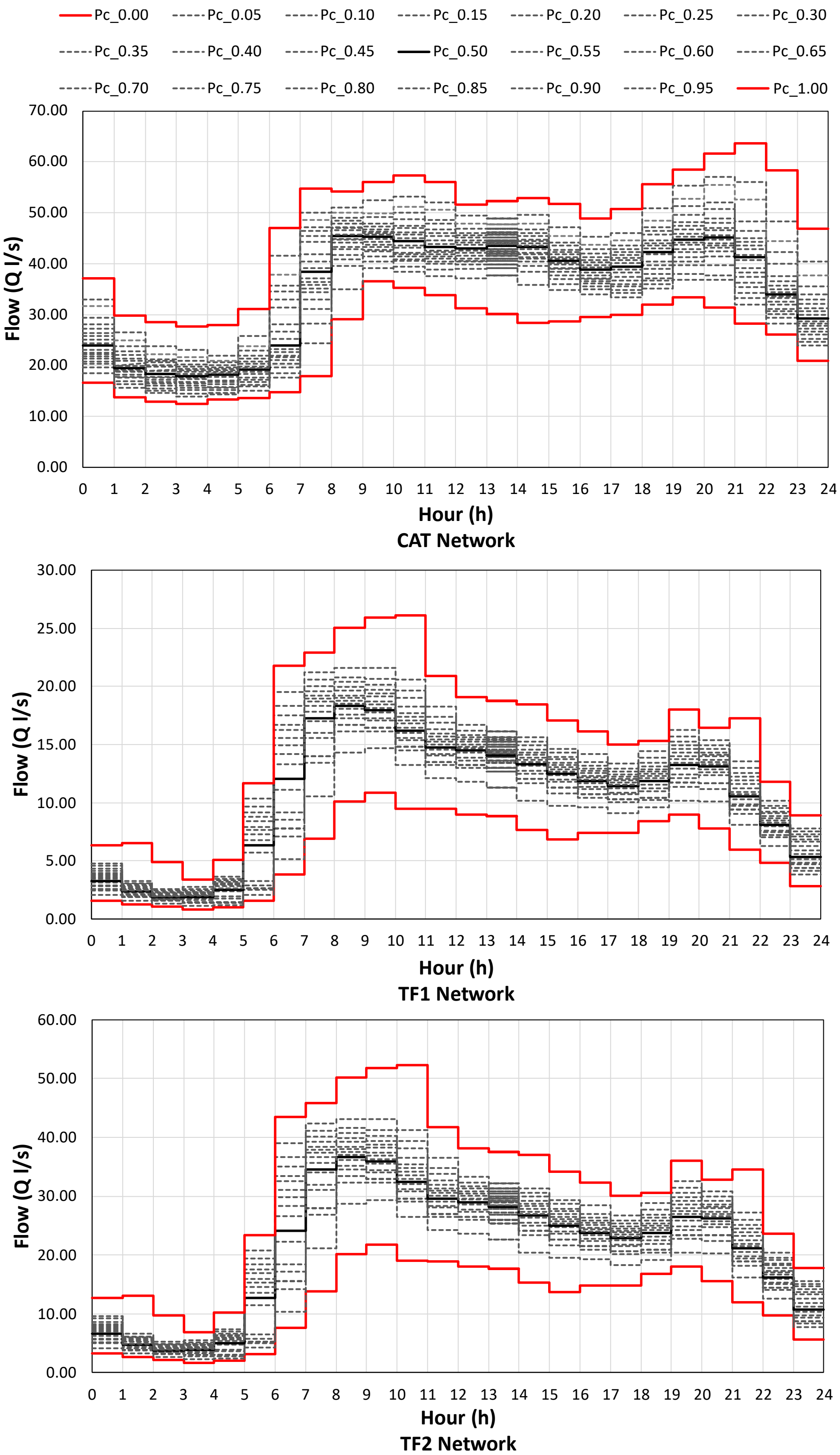


Figure 27. Demand Pattern Scenarios for CAT, TF1 and TF2 WDN

Table 30. Importance priority of technical, environmental, and economic criteria in every group of experts

Group of Experts	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

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.

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 without control system optimization. Run 2 is drawn from the work of Briceño-León et al. [114] 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 23). Finally, Run 4 is an upgrade of Run 3, incorporating the multiple demand scenarios in the first and second stages of the methodology.

5.3.2. Results

Table 31-33 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.

Table 31. Ultimate solutions (CAT-PS) four 5 run optimizations

Parameters of Design		**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	35.5	35.5	35.5	35.5
	Q_{max} (l/s)	45.4	45.4	45.4	45.4	63.6
	Q_{min} (l/s)	17.9	17.9	17.9	17.9	12.5
	ΔH (m)	20.0	20.0	20.0	20.0	20.0
	R	0.0040	0.0040	0.0040	0.0040	0.0040
	c	2	2	2	2	2
	H_{max} (m)	28.2	28.2	28.2	28.2	36.0
	H_{min} (m)	21.3	21.3	21.3	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 (m^2)	129.6	129.6	129.6	140.8	192.5
	C2	2	2	2	4	4
	C3	2 VSP with FC	2 VSP with FC	2 FSP with NC	4 FSP with NC	4 VSP with FC
Environmental Criteria	C4	0.36	0.36	0.36	0.7	0.7
	C5 (kg)	40025	40025	59885	46098	39021
	C6 (%)	100%	100%	72%	83%	100%
Economic Criteria	C7 (€/year)	3,153.30	3,153.30	2489.42	5,022.77	12,762.06
	C8 (€/year)	9,465.32	9,308.87	13558.05	10,442.70	9,033.59
	C9 (€/year)	890.95	890.95	731.00	1,279.92	1,341.26
LCC (€/year)		13,509.57	13,353.12	16,778.47	16,745.39	26,136.91

C1 Size of the PS; C2: Flexibility of the PS (number of pumps); C3: Control system; C4 MEI; C5: Greenhouse emission; C6: Performance of the regulation system; C7: Investment costs; C8: Operational costs; and C9: Maintenance costs.

Table 32. Ultimate solutions (TF1-PS) four 5 run optimizations

Parameters of Design		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	10.61	10.61	10.61	10.61
	Q_{max} (l/s)	18.3	18.3	18.3	18.3	26.1
	Q_{min} (l/s)	1.9	1.9	1.9	1.9	0.8
	ΔH (m)	51.19	51.19	51.19	51.19	51.19
	R	0.0059	0.0059	0.0059	0.0059	0.0059
	c	2	2	2	2	2
	H_{max} (m)	53.2	53.2	53.2	53.2	55.2
	H_{min} (m)	51.2	51.2	51.2	51.2	51.2
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 (m^2)	51.75	51.75	51.75	51.75	77.40
	C2	2	2	2	2	2
	C3	2 VSP with PC	2 VSP with PC	2 FSP with NC	2 FSP with NC	2 FSP with PC
Environmental Criteria	C4	0.70	0.70	0.70	0.70	0.10
	C5 (kg)	27434	26890	38686	36714	40544
	C6 (%)	98%	98%	78%	90%	90%
Economic Criteria	C7 (€/year)	4,290.27	4,290.27	3,574.13	2,214.51	2,359.91
	C8 (€/year)	6,324.40	6,200.03	8,761.07	8,295.10	9,113.48
	C9 (€/year)	801.82	801.82	700.12	700.12	717.77
LCC (€/year)		11,415.99	11,292.11	13,035.32	11,209.73	12,191.16

C1 Size of the PS; C2: Flexibility of the PS (number of pumps); C3: Control system; C4 MEI; C5: Greenhouse emission; C6: Performance of the regulation system; C7: Investment costs; C8: Operational costs; and C9: Maintenance costs.

Table 33. Ultimate solutions (TF2-PS) four 5 run optimizations

Parameters of Design		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	21.23	21.23	21.23	21.23
	Q_{max} (l/s)	36.7	36.7	36.7	36.7	52.3
	Q_{min} (l/s)	3.8	3.8	3.8	3.8	1.7
	ΔH (m)	30.0	30.0	30.0	30.0	30.0
	R	0.0142	0.0142	0.0142	0.0142	0.0142
	c	2	2	2	2	2
	H_{max} (m)	49.1	49.1	49.1	49.1	68.8
	H_{min} (m)	30.2	30.2	30.2	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
Technical Criteria	C1 (m^2)	129.6	129.6	129.6	115.20	192.5
	C2	2	2	2	4	6
	C3	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	0.26	0.26	0.26	0.7	0.7
	C5 (kg)	44479	43656	56706	42578	40098
	C6 (%)	100%	100%	81%	86%	100%
Economic Criteria	C7 (€/year)	3,423.57	3,423.57	2,705.50	7,001.67	11,363.13
	C8 (€/year)	10,267.82	10,078.69	13,041.15	9,779.13	9,259.79
	C9 (€/year)	890.95	890.95	737.07	1,366.95	2,050.51
LCC (€/year)		14,581.44	14,393.21	16,483.72	18,147.75	22,673.44

C1 Size of the PS; C2: Flexibility of the PS (number of pumps); C3: Control system; C4 MEI; C5: Greenhouse emission; C6: Performance of the regulation system; C7: Investment costs; C8: Operational costs; and C9: Maintenance costs.

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 28 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.

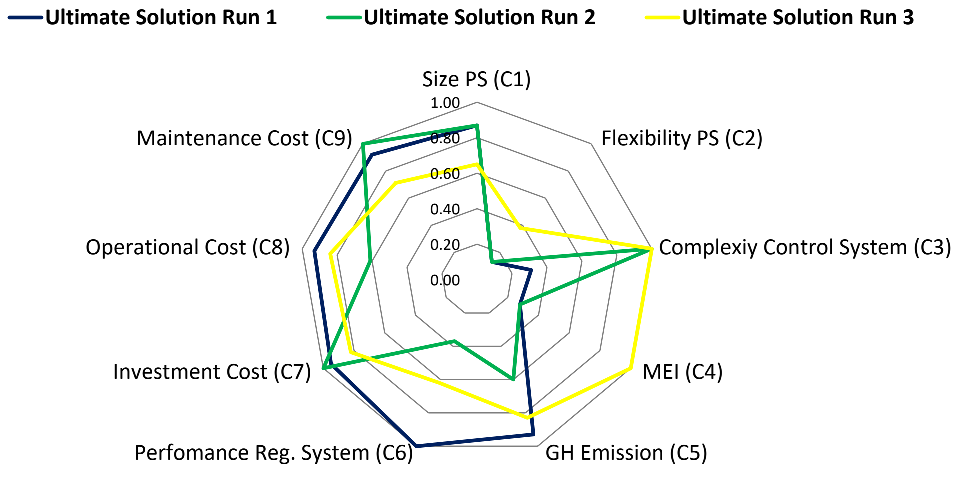


Figure 28. Radial Chart of AHP scores of the nine subcriteria considered in AHP for the three ultimate solutions of PS design in the CAT network

As an additional example of the results yielded by the methodology, Figure 29 and Figure 30 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 five 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.

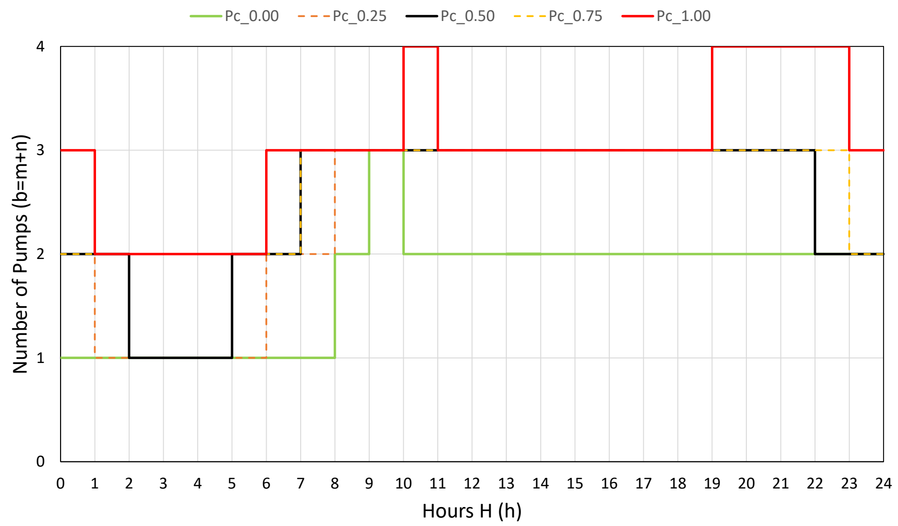


Figure 29. Number of Pumps in operation (b =0 FSP-n VSPs) in CAT-PS (run 4) in every time slot for different demand pattern scenarios

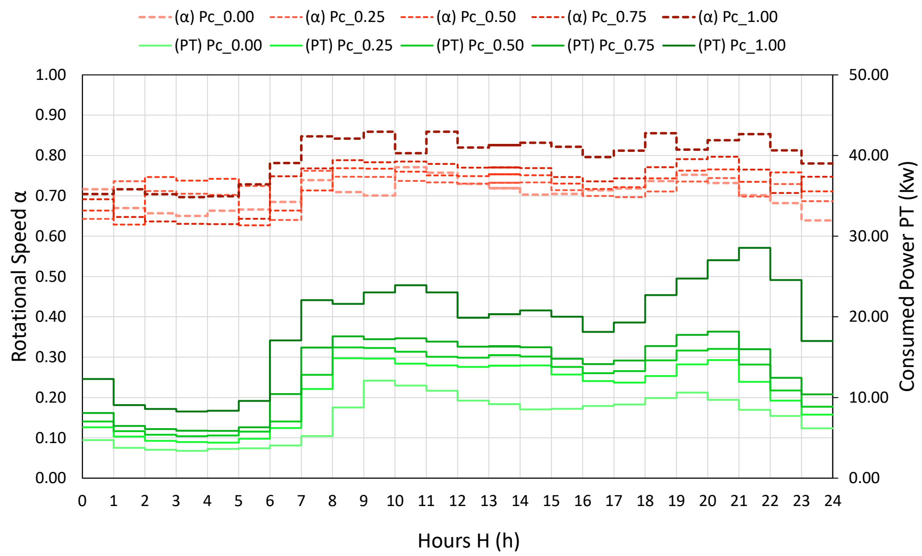


Figure 30. Ratio of rotational speed ratio (α = N/N0) of VSPs and Consumed Power (PT) in CAT-PS (run 4) in every time slot for different demand pattern scenarios

5.3.3. 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.

<u>Comparison of design based on minimization of LCC without and with control system optimization</u>

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 31-33). 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 [89]. 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.

<u>Comparison of design based on minimization of LCC and on AHP</u>

As Tables 31-33 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 VSP 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 31-33). 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 with NC). 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 31, 32 and 33). 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 VSP 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 plays 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.

5.4. Conclusions

In this study, 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 PS with storage.

5.5. Appendix section[2][3]

5.5.1. Economic criteria

Investment costs

This cost entails the purchase and installation of the elements of the pumping station including the pumps, pipes, valves, minor accessories, and control system devices. The expression to determine the investment cost and the installation cost of the elements of the pumping station are based on the work Briceño-León et al. [112]. Nevertheless, this proposed work generalized the installation cost of the elements of the pumping station with a equation showed in Table 34.

$$C_{Inv} = \left[(C_{PS} \cdot b) \cdot FA_{PS} + \left(C_{pipe} \cdot L_T\right) \cdot FA_{pipe} + \left(\sum_{i}^{Acc_i} C_{Acc_i} \cdot N_{Acc_i} \right) \cdot FA_{Acci} + \left(\sum_{j}^{RM_j} C_{RM_j} \cdot N_{RM_j} \right) \cdot FA_{RMj} \right] \quad (67)$$

Where C_{Inv} = investment cost of the pumping station; C_{PS} = unit cost of every pump unit; b = number of pumps installed in the station; FA_{PS} = pump amortization factor; C_{pipe} = unit cost of pipelines; L_T = total length of the pipelines; FA_{pipe} = pipeline amortization factor; C_{ACCi} = unit cost of every minor accessory in the station (e.g., valves, elbow or tee connectors); N_{ACCi} = number of units of every one of minor accessory in the PS; FA_{ACCI} = amortization factor of every one of the minor accessories; C_{RMj} = unit cost of every device of the control system (pressure switch, flow meters, pressure transducer, PLC, VFD); N_{RMj} = number of units of every one of the devices in the control system; FA_{RMj} = amortization factor of the devices of the control system.

The unit cost of all the elements in the PS includes the purchase and the installation cost. The costs of the pump, PLC, pressure transducer and pressure switch are obtained from a database of the commercial cost provided by the factory, while the unit cost of pipelines, valves, elbow, tee connectors, flow meter and the VFD are obtained by mathematical expression. This expression is obtained by the adjust of commercial costs from catalogues to a polynomic equation. This general expression is shown in the following Table 34.

The amortization factor (*FA*) of every one of the elements in the PS is obtained by.

$$FA_i = \frac{T_i \cdot (1 + T_i)^{N_{LC}}}{(1 + T_i)^{N_{LC}} - 1} \quad (68)$$

[2] The published technical article presented in this chapter 5 includes an appendix section. This section is relevant for the development of this methodology. For instance, this appendix section is described as a sub-index in this chapter 5.

[3] It is important to mention that the appendix section of the technical article included a database of the pump models. However, this database is presented in the annexes section of this thesis.

The terms FA_i = amortization factor of the elements in the infrastructure of the PS; Ti = annual interest rate; N_{LC} = number of life-cycle years of the elements in the PS.

Table 34. Unit Cost of different elements in a Pumping Station

$C_{(x)} = C_1 + C_2 \cdot X + C_3 \cdot X^2 + C_4^{C_5 \cdot X}$						
Element	X	C_1	C_2	C_3	C_4	C_5
Pipe	ND (mm)	10.13	0.20	0.0005		
Elbow connector	ND (mm)	-	-	-	29.17	0.01
Tee connector	ND (mm)	-	-	-	42.60	0.01
Section Valve	ND (mm)	63.63	0.79	0.01	-	-
Check Valve	ND (mm)	35.63	-0.14	0.01	-	-
Flow meter	D_{in} (mm)	885.70	-9.22	0.06	-	-
Variable Frequency Drive	P (KW)	168.19	116.08	-0.60	-	-

The parameters and variables used in this table are the following.

- $C_{(X)}$: Function Cost of the element
- C_1, C_2, C_3, C_4, C_5 parameters of the polynomial equation
- X: Variable of the function
- *ND*: Nominal Diameter in mm
- D_{in}: Internal Diameter in mm
- P: Installed Power in KW

Maintenance Costs

These costs are associated to the maintenance activities and the frequency of implementation for the elements in the infrastructure of the PS. This cost is expressed annually, so the frequency of implementation of the activities are defined as the number of times to implement the maintenance activities in a year. Maintenance costs are defined in equation (69).

$$C_{Maint} = \left[\left(\sum_{i}^{APS_i} C_{APSi} \cdot F_{APSi} \cdot b \right) + \left(C_{pipe} \cdot F_{pipe} \cdot L_T \right) + \left(\sum_{j}^{Acc_j} C_{Acc_j} \cdot F_{Acc_j} \cdot N_{Acc_j} \right) + \left(\sum_{k}^{RM_k} C_{RM_k} \cdot F_{RM_k} \cdot N_{RM_k} \right) \right] \quad (69)$$

Where C_{Maint} = maintenance cost of the PS. The term C_{APSi} is the unit cost of maintenance activities related to the pump (subscript APS_i = every maintenance activity); F_{APi} = annual frequency of maintenance activities; b = the number of pumps in the PS; C_{pipe} = unit cost of the maintenance activity related to the pipelines, expressed in unit of length of the pipe (€/m). F_{pipe} = annual frequency of pipelines maintenance; L_T = total length of the pipes; C_{ACCj} = unit cost of the maintenance activity for the accessories in the PS (subscript Acc_j = accessories in the PS: valves, elbow, and tee connectors); F_{ACCj} = annual frequency of maintenance for each accessory; N_{ACCJ} = number of units of each accessory; $C_{RM,j}$ = unit cost of maintenance of every device of the control system in the PS (subscript RM_j = every devices in a control system: pressure switch, flow meter, transducer pressure, PLC, and VFD); F_{RMk} = annual frequency of maintenance and of every one of the devices in the control system; and N_{RMj} = number of units of every one of the devices in the control system. Every maintenance activity of the PS and their frequency of implementation is based on the recommendation for the factory of these elements. The unit cost is obtained from a database of maintenance costs. These data are showed in the following Table 35.

Table 35. Maintenance Activities in a Pumping Station

Activity	Annual Frequency	Unit Cost
Maintenance Activities in the pump		
Revision of the pump	12	1.48 €
Lubrication of mechanical elements by pumping unit	2	3.82 €
Measurement and analysis of electrical parameters and mechanical vibrations	2	20.18 €
Lubrication of electric motor bearings	2	5.84 €
Adjustment of fasteners per pumping unit	2	6.07 €
Electric motor insulation test	1	9.43 €
Winding resistance test	1	9.43 €
Maintenance Activity of the pipelines		
Pipeline per unit of length	2	1.07 €
Maintenance Activity of Valves		
Cleaning, Analysis of vibrations, and changes of accessories in the valves	1	46.40 €
Maintenance Activity of Minor Accessories		
Elbow, Tee connectors	2	1.07 €
Maintenance Activities of Devices in the Control System		
Pressure switch	2	3.03 €
PLC	1	37.34 €
Transducer Pressure	2	9.75 €
Frequency Drive	1	22.43 €
Flow and Pressure meter	1	58.26 €

5.5.2. AHP method

This method determines the priority or importance weight of the criteria considered in a PS design. The group of experts judges how important is one criterion over another through a numeric scale (1, 1.5, 2.33, ,4 and 9), where 1 means the same importance and 9 the maximum importance. The pairwise comparisons of the criteria are organized in a quadratic matrix of (*Nc x Nc*), where *Nc* is the number of criteria, and these criteria are placed in rows and columns of the matrix to form a the pairwise comparisons values of one criterion over another ($a_{i,j}$). The sub-term *i* represent the criteria placed in rows and *j* represents the criteria placed in columns. These pairwise comparisons are reciprocal to each other (i.e., the reciprocal comparison $a_{i,j}$ is represented by $a_{j,i}$ and is defined by the relation $1/a_{i,j}$).

Table 36 illustrates an example of pairwise comparison values ($a_{i,j;}$ $a_{j,i}$) of two criteria (*Nc* = 2), C1 and C2 to show how calculate the importance weight of every criterion. The term $Na_{i,j}$ are the normalized values of the pairwise comparison of the criteria ($a_{i,j}$) and C_i is the Priority of every i criterion. These terms are obtained as is shown in the equations of Table 36. In addition, Table 37 shows the comparison of the conventional AHP scale with the proposed scale.

Table 36. Importance Weight of a pairwise comparison criteria C1 and C2

	Pairwise comparison		**Normalized Values**		**Priority**
	C1 ($a_{i,j}$)	C2 ($a_{i,j}$)	$Na_{i,j} = \frac{a_{i,j}}{\sum_{i=1}^{i=Nc} a_{i,j}(columns)}$		$C_i = \frac{\sum_{i=1}^{i=Nc} Na_{i,j}(rows)}{Nc}$
C1 ($a_{j,i}$)	1	4	0.80	0.80	0.80
C2 ($a_{j,i}$)	1/4	1	0.20	0.20	0.20
$\sum_{i=1}^{i=Nc} a_{i,j}$	1.25	5			

Table 37. New Scale for pairwise comparison of the criteria

	Saaty's scale		**New scale**		
NS	C_i	C_j	C_i	C_j	NS
1	50.00%	50.00%	50.00%	50.00%	1.00
2	67.67%	33.33%	55.00%	45.00%	1.22
3	75.00%	25.00%	60.00%	40.00%	1.50
4	80.00%	20.00%	65.00%	35.00%	1.86
5	83.33%	16.67%	70.00%	30.00%	2.33
6	85.71%	14.29%	75.00%	25.00%	3.00
7	87.50%	12.50%	80.00%	20.00%	4.00
8	88.89%	11.11%	85.00%	15.00%	5.67
9	90.00%	10.00%	90.00%	10.00%	9.00

C_i, C_j: Importance percentages (%). NS: Numerical Scale

5.5.3. Assessment of Non-quantitative criteria

Complexity of the control system criterion

The criterion Complexity of the control system is assessed by a numeric score (from 0 to 1), whereas less complex is the control system high is the score. This numeric scale is obtained through a pairwise comparison of the control system strategies and the obtained priority of every control system strategy as is shown in Table 38. The relation of the priority of every control system strategy (C_i) and the maximum obtained priorities of the control system strategies (C_{max}) determines the score of every control system strategy.

Table 38. Numeric score of control system strategies.

Control System Strategies	1	2	3	4	5	Priority (C_i)	Score = $\frac{C_i}{C_{max}}$
1	1.00	1.22	1.50	2.33	4.00	0.33	1.00
2	0.82	1.00	1.22	1.50	2.33	0.24	0.72
3	0.67	0.82	1.00	1.22	1.50	0.19	0.57
4	0.43	0.67	0.82	1.00	1.22	0.14	0.44
5	0.25	0.43	0.67	0.82	1.00	0.11	0.32

<u>MEI index criterion</u>

In a similar way, the MEI index criterion is assessed through a numeric score from 0 to 1, where a high score is assigned if the MEI index is high. The scores of MEI index are obtained through a matrix of the pairwise comparison of the different values of MEI index in a pump model as is shown in Table 39.

Table 39. Numeric Score of MEI Index

MEI Values	0.1	0.2	0.3	0.4	0.5	0.6	0.7	Priority (C_i)	Score = $\frac{C_i}{C_{max}}$
0.1	1.00	0.82	0.67	0.43	0.25	0.18	0.11	0.04	0.15
0.2	1.22	1.00	1.00	0.67	0.43	0.25	0.18	0.07	0.21
0.3	1.50	1.22	1.00	0.82	0.67	0.43	0.25	0.09	0.28
0.4	2.33	1.50	1.22	1.00	0.82	0.67	0.43	0.12	0.38
0,5	4.00	2.33	1.50	1.22	1.00	0.82	0.67	0.16	0.52
0.6	5.67	4.00	2.33	1.50	1.22	1.00	0.82	0.22	0.71
0.7	9.00	5.67	4.00	2.33	1.50	1.22	1.00	0.31	1.00

Chapter 6. Case study and discussion

The development of this work consists of in three phases. The first phase is a methodology of optimization in PS control systems. The second phase is a methodology of a PS design considering technical and economic criteria based on the AHP. Finally, the third phase is an improvement of the second phase but including environmental criteria and demand variability in the PS design methodology. These three phases were presented in three technical papers, which are shown in chapters 3, 4 and 5 of this thesis. The three developed methodologies presented in the technical papers includes their own case study. However, this chapter presents two case studies to be applied in these three methodologies with the objective of making a general discussion of the methodologies developed in this work.

6.1. Data of the case study

Two case studies were considered in this work, namely AN and EF WDN. The yearly average demand of this work are 40.00 l/s and 24.00 l/s, respectively.

The database of the pump model used in the case studies is the same as that used in chapter 5. This database features the parameters of the head curve (*Q, H*), efficiency curve (*Q, η*), and the best efficient point (BEP) of the pump models. In addition, it includes their respective purchase, installation, and maintenance costs of pumps and accessories (see appendix section of Chapter 5).

In AN and EF WDN were considered the variability of demand. The demand patterns used in both networks are based on the case study of chapter 5. Both demand patterns are composed of 21 daily demand scenarios in a horizon time of a year. These demand scenarios are ordered from lowest to the highest daily demand scenario with a probability of non-exceedance (P_c) between to 0 and 1 with an increasing interval of 0.05. The demand pattern of AN and EF WDN are showed in Figure 31.

A single daily electric tariff is considered for both networks. This daily tariff is distinguished by off-peak, peak, and plain hour tariffs (see Figure 32).

All the required data for the case studies (i.e., database of pump models, unit costs of the elements in a PS, demand patterns, and electric tariff) were used in all developed methodologies in the same way in order to understand the effect of the proposed methodologies.

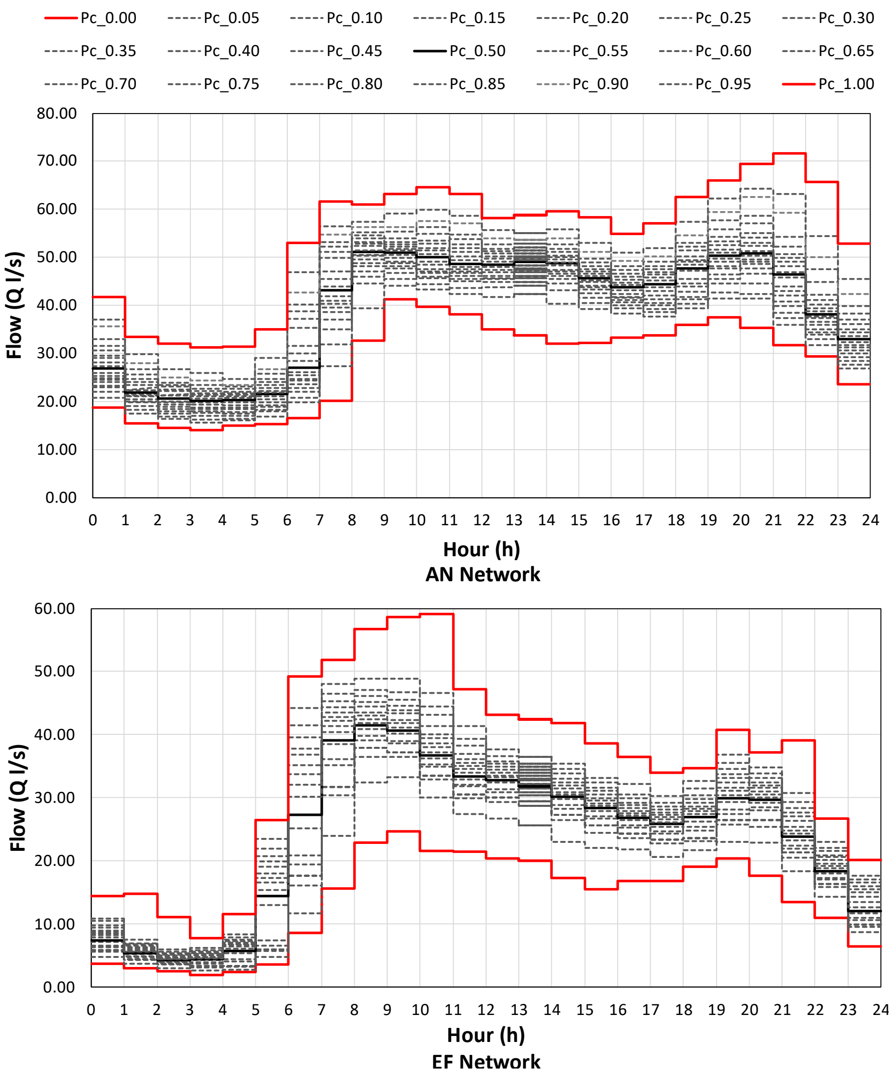


Figure 31. Demand Patterns of AN and EF WDN

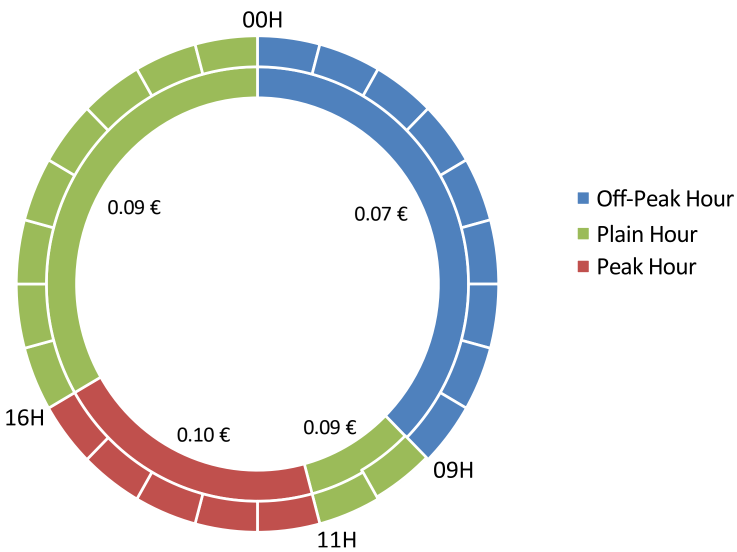


Figure 32. Electric Tariff

The framework of these developed methodologies is based on known hydraulic conditions of the network. In this way, Table 40 presents the hydraulic conditions of AN and EF networks under two demand analysis scenarios, single demand pattern (i.e., yearly average demand) and variability of demand. These hydraulic conditions include the mean flow, maximum flow, minimum flow (Q_m, Q_{max}, Q_{min}), the variables of the set-point curve (*ΔH, R, c*), and the maximum and minimum required head (H_{max}, H_{min}) in every demand analysis scenario. The mean flow (Q_m) of AN network is greater than EF network, but the slope of the set-point curve in AN network is lower than EF network. In short, the variation of critical conditions of head are similar for both networks.

Table 40. Hydraulic Conditions of AN and EF networks

	AN Network		EF Network	
Hydraulic Parameters	**Single Demand**	**Variability of Demand**	**Single Demand**	**Variability of Demand**
Q_m (l/s)	40	40	24	24
Q_{max} (l/s)	51.2	71.6	41.5	59.1
Q_{min} (l/s)	20.1	14	4.3	1.9
ΔH (m)	22	22	29.5	29.5
R	0.0035	0.0035	0.0109	0.0109
c	2	2	2	2
H_{max} (m)	31.2	38.8	48.2	67.5
H_{min} (m)	23.4	22.7	29.7	29.5

6.2. Results

6.2.1. Operating optimization of PS control systems

The proposed methodology for the optimization of the PS control system is based on known hydraulic conditions of the network (see Table 40) and a pump model previously defined. The objective of the first phase of this work (optimization of the PS control system) is to compare the classical PS control system and the proposed control system optimization control system in terms of operational costs. In this way, this framework was applied in AN and EF networks. The variability of demand was considered in the operation of both networks.

Table 41 shows the characteristics of the pumps defined to operate in each WDN. These characteristics includes the pump model number, the BEP of the pumps (Q_0, H_0, η_0), the characteristic parameters of the pumping curve (H_1, *A, B*) and efficiency curve (*E, F*), the required number of pumps, and the control system configuration.

Table 41. Pump Characteristics of AN and EF Network

Parameters of the pump	**AN Network**	**EF Network**
Model	61	56
Q_0 (l/s)	19.16	13.41
H_0 (m)	48.81	75.73
η_0 (%)	83%	80%
H_1	65.09	100.97
A	$4.43 \cdot 10^{-2}$	$1.40 \cdot 10^{-1}$
B	2	2
E	$8.67 \cdot 10^{-2}$	$1.19 \cdot 10^{-1}$
F	$2.26 \cdot 10^{-3}$	$4.45 \cdot 10^{-3}$
b	3 pumps	4 pumps
Control System	3 VSP with FC	4 VSP with FC

Table 42 shows the results of the total number of pumps (b_T), the annual operational cost of both WDN applying the classical control system operation and the optimization of the control system. In addition, this Table 42 shows the percentage of operational costs savings in the network as result of the optimization of the PS control system. As expected, there is a significant save of energy consumption in both networks when the control system of the PS is optimized.

Table 42. Classic Control System Operation and Optimization of Control System Operation for AN and EF PS

		AN-PS Control System Operation		**EF-PS Control System Operation**	
		Classic	**Optimization**	**Classic**	**Optimization**
Results	b_T	3 pumps	4 pumps	4 pumps	4 pumps
	Op. Cost (€)	11,856.57 €	10,446.85 €	10,943.63 €	9,784.37 €
Ope. Cost Savings (%)		12%		11%	

The difference of the classical control system and the optimization of the control system in a PS operation could be better illustrate in Figure 33 and Figure 34 for AN network and Figure 35 and Figure 36 for EF networks. Figure 33 and Figure 35 represents the number of pumps (*b*) in operation in every time slot with the classic control system operation and with the optimization of the control system for AN and EF WDN. Figure 34 and Figure 36 represents the consumption power by the PS (P_T) in every time slot with the classic control system operation and with the optimization of the control system for AN and EF networks. These Figures 33-36 show the temporal pattern of the number of pumps and power consumption for 1 of the 21 daily demand scenarios. As expected, the temporal pattern of the optimal number of pumps are not necessary the same as the number of pumps in the classic control system operation. In addition, the temporal power consumption of the PS with the optimization of the control system is lower than the classical control system.

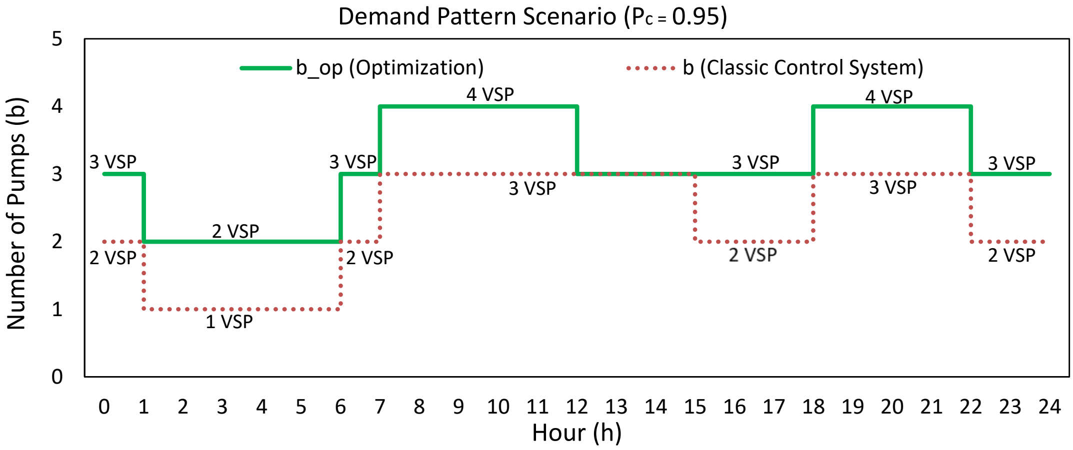


Figure 33 . Number of pumps in every time slot with the classic control system and with the optmization of the contorl system for AN network

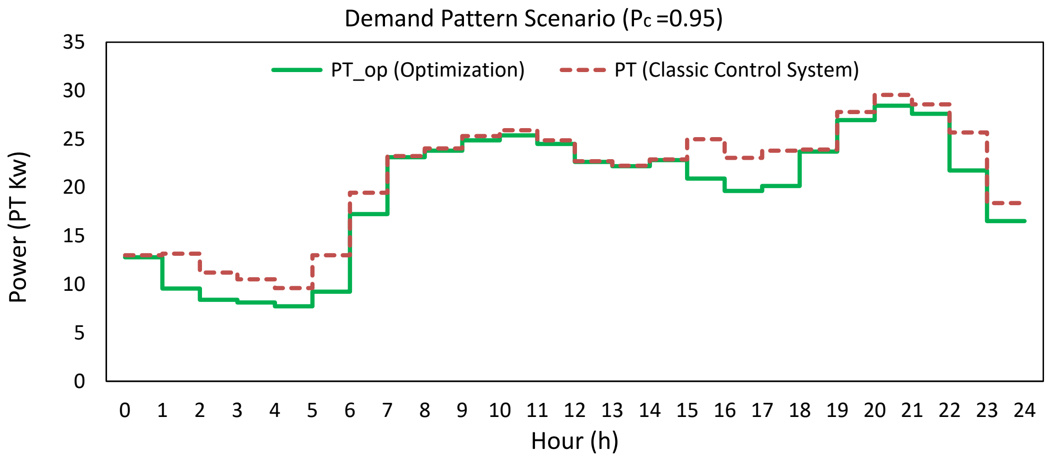


Figure 34. Consumption Power of the PS with the classic control system and with the optimization of the control system for AN network

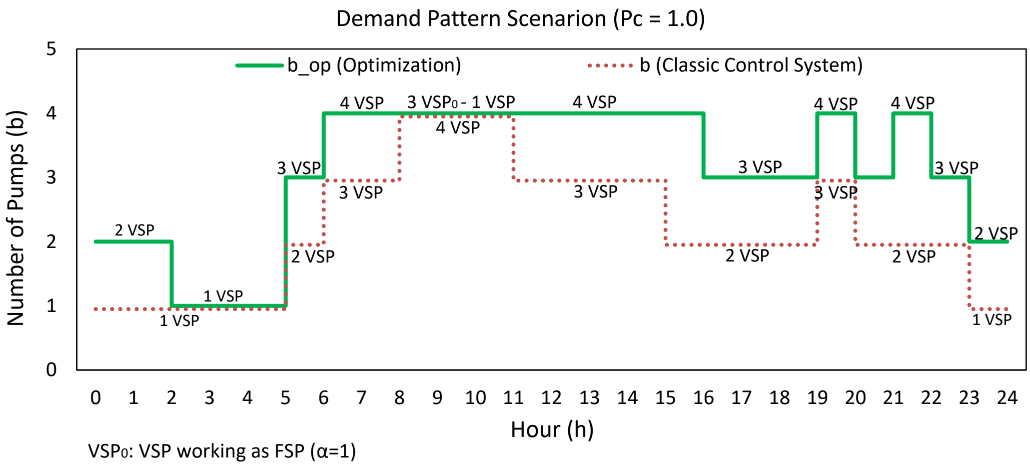


Figure 35. Number of pumps in every time slot with the classic control system and with the optimization of the control system for EF network

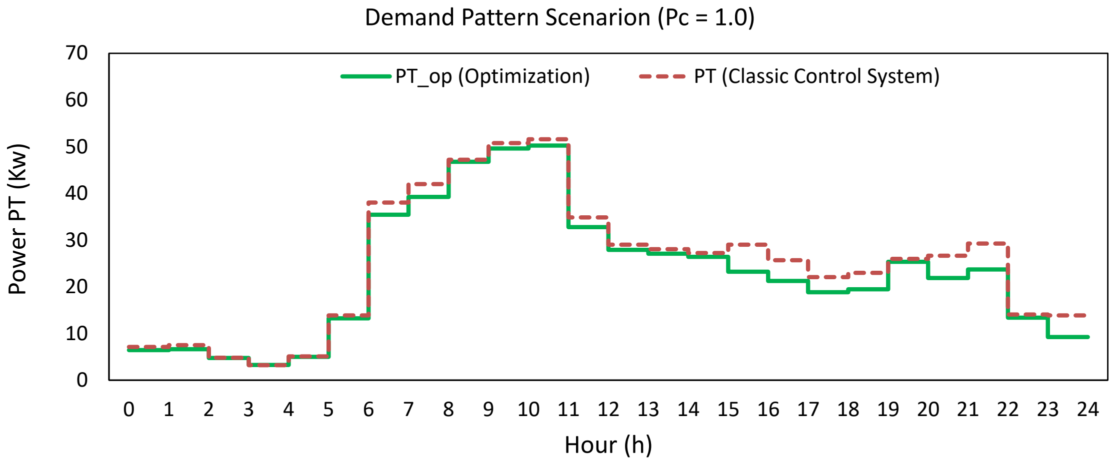


Figure 36. Consumption Power of the PS with the classic control system and with the optimization of the control system for EF network

As an additional example to illustrate how the optimal control system of a PS operates in contrast to the classic control system, Figure 37 shows the optimal number of pumps in operation (b_{op}) and the number of pumps according to the classic control system (*b*) in every flow rate for AN network. Also, this Figure 37 displays the limits of operational range for each number of pumps according to the classic control system. These limits are represented by dot lines in the figure. As shown, the number of pumps in operation of the classic control system *(b)* change as the operational range, whereas the optimal number of pumps (b_{op}) does not necessarily follow the minimum number of pumps (b_{min}) for each operational range.

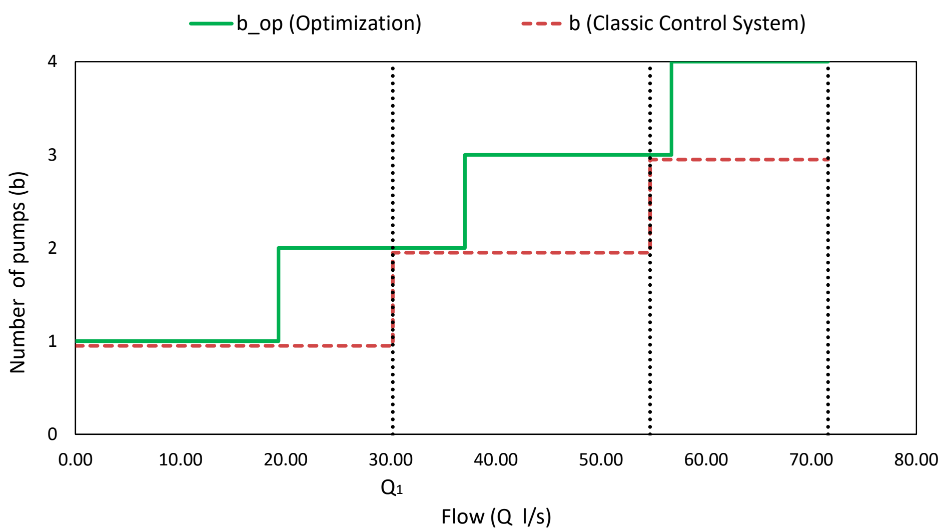


Figure 37. Optimal number of pump (b_{op}) and the number of pumps of the classic control system (b) for AN network

6.2.2. Pumping station design approaches

The second and third phase of this thesis are related with the two PS design approaches developed during this work. The second phase developed a first PS design approach considering technical and economic criteria based on AHP. The third phase developed a second PS design approach incorporating the optimization of control system, the consideration of environmental criteria and variability of demand in the design process. In addition, this PS design approach proposed a new scale of evaluation in the AHP.

The aim of these PS design approaches is to analyze the effects of considering the optimization of the control system during the design process, the effects of considering technical and environmental criteria, and the variability of demand in a PS design. In this way, these PS design approaches were discretized into 5 PS design proposals for AN and EF network in the case study in order to analyze the effects of each one of different criteria considered for the PS design.

- Proposal 1 represents the classic method used in a PS design based on LCC minimization without AHP method. In addition, this proposal does not include the optimization of the control system operation and it is based on a single demand scenario.
- Proposal 2 considers technical criteria (e.g., number of pumps, and complexity of control system) and economic criteria (investment, operational and maintenance costs) applying the AHP in the PS design and based in a single demand scenario.
- Proposal 3 is an improvement of Proposal 2, modifying the conventional AHP scale and considering the optimization of control system operation during the design process.
- Proposal 4 is an upgrade of Proposal 3. This proposal discretizes the sub-criterion number of pumps as two technical sub-criteria, size of the PS and flexibility of PS. In addition, it incorporates environmental criteria (e.g., MEI, GHG emissions, and efficiency of regulation) in the AHP.
- Proposal 5 represent the final propose of this work and is an upgrade of run 4 considering variability of daily demand scenarios in a year horizon time.

Tables 43 and 44 summarized all the criteria and sub-criteria considered in a PS design during the development of different design proposals.

Table 43. Definition of the criteria and sub-criteria considered in proposals 2 and 3

Criteria	**Sub Criteria**	
Technical Criteria	Number of pumps	C1
	Complexity of Control System	C2
Economic Criteria	Investment Cost	C3
	Operational Cost	C4
	Maintenance Cost	C5

Table 44. Definition of the criteria and sub-criteria considered in proposals 4 and 5

Criteria	Sub Criteria	
Technical Criteria	Size of PS	C1
	Flexibility of PS	C2
	Complexity of Control System	C3
Environmental criteria	MEI	C4
	GHG Emission	C5
	Efficiency of regulation	C6
Economic Criteria	Investment Cost	C7
	Operational Cost	C8
	Maintenance Cost	C9

The overall priorities of technical, economic, and environmental criteria with their respective sub-criteria in the different five PS design proposals are detailed in Tables 45 and 46. The priorities are expressed in a scale from 0 to 1. The higher score, the higher priority the criterion has in the PS. These results were obtained from pairwise comparisons based on the results of the surveys in different group of experts. These 45 and 46 show that in proposals 2, 3, 4 and 5, the economic criteria have the highest priority for a PS design, followed by technical criteria. Environmental criteria are neglected in proposals 2 and 3, while in proposals 4 and 5 environmental criteria have the lowest priority. In proposals 2 and 3, the ranking of priorities of the sub-criteria are the same but with different scores. The sub-criterion operational cost has the highest priority for the PS design in proposals 2 and 3, while the sub-criterion complexity of control system has the lowest priority in proposals 2 and 3. In proposals 4 and 5, the highest priority is the sub-criterion operational cost, while the lowest priority is the environmental sub-criteria MEI.

Table 45. Importance weight of Criteria and Sub-Criteria in the design proposals 1,2 and 3

Criteria			Proposal 1	Proposal 2	Proposal 3
	Technical Criteria		-	0.33	0.33
	Economic Criteria		-	0.67	0.67
Technical Criteria	Number of Pumps	C1	-	0.2	0.19
	Complexity of Control System	C2	-	0.13	0.14
Economic Criteria	Investment Cost	C3	-	0.14	0.17
	Operational Cost	C4	-	0.31	0.29
	Maintenance Cost	C5	-	0.21	0.21

Table 46. Importance weight of Criteria and Sub-Criteria in the design proposals 4 and 5

Criteria			Proposal 4	Proposal 5
Technical Criteria			0.36	0.36
Environmental Criteria			0.19	0.19
Economic Criteria			0.45	0.45
Technical Criteria	Size of the PS	C1	0.08	0.08
	Flexibility of operation	C2	0.13	0.13
	Complexity of control system	C3	0.15	0.15
Environmental Criteria	MEI	C4	0.06	0.06
	GHG emissions	C5	0.05	0.05
	Efficiency of regulation	C6	0.08	0.08
Economic Criteria	Investment cost	C7	0.13	0.13
	Operational cost	C8	0.19	0.19
	Maintenance cost	C9	0.13	0.13

The ultimate solutions of the five design proposals for the PS in AN and EF networks are showed in Tables 47 and 48 respectively. These tables describe the characteristics of the pump model selected in every design proposal. These pump characteristics includes the BEP (Q_0, H_0, η_0) and the minimum number of pumps required (b_{min}). In addition, these tables show the characteristic of the 9 sub-criteria considered in the PS for each solution of the 5 design proposals for AN and EF networks. As expected, every proposal for the PS design in both networks yields different solutions and with different characteristics in the 9 sub-criteria. The differences of every PS design approach will be analyzed later in the discussion section of this work.

Table 47. Ultimate Solutions of the five design proposals in AN WDN

		AN Network				
		Single Demand				Var. Demand
		Proposal 1	Proposal 2	Proposal 3	Proposal 4	Proposal 5
Pump model Selected	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	6	3
Technical Criteria	C1 (m^2)	154	154	154	144	193
	C2	2	2	2	6	4
	C3	2 VSP & FC	2 FSP & PC	2 VSP & FC	6 FSP & FC	4 VSP & FC
Environmental Criteria	C4	0.36	0.36	0.36	0.7	0.7
	C5	48920	55491	47611	47425	47467
	C6 (%)	100%	87%	100%	93%	100%
Economic Criteria	C7 (€/year)	3,267.28	2,616.48	3,267.28	7,222.05	12,762.06
	C8 (€/year)	11,381.90	12,819.45	11,073.58	10,993.88	10,988.36
	C9 (€/year)	897.39	743.50	897.39	1,918.87	1,341.26
LCC (€)		15,546.56	16,179.44	15,238.24	20,134.80	25,091.68

Table 48. Ultimate Solutions of the five design proposals in EF WDN

		EF Network				
		Single Demand				Var. Demand
		Proposal 1	**Proposal 2**	**Proposal 3**	**Proposal 4**	**Proposal 5**
Pump Characteristics	Model	30	64	32	60	56
	Q_0 (l/s)	19.47	24.25	22.71	16.64	13.41
	H_0 (m)	47.65	32.72	61.06	44.99	75.73
	η_0 (%)	70%	77%	61%	83%	80%
	b_{min}	3	2	2	3	4
Technical Criteria	C1 (m^2)	123	130	130	123	141
	C2	3	2	2	3	4
	C3	3 VSP & FC	2 FSP & NC	2 VSP & FC	3 FSP & PC	4 VSP & FC
Environmental Criteria	C4	0.10	0.70	0.10	0.7	0.7
	C5	48196	72184	55585	51544	42399
	C6 (%)	100%	64%	100%	81%	100%
Economic Criteria (€/year)	C7	4,320.39	6,704.03	4095.24	6,116.02	13,018.18
	C8	11,119.74	16,354.37	12,829.65	11,794.97	9,784.37
	C9	1,184.63	731.00	890.50	1,008.31	1,484.74
LCC (€)		16,624.76	23,789.40	17,815.85	18,919.30	24,287.29

The weighted scores of the 9 sub-criteria considered in the PS design with their respective importance weight were calculated for the PS solutions in the five proposals for AN and EF networks in order to compare the performance in the sub-criteria for the five PS design proposals. The obtained scores of the ultimate solutions of the five design proposals were obtained by comparing all the potential solutions in every one of the five proposals. The obtained scores of the ultimate solutions in every PS design proposal in the 9 sub-criteria are described in a radial chart in Figures 38 and 39 for AN and EF network respectively.

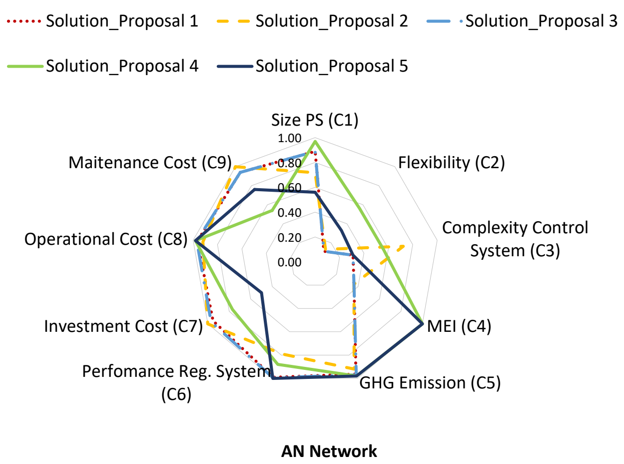


Figure 38. Radial chart of AHP scores considered in the 9 sub-criteria for the solutions of the five design proposals in AN network.

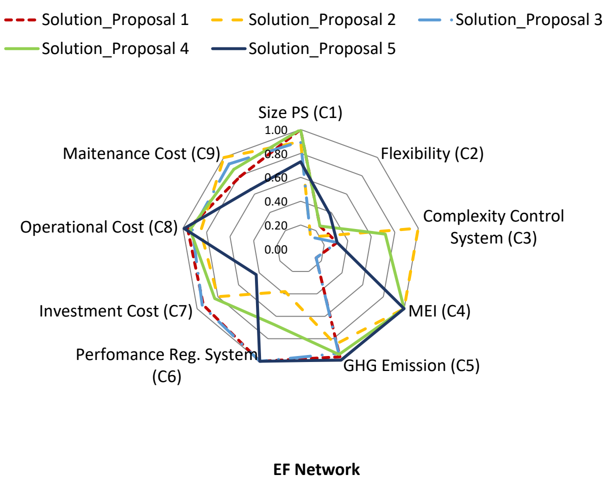


Figure 39. Radial chart of AHP scores considered in the 9 sub-criteria for the solutions of the five design proposals in EF network.

The solution of proposal 4 (modified AHP considering technical, economic, and environmental criteria with control system optimization) and proposal 5 (including variability of demand) in both networks stands out from the solutions of the other proposals with a balanced performance in the scores obtained in the 9 criteria. Even though proposal 5 has higher stressing condition of demand than the other 4 proposals, the performance in environmental sub-criteria and in operational costs are excellent and in other cases are higher than in the other proposals. On the other hand, the principal characteristic of the solutions in proposal 3 (Modified AHP considering technical and economic criteria with control system optimization) in both networks are that they have a balanced performance in the scores of the sub-criteria size of the PS, investment cost, operational cost, and maintenance cost. In a similar way, the main feature of the solutions in proposal 2 (AHP considering technical and economic criteria without control system optimization) in both networks were highlighted for having a balanced performance in the scores of the sub-criteria size of the PS, complexity of control system, investment cost and maintenance cost.

The main difference of the solutions in proposal 3 and 2 lies in the control system. The original AHP evaluation scale performed in proposal 2 made that the difference in scores between different control systems was high, especially with the type of pump used (FSP or VSP) in the control system. Therefore, the solutions in proposal 2 in both networks are restricted with simple control system. On the contrary, the modified AHP performed in proposal 3 made that the difference in scores between the different control system was lower and the yielded solutions are not restricted with simple control system. On, the other hand, the solutions of proposal 1 (classic design) in both networks were highlighted for having high scores in the sub-criteria investment, operational, and maintenance costs.

In order to show the effects of increasing the stressing conditions of demand in the operation of a PS, Figures 40 and 41 illustrate the number of pumps in operation (b), the rotational speed ratio (α) and the consumed power (P_T) in every time slot of the ultimate solution of proposal 5 (based on the modified AHP considering technical, economic and environmental criteria and multiple daily demand scenarios) for AN network. These figures show the temporal patterns for five different scenarios of probability of non-exceedance of the daily demand (*P_c = 0.05*; *P_c = 0.25*; *P_c = 0.50*; *P_c = 0.75*; *P_c = 1*). As it was expected, the variables of the PS (*b, α, P_T*) increase in every time slot as the daily demand increase.

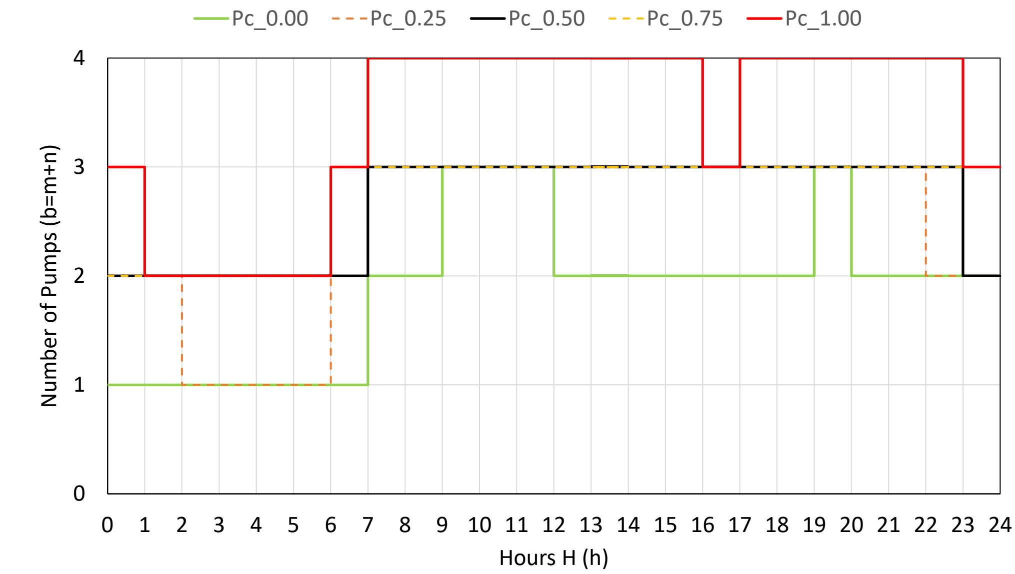


Figure 40- Temporal pattern of the number of pumps (0 FSP- 4VSP) of the ultimate solution in proposal 5 for different daily demand scenarios in AN Network

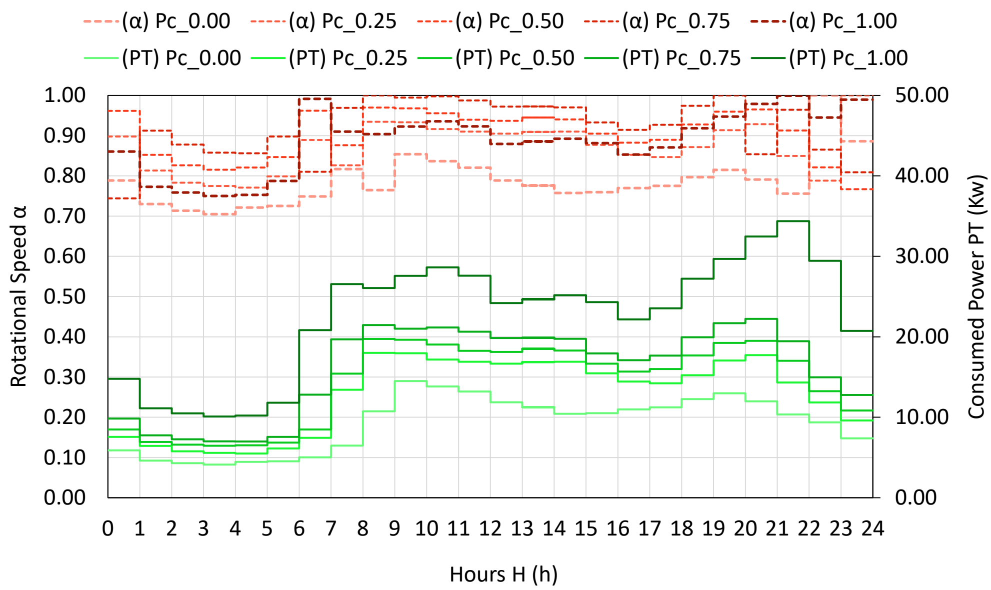


Figure 41. Temporal pattern of the rotation speed ration (α=N/N_0) of VSP (same value for all the VSP) and consumed power (P_T) of the ultimate solution in proposal 5 for different daily demand scenario in AN Network

6.3. Discussion

6.3.1. Effects of considering the optimization of control system during the process of PS design

The optimization of the control system in the PS design means important savings in the energy consumption in AN and EF networks in comparison when the PS operates according to the classic control system (See table 42). An important aspect to highlight in the optimization of the control system in the PS is the optimal number of pumps (b_{op}) is not necessarily the minimum number of pumps according to the operational range of the PS (see Figure 37). In fact, a number of VSP greater than the minimum required could mean a lower energy consumption in the PS. Besides, a greater number of pumps improves the flexibility of PS operation in stressing demand conditions and improves the PS efficiency.

In addition, the optimization of the PS control system allows to redefine the total number of pumps (b_T) as evidenced in the ultimate solution of the design proposal 5 in AN network (see Table 47). In this specific case, the total number of pumps (b_T) was redefined to 4 pumps instead of 3 pumps that is the minimum required number. This insight is one of the principal contributions of this work, when usually the optimization of PS operation is restricted to the number of pumps previously defined in the design. In short, the main effects of considering the optimization of control system in a PS design are that the optimization process improves the performance of the sub-criteria operational costs, GHG emission and sometimes it could improve the performance in the flexibility of the PS operation.

6.3.2. Effects of considering techno-economic criteria based on AHP in contrast to classic PS design

In both networks, the ultimate solutions of design proposal 2 (AHP to technical and economic criteria without control system optimization) tends to feature simpler control systems than in approach 1 (See Tables 47 and 48). In the opposite way, the solutions of proposal 1 (classic design) feature low annual costs of investment, operational and maintenance. For example, in AN network where the mean flow is higher than EF network and the slope of the set-point curve is lower than EF network, the pump models of the solutions in proposals 1 and 2 are the same. The difference of the solutions in proposals 1 and 2 lies in the control system. Proposal 1 yields a solution of 2 VSP with FC, while proposal 2 yields a solution of 2 FSP with PC.

In the case of EF network with a mean flow lower than AN network, but a higher slope of the set-point curve than AN network, the solutions of proposals 1 and 2 feature different pump models and different control systems. Proposal 1 yields a solution of 3 VSP with FC, while proposal 2 yields a solution with a smaller number of pumps, but with a larger flow, and without control mode (2 FSP with no control). One of the most important sub-criterion in PS design proposal 2 is the number of pumps. Smaller number of pumps in this design proposal is considered as positive aspect. Therefore, proposal 2 aims to yield solutions with smaller number of pumps than proposal 1. Even operational costs and LCC of solutions of both networks in proposal 2 are higher than in proposal 1, and economic criteria have a high importance weight in a PS design, these solutions are selected by proposal 2 because this approach also considers technical criteria in the PS design.

In both networks, the sub-criterion C3 (Complexity of Control System) in proposal 2 has a great influence to select the final solution. In addition, the original AHP scale used in the pairwise comparisons increase the difference in the ratings obtained for different control systems, especially with control systems with VSP whose rating is very low in comparison with control systems with FSP. Therefore, the control systems of the solutions in proposal 2 in both networks are simple. In summary, design proposal 2 aims to select a solution with few number of pumps, simple control system and low investment, operational and maintenance costs.

6.3.3. Effects of modifying AHP scale and considering the optimization of control system in a PS design

The effects of modifying the AHP evaluation scale in a PS design can be analyzed by comparing the characteristic of the ultimate solutions in proposal 2 (AHP to techno-economic criteria without control system optimization) and proposal 3 (Modified AHP to techno-economic criteria with control system optimization). The modification of AHP scale was performed in proposal 3 so that the importance percentages of the criteria change gradually. This modification allows the rating obtained from the different control systems were more gradual among them. In this way, the principal difference of the solutions in proposal 2 and 3 in both networks is the control system (Tables 47 and 48).

In AN network, the pump models of the solutions in proposal 2 and 3 were the same, but with different control system. Proposal 3 yielded a solution of 2 VSP with FC, whreas the solution in proposal 2 was 2 FSP with PC. On the other hand, in AN network, the solutions of proposal 1 and 3 are the same. However, the optimization of control system performed in proposal 3 made the solution has lower operational costs and lower LCC than the solution in proposal 1. In EF network, the pump models, and the control system of the solutions in proposals 2 and 3 are different. The solution of proposal 3 was 2 VSP with FC, while the solution in proposal 2 was 2 FSP with no control. Although the sub-criterion complexity of the control system was considered in proposal 3, this does not imply the solutions must necessarily be restricted to simple control systems.

6.3.4. Effects of adding environmental criteria in AHP to technical and economic criteria

The main difference of design proposal 3 (Modified AHP to techno-economic criteria with control system optimization) and design proposal 4 (Modified AHP to technical, environmental, and economic criteria with control system optimization) are the inclusion of the sub-criteria PS size and PS flexibility, instead of the sub-criterion number of pumps, and the inclusion of environmental criteria.

In this way, the effects of adding environmental criteria in a PS design are determined comparing the solutions of proposal 3 and 4 in AN and EF networks. In both networks, the solutions of proposals 3 and 4 are completely different with different pump model, different number of pumps and different control system (Tables 47 and 48). For example, in AN network, proposal 4 yields a solution with 6 FSP and FC, whereas the solution of approach 3 is 2 VSP with FC. In EF network, the solution of proposal 4 is 3 FSP with PC, while the solution of approach 3 is 2 VSP with FC.

A common sight to highlight in both networks is the solution of proposal 4 has a greater number of pumps than the solution in proposal 3. The sub-criteria PS size and PS flexibility are associated with the number of pumps. The number of pumps and the PS size have a similar connotation in proposals 3 and 4. Both sub-criteria are evaluated positively as long as their values are small. However, the connotation of the number of pumps and PS flexibility are different in proposals 3 and 4. The PS flexibility is evaluated positively as long as the number of pumps are greater.

In this way, the inclusion of the sub-criterion size of PS in proposal 4 does not have effect the selection of the ultimate solution in contrast with proposal 3. The inclusion of the sub-criterion PS flexibility has an impact on the selection of the ultimate solution in proposal 4. A larger number of pumps but with smaller pump sizes in terms of flow in the solution of proposal 4 allows the efficiency of the PS to be higher in comparison to the solution in proposal 3. In fact, though the control system of the solution in proposal 4 was operated by FSP and proposal 3 is operated by VSP, the operational cost and GHG emission of the solution in approach 4 were lower than in proposal 3. The main effect of adding environmental criteria to the AHP means the solution in proposal 4 has better performance in environmental criteria than the solution in proposal 3, despite environmental criteria had been assigned a low importance weight in the AHP. In short, proposal 4 aims solutions with a better flexibility in operation (lager number of pumps), good characteristics in terms of economic and environmental criteria.

6.3.5. Effects of considering the variability of daily demands in a PS design.

The effects of considering variability of demand in a PS design can be determined by comparing the solutions obtained in proposal 4 (Modified AHP to technical, environmental, and economic criteria with a single demand pattern) and proposal 5 (Modified AHP to technical, environmental, and economic criteria with multiple demand patterns). The consideration of multiple daily demands organized in scenarios of probability of non-exceedance over a one-year time horizon, makes the variation of stressing conditions be higher than when considering a single demand pattern, i.e., yearly average daily demand. It makes that proposal 5 yield solutions based on a pump model with a larger number of pumps or pumps with larger flow than the solution in proposal 4 in AN and EF network. In addition, proposal 5 forces the AHP to yield a solution based on a control system with VSP and FC in both networks to meet the highly variation of stressing conditions of the networks.

For example, in AN network, proposal 5 yields a solution of 4 VSP with a larger flow and FC, whereas the solution of proposal 4 is 6 FSP with FC. In this network, it is important to highlight the total number of pumps (b) in proposal 5 is 4, and the minimum required number of pumps (b_{min}) is 3. This aspect allows to visualize the importance of including the optimization of control system during the PS design process. The optimization of control system allows not only save operational costs, but also to redefine the total number of pumps.

In EF network, proposal 5 yields a solution of 4 VSP with a larger flow and FC, while the solution of proposal 4 is 3 FSP with PC. In short, proposal 5 aims solutions in the PS with a balance in the performance of technical, environmental, and economic criteria as it happens in proposal 4. The difference lies in the control system because of the highly variation of stressing condition of the networks the PS must meet these conditions.

Chapter 7. Conclusions

7.1. Introduction

PS is one of the most important components in WDN. In fact, a large part of the total energy consumed in WDN comes from PS. Therefore, the optimization of PS operation and proper PS design are extremely important strategies to be developed in order to improve the service in a water supply system.

It is important to remember some gaps in research works referred on PS identified during the development of this work. In one hand, most of optimization techniques in pump scheduling are based with a number of pumps that were previously fixed by a designer according to his experience. Up to now, there is not an optimization technique does not allow to define the number of pumps in analytic form. Besides, these optimization techniques do not take into account the efficiency of frequency drive to calculate the energy consumption in PS. On the other hand, in traditional approach of PS design, its parameters, such as the pump model and the number of pumps are defined according to the designer's judgment. This traditional approach of design is based on a single objective which is LCC, and it usually includes only a single demand pattern. This classic design method neglects important aspects in the design. A PS is a comprehensive project, involving multiple criteria for its implementation, such as technical, economic, and environmental criteria.

In this way, the main objective accomplished in this thesis is the development of a comprehensive methodology of a PS design considering technical, economic, and environmental criteria based on the multicriteria decision method AHP and including the variability of demand in the design. This developed methodology reduces the level of subjectivity of the designer so that the PS design be more robust and reliable. The main objective of this thesis has been developed in three stages. The first stage presents a methodology of PS control system optimization combining FSP and VSP. This optimization includes a mathematical expression to estimate the efficiency of the frequency drive of VSP in the energy consumption of the PS. Finally, this methodology allows to redefine the number of pumps of the PS. The second stage developed a methodology of PS design considering a multcriteria decision analysis. This methodology of PS design includes technical and economic criteria based on the AHP technic. In the third stage, the main objective of this work is achieved. This stage presents a PS design methodology considering technical, economic, and environmental criteria based on the AHP. In addition, this methodology includes the optimization of PS control system and considers the variability of demand in the design process.

This section presents the conclusions obtained from the methodologies developed in the three stages of the thesis. Finally, this section presents a review of limitations of the developed methodologies and future developments for this research.

7.2. Optimization of control system operation in PS

One of the conclusions of this developed methodology of PS operation optimization is that this control system optimization discusses the classical operation of PS control system. The consumption energy of PS in the operation of classical control system is restricted with the minimum required number of pumps which depends on the operational range of the PS. In contrast, the consumption energy in the optimization of control system is obtained by searching the optimal number of FSP and VSP for each time slot without restricting with a minimun number of pumps. In addition, in the classical approach, first the total number of pumps in the PS is fixed and then the operation of the control system mode is performed. On the opposite form, the minimum required number of pumps is a reference point to begin the iterative process of the control system optimization and then is redefined the number of pumps in the PS. The optimization process consists of adding a unit of VSP to the minimum required number of pumps for a flow rate at every time slot until obtain the optimal PS energy consumption.

The obtained results of performed this control system approach in AN and EF network in the general case study prove that operating with a number of VSP greater than the minimum required could feature saving of energy consumption in the PS. These results show important savings over 10% in annual operational costs of PS in comparison with classical operation of control system in the PS. In fact, the total number of pumps in PS-AN network obtained from the optimization control system is greater than the number of pumps previously set.

One contribution of this developed methodology of PS control system optimization is that it allows to redefine the total number of pumps in the PS in analytic form. In this way, this optimization could avoid that the subjectivity to define the number of pumps in a PS design. Another contribution of this methodology is that it has performed an expression to estimate the efficiency of the frequency drive in VPS which is function of the rotational speed and the load. The consideration of the efficiency of frequency drive helps the optimization process to improve the accuracy and reliable in the simulation of the PS operation.

7.3. Design of PS considering technical and economic aspects based on the AHP method

One of the contributions accomplished in this thesis is the development of a PS design considering multicriteria decision based on the AHP technic. While traditional PS design approach is based on minimizing LCC, this approach contemplated the possibility of including technical and economic criteria to select the ultimate solution in a PS design. This methodology has achieved decreased the level of subjectivity by the designer in determining the pump model, number of pumps and control system in the PS. This approach aims to determine the overall importance weight of the sub-criteria in a PS design. An important aspect of this PS design approach is the priorities of the sub-criteria considered in this methodology were weighted to the consistency index ratio of the survey performed to different group of experts (e.g., academy, commercial, construction, consultancy, management, operation, and direction). In addition, the overall score of the potential solutions for the PS were obtained by weighting the scores of the solution in every sub-criterion with its respective importance priority. This aspect allows to select the ultimate solution for the PS reducing the uncertainty of the designer when designing a PS.

Important ideas to highlight in the obtained results applying this PS design approach are the following.

Even though, the sub-criterion operational cost in this approach has the highest priority in the design, this sub-criterion is not necessarily the most influential criterion in the selection of the ultimate solution in the PS design. This sub-criterion has opposite interest with other sub-criteria, such as investment and maintenance costs and complexity of the control system. Low operational costs imply to use a more complex control system and therefore higher investment and maintenance costs. The solutions obtained with this approach stand out in having high scores in the sub-criteria number of pumps, complexity of control system, investment, and maintenance costs. Summing up, the inclusion of technical criteria (the number of pumps and the complexity of control system) determine an important influence in the selection of the ultimate solution in the PS design.

The original AHP scale used in this approach has limitations to score some sub-criteria. The original AHP score makes that their respective percentage equivalence in the pairwise comparison of the criteria be not proportional between together. It affects scoring qualitative sub-criterion, such as complexity of PS control system. The ranking obtained for the different control system strategies is not proportional. This has affected the ratings of some control systems (VSP with PC/FC) to be extremely low compared to other control systems (FSP with PC or FC). In addition, it forced to select simple control systems in the solutions. In addition, this approach does not contemplate optimization approach in the control systems. Another limitation of this PS design approach is it neglected other important aspects in a PS design, such as flexibility of operation in the PS and environmental criteria. In addition, this approach did not contemplate the yearly variability of demand in the design.

Thus, this thesis has improved an updated PS design approach including environmental criteria in the AHP evaluation and considering the optimization in PS control systems and the variability of demand in the design process. The main conclusions of this last stage of this work is presented in the following section of this chapter.

7.4. PS design considering technical, environmental and economic criteria based on the AHP method and considering variability of demand

In this last stage of the work, the main contributions of this PS design approach are the following.

The modification of the AHP scale to score the different sub-criteria considered in the design is one of the contributions performed in this PS design approach. The modification of the AHP scale allowed that the equivalent percentage weight of the numeric scale used in the criteria be proportional to each other. The most significant effect of modifying the AHP scale was the obtained scores in the evaluation of the control system configurations. These scores were more proportional to each other. For instance, the differential of the obtained scores of the control system FSP with PC or FC and the control system VSP with PC or FC are smaller in comparison to the evaluation of the original AHP scale. Therefore, it led the control system configuration of the solutions applying this approach were more suitable according to the stressing conditions of the networks.

Another contribution of this methodology is the inclusion of the sub-criterion flexibility operation as technical criteria and the inclusion of environmental criteria in the AHP evaluation to design the PS. The application of this approach to design a PS led to select solutions with greater number of pumps (i.e., better performance in flexibility of operation) and better MEI index than the traditional approach (LCC minimization) or the approach (AHP with technical and economic criteria) In addition, a greater number of pumps with better MEI index and simple control system (FSP with PC or FC) can determine a better performance in operational cost even though the solutions of the other approaches use VSP with PC or FC. Of course, these solutions imply to get higher investment and maintenance costs. However, this is contrasted with excellent performance in economic criteria (MEI, GHG emissions and performance of regulation) and operational cost. Besides, the AHP evaluation determined the operational cost with the highest priority in the PS design. Although the AHP determined that environmental criteria are the criteria with the lowest priority in the PS design, environmental criteria have a great influence in the selection of the ultimate solution in the design.

A PS is normally designed with a single daily demand patten (i.e., average annual daily demand pattern). Nevertheless, this new PS design approach analyzed multiple daily demand scenarios in a one-year horizon time in order to simulate the variability of demand in the PS design. Therefore, is important to highlight this contribution in this PS design methodology. The consideration of demand variability implies highly stressing condition of operation in the demand and required head of the network. These new operating conditions leads to select a solution with larger pump models in terms of flow, larger number of pumps and a control system with better regulation performance as evidenced the obtained solutions of this approach in the general case study of this thesis. In addition, the inclusion of variability of demand helps to perform a more real reproduction in the operation of a PS and more accurate assessment in the 9 sub-criteria considered for the PS design. In short, it allows a PS design to be more reliably and robust to different operating conditions that the network could have.

An important advantage of this PS approach in comparison with the classical approach is that the obtained solution of this new approach has more balance performance in the 9 sub criteria considered in the design. Excellent performance in operational costs and in environmental criteria are highlighted in the performance of the 9 sub-criteria. Even if, LCC are smaller in the traditional approach of PS design, the solution of this approach could have poor performance in some sub-criteria such as, flexibility of operation and environmental criteria. In short, this new PS design approach led that the selected solution be technically feasible, economically profitable, and environmentally responsible.

7.5. Future Developments

In this work, a methodology to optimize the operation of a PS control system was developed. However, this optimization was performed only in water distribution networks (WDN) without storage system. This methodology could also be performed in WDN with storage system as future development. In this way, this methodology would be based on the required curve of head and flow (*Q, H*) of the network in every time slot considering other hydraulic constraints, such as the maximum and minimun level of the storage system.

An important aspect of this methodology is the development of a mathematical expression that allows calculate the efficiency of the frequency drive in VSP. This mathematical expression is based on different efficiency curve of frequency drivers obtained in the bibliography of this work. However, it could be important to validate these data by performing laboratory essays that assess the efficiency of different frequency drives. Undoubtedly deepen the efficiency of variable-frequency drives would improve the design of PS.

The AHP method was applied in this work to design a PS for a WDN considering technical, economic, and environmental criteria. However, this multi-criteria decision method could also be applied in the rehabilitation of an existing PS in WDN. The constrains that the WDN rehabilitation might have on existing PS could be considered in the criteria for making the most appropriate decisions on rehabilitation strategies for PS operation.

In addition, it has developed a comprehensive methodology of PS design considering technical, environmental, and economic aspects. The multicriteria decision analysis method AHP was applied in this methodology to evaluate the potential solutions of the PS and select an ultimate solution in the design according to the ranking obtained in the analysis of the AHP method. An important aspect of this methodology is the survey to a group of experts to determine the priorities of the criteria in a PS design. Moreover, the consistency index of the surveys has been considered to determine the weight of the overall importance of the criteria in the PS design in order to minimize the subjectivity of the group of experts. However, it would also be important to analyze the incidence of the importance of the criteria in the design. In this way, a future development could be a sensitivity analysis of the importance priority of the criteria in a PS. It allows to determine how influential is the opinion of group of experts of the PS criteria in the obtained solution in the PS design. In addition, it could be interesting to perform another sensitivity analysis to the required data in this PS design approach, such as the set-point curve of the network, demand patterns, dimension of the PS layout to evaluate the impact of these design variables in the obtained solutions.

The AHP method applied in this methodology of PS design present limitations to evaluate the priorities of the criteria of the PS. The AHP assumes an independence of the criteria and sub-criteria. This represents an oversimplification to evaluate the priorities of the criteria and sub-criteria and may affect the consistency of the evaluation of the criteria. For example, the sub-criteria flexibility of operation, complexity of PS control system, investment cost, operational cost, maintenance cost, GHG emission are dependent and have a relationship to each other. This reciprocal relationship of the sub-criteria is neglected in the AHP evaluation. Thus, a future development of this research could be to consider the relationship of the criteria in the PS design. In this way, a suitable multcriteria decision method to apply in this methodology could be the Analytic Network Process (ANP) which contemplates the relationship of the criteria. This multicriteria decision method could allow to improve the consistency of the results in the evaluation of the criteria.

The variability of demand was considered in a PS design methodology developed in the last stage of this thesis. This analysis considered multiple daily demand scenarios in one year horizon time and organized by probabilities of non-exceedance from 0 to 1. However, these data of daily demand scenarios were obtained from a historical statistical analysis. In this way, a future development of this research could be the inclusion of a methodology to forecast the demands of the network to the PS design to reproduce in a real time the operation of the PS. The Forecast demand will allow to improve the reliability of operation and design of the PS.

Chapter 8. Quality indicators

During the development of the thesis, four technical papers have been published in international journals of water. In addition, it has been able to participate and publish three conference articles in national and international conferences for development of this thesis.

Technical Paper Published	
Journal	**Technical Paper**
Journal of Water MPDI (Switzerland)	C. X. Briceño-León, P. L. Iglesias-Rey, F. J. Martinez-Solano, D. Mora-Meliá, and V. S. Fuertes-Miquel, “Use of fixed and variable speed pumps in water distribution networks with different control strategies,” Water, vol. 13, no. 4, pp. 479, 2021
Journal of Water MPDI (Switzerland)	C. X. Briceño-León, D. S. Sanchez-Ferrer, P. L. Iglesias-Rey, F. J. Martinez-Solano, and D. Mora-Meliá, “Methodology for pumping station design based on analytic hierarchy process (AHP),” Water, vol. 13, no. 20, pp. 2886, 2021.
Journal of Sustainability MPDI (Switzerland)	Sánchez-Ferrer, D. S., Briceño-León, C. X., Iglesias-Rey, P. L., Martínez-Solano, F. J., & Fuertes-Miquel, V. S. “Design of Pumping Stations Using a Multicriteria Analysis and the Application of the AHP Method”. Sustainability, vol. 13, no. 11, pp. 5876, 2021.
Journal of Water Resources Planning and Management ASCE (United States)	C. X. Briceño-León, P. L. Iglesias-Rey, F. J. Martinez-Solano, and E. Creaco, “Integrating demand variability, and technical, environmental and economic criteria in the design of pumping stations serving closed distribution networks” J. Water Resources Planning and Management, vol. 149, Issue 3, pp. 04023002, 2023.

National and International Conferences Participated		
Conference	**Place**	**Title**
4th International Electronic Conference on Water Sciences	Basel, Switzerland	Influence of the regulation mode in the selection of the number of Fixed Speed Drives (FSD) and Variable Speed Drives (VSD) pumps in water pumping stations.
24th International Congress on Project Management and Engineering	Alcoi, Spain	Proyecto de optimización en la operación de estaciones de bombeo para redes de agua.
2nd International Join Conference on Water Distribution System Analysis (WDSA) and Computing and Control In the Water Industry (CCWI)	Valencia Spain	Pumping Station Design with an analysis of variability of demand and considering techno-economic and environmental criteria through the AHP Method.

Chapter 9. Abbreviations

ACO	Ant Colony Optimization
AHP	Analytic Hierarchy Process
ANP	Analytical Network Process
ANN	Artificial Neural Network
BEP	Best Efficient Point
EPA	Environmental Protection Agency
FC	Flow Control
FSP	Fixed Speed Pump
GA	Genetic Algorithm
GHG	Greenhouse Gases
LCC	Life Cycle Cost
MEI	Minimum Efficiency Index
MCDM	Multicriteria Decision Making
NC	No Control
PC	Pressure Control
PLC	Programmer Logic Control
PS	Pumping Station
PSO	Particle Swarm Optimization
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goals
SPA	Short Path Algorithm
TOPSIS	Technic for Order Preference by Similarity to Ideal Solution
UN	United Nations
WDN	Water Distribution Networks
VBA	Visual Basic Application
VFD	Variable Frequency Drive
VSP	Variable Speed Pump

Chapter 10. References

[1] C. Copeland and N. Carter, “Energy-Water Nexus : The Water Sector’s Energy Use,” *Congressional Reseach Service*, 2014.

[2] K. L. Lam, S. J. Kenway, and P. A. Lant, “Energy use for water provision in cities,” *J. Clean. Prod.*, vol. 143, pp. 699–709, 2017.

[3] United Nations Water, “Development Report 2020: Water and Climate Change,” París, 2020.

[4] Environmental Protection Atgency (USA). Ensuring a sustainable future: An energy management guidebook for wastewater and water utilities. Washintong DC, Government Printing Office, 2008

[5] B. K. Westerling (2013), “10 Tips To Save Energy On Pumping Systems,” [Online]. https://www.wateronline.com/doc/tips-to-save-energy-on-pumping-systems-0001

[6] D. F. Moreira and H. M. Ramos, “Energy Cost Optimization in a Water Supply System Case Study,” *J. Energy*, vol. 2013, pp. 1–9, 2013.

[7] P. Planells Alandi, P. Carrión Pérez, J. F. Ortega Álvarez, M. Á. Moreno Hidalgo, and J. M. Tarjuelo Martín-Benito, “Pumping Selection and Regulation for Water-Distribution Networks,” *J. Irrig. Drain. Eng.*, vol. 131, no. 3, pp. 273–281, 2005.

[8] F. J. Martínez-Solano, P. L. Iglesias-Rey, D. Mora-Meliá, and V. S. Fuertes-Miquel, “Using the set point concept to allow water distribution system skeletonization preserving water quality constraints,” *Procedia Eng.*, vol. 89, pp. 213–219, 2014.

[9] Jensen Engineered Systems, *Pump Station Design Guidelines – Second Edition*, Sparks-Nevada, Jensen Eng., no. 855., 2012.

[10] V. S. Fuertes-Miquel, G. Lopez-Patiño, Regulación de redes de distribución del agua in Modelación y diseño de redes de abastecimiento de agua, Grupo Mécanica de Fluidos (Universitat Politécnica de Valencia), Valenica-España, 2002.

[11] C. León-Celi, “Optimisation of both energy use and pumping costs in water distribution networks with several water sources using the setpoint curve.”, Doctoral Thesis, Universitat Politécnica de Valencia (Valencia Tech), 2018.

[12] F. K. Odan, L. F. Ribeiro Reis, and Z. Kapelan, “Real-time multiobjective optimization of operation of water supply systems,” *J. Water Resour. Plan. Manag.*, vol. 141, no. 9, pp. 04015011, 2015.

[13] Department of the Army Corps of Engineers United States, *Structural and Architectural Design of Pumping Stations (Engineer Manual)*. Washington DC-USA, 1989.

[14] M. Jayanthi and T. Ravishankar, “Techno economic evaluation of windmill for water pumping in coastal areas for aquaculture,” *Indian J. Fish*, vol. 52, pp. 413–419, 2005.

[15] S. Nair, B. George, H. M. Malano, M. Arora, and B. Nawarathna, "Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods," *Resour. Conserv. Recycl.*, vol. 89, pp. 1–10, 2014.

[16] T. L. Saaty, *Analytic Hierarchy Process*, New York-USA, McGraw Hil, 1980.

[17] R. L. Sanks, *Pumping Station Design (Second Edition)*. Woburn-USA, Butterworth-Heinemann, 1998.

[18] L. Frenning, Ed., *Pump Life Cycle Costs: A guide to LCC analysis for pumping systems*. Hydraulic Institute & Europump, 2001.

[19] Jowitt, P. W; Germanopoulos, G. "Optimal Pump Scheduling in Water-Supply Networks," *J. Water Resour. Plan. Manag.*, vol. 118, no. 4, pp. 406–422, 1992.

[20] Yu G.; Powel, R. S; Sterling, M., "Optimized Pump Scheduling in water distributin systems," *J. Optim. Theory Appl.,83*, pp. 463–488, 1994.

[21] K. Lansey and K. Awumah, "Optimal Pump Operations Considering Pump Switches" *J. Water Resour. Plan. Manag.*, vol. 120, no. 1, pp. 17–35, 1994.

[22] A. B. A. Sakarya and L. W. Mays, "Optimal Operation Of Water Distribution Pumps Considering Water Quality," *J. Water Resour. Plan. Manag.*, vol. 126, pp. 210–220, 2000.

[23] G. McCormick and R. S. Powell, "Optimal Pump Scheduling in Water Supply Systems with Maximum Demand Charges," *J. Water Resour. Plan. Manag.*, vol. 129, no. 5, pp. 372–379, 2003.

[24] C. Wegly, M. Eusuff, and K. Lansey, "Determining Pump Operations using Particle Swarm Optimization," *Build. Partnerships (ASCE)*, pp. 1–16, 2000.

[25] G. McCormick and R. S. Powell, "Derivation of near-optimal pump schedules for water distribution by simulated annealing," J. Oper. Res. Soc., vol. 55, no. 7, pp. 728–736, 2004.

[26] M. López-Ibáñez, T. D. Prasad, and B. Paechter, "Ant Colony Optimization for Optimal Control of Pumps in Water Distribution Networks," J. Water Resour. Plan. Manag., vol. 134, no. 4, pp. 337–346, 2008.

[27] L. Henrique, M. Costa, B. D. A. Prata, H. M. Ramos, M. Aurélio, and H. De Castro, "A Branch-and-Bound Algorithm for Optimal Pump Scheduling in Water Distribution Networks," Water Resour. Manag., pp. 1037–1052, 2016.

[28] N. Lamaddalena and S. Khila, "Efficiency-driven pumping station regulation in on-demand irrigation systems," Irrig. Sci., vol. 31, no. 3, pp. 395–410, 2013.

[29] V. B. da S. Baptista, J. I. Córcoles, A. Colombo, and M. Á. Moreno, "Feasibility of the use of variable speed drives in center pivot systems installed in plots with variable topography," Water (Switzerland), vol. 11, no. 10, pp. 2192, 2019.

[30] A. Sperlich, D. Pfeiffer, J. Burgschweiger, E. Campbel, M. Beck R. Gnirss, and M. Ernst, "Energy efficient operation of variable speed submersible pumps: Simulation of a ground water well field," *Water (Switzerland)*, vol. 10, no. 9, pp. 1255, 2018.

[31] E. Creaco, E. Lanfranchi, C. Chiesa, M. Fantozzi, C. A. Carrettini, and M. Franchini, "Optimisation of leakage and energy in the Abbiategrasso district," Civ. Eng. Environ. Syst., vol. 33, no. 1, pp. 22–34, 2016.

[32] S. Lingireddy and D. J. Wood, "Improved Operation of Water Distribution Systems Using Variable-Speed Pumps," J. Energy Eng., vol. 124, no. 3, pp. 90–103, 2002.

[33] W. Wu, A. R. Simpson, H. R. Maier, and A. Marchi, "Incorporation of Variable-Speed Pumping in Multiobjective Genetic Algorithm Optimization of the Design of Water Transmission Systems," J. Water Resour. Plan. Manag., vol. 138, no. 5, pp. 543–552, 2012.

[34] S. S. Hashemi, M. Tabesh, and B. Ataeekia, "Ant-colony optimization of pumping schedule to minimize the energy cost using variable-speed pumps in water distribution networks," Urban Water Journal, vol. 11, no. 5. pp. 335–347, 2014.

[35] E. Price and A. Ostfeld, "Graph Theory Modeling Approach for Optimal Operation of Water Distribution Systems," J. Hydraul. Eng., vol. 142, no. 3, pp. 04015061, 2015.

[36] Z. Rao and F. Alvarruiz, "Use of an artificial neural network to capture the domain knowledge of a conventional hydraulic simulation model," J. Hydroinformatics, vol. 9, no. 1, pp. 15–24, 2007.

[37] C. Giacomello, Z. Kapelan, and M. Nicolini, "Fast Hybrid Optimization Method for Effective Pump Scheduling," J. Water Resour. Plan. Manag., vol. 139, no. 2, pp. 175–183, 2012.

[38] M. Abdallah and Z. Kapelan, "Iterative Extended Lexicographic Goal Programming Method for Fast and Optimal Pump Scheduling in Water Distribution Networks," J. Water Resour. Plan. Manag., vol. 143, no. 11, pp. 04017066, 2017.

[39] D. Figueiredo, R. Alves, and T. Luna, "Improving energy efficiency in water supply systems with pump scheduling optimization," J. Clean. Prod., vol. 213, pp. 342–356, 2018.

[40] M. Abdallah and Z. Kapelan, "Fast Pump Scheduling Method for Optimum Energy Cost and Water Quality in Water Distribution Networks with Fixed and Variable Speed Pumps," J. Water Resour. Plan. Manag., vol. 145, no. 12, pp. 04019055, 2019.

[41] H. Wang, X. Lei, S. T. Khu, and L. Song, "Optimization of pump start-up depth in drainage pumping station based on SWMM and PSO," Water (Switzerland), vol. 11, no. 5, pp. 1002, 2019.

[42] S. Carpitella, B. Brentan, I. Montalvo, J. Izquierdo, and A. Certa, "Multi-criteria analysis applied to multi-objective optimal pump scheduling in water systems," Water Sci. Technol. Water Supply, vol. 19, no. 8, pp. 2338–2346, 2019.

[43] A. Ostfeld, "Optimal Desing and Operation of Multiquality Networks under Unsteady Conditions," J. Water Resour. Plan. Manag., vol. 131, no. April, pp. 116–124, 2005.

[44] J. Nault and F. Papa, "Lifecycle Assessment of a Water Distribution System Pump," J. Water Resour. Plan. Manag., vol. 141, no. 2014, pp. A4015004, 2015.

[45] T. Walski and E. Creaco, "Selection of Pumping Configuration for Closed Water Distribution Systems," J. Water Resour. Plan. Manag., vol. 142, no. 6, pp. 04016009, 2016.

[46] K. Diao and R. Sitzenfrei, "The Impacts of Spatially Variable Demand Patterns on Water Distribution System Design and Operation," Water (Switzerland), vol. 11, no. 3, pp. 567, 2019.

[47] A. Martin-Candilejo, D. Santillán, A. Iglesias, and L. Garrote, "Optimization of the design of water distribution systems for variable pumping flow rates," Water (Switzerland), vol. 12, no. 2, pp. 359, 2020.

[48] J. H. Gutiérrez-Bahamondes, D. Mora-Meliá, P. L. Iglesias-Rey, F. J. Martínez-Solano, and Y. Salgueiro, "Pumping Station Design in Water Distribution Networks Considering the Optimal Flow Distribution between Sources and Capital and Operating Costs," Water 2021, Vol. 13, Page 3098, vol. 13, no. 21, p. 3098, 2021.

[49] V. M. Leiby and M. E. Burke, Energy Efficiency Best Practices for North American Drinking Water Utilities. Albany New York-USA, WRF, 2011.

[50] E. Salomons, M. Housh, and M. Asce, "A Practical Optimization Scheme for Real-Time Operation of Water Distribution Systems," J. Water Resour. Plan. Manag., vol. 146, no. 4, pp. 04020016, 2020.

[51] M. Manteigas, A. Andrade-Campos, A. André, and B. Coelho, "Cost-Efficient Algorithms for a Pump Horizon Control in Water Supply System," Water Resour. Manag., vol. 148, no. 1, pp. 04021091, 2021.

[52] N. Naval and J. M. Yusta, "Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation," J. Clean. Prod., vol. 316, pp. 128386, 2021.

[53] X. Liu, N. Li, H. Mu, M. Li, and X. Liu, "Techno-energy-economic assessment of a high capacity offshore wind-pumped-storage hybrid power system for regional power system," J. Energy Storage, vol. 41, pp. 102892, 2021.

[54] A. V. M. Garcia, P. A. López-Jiménez, F. J. Sánchez-Romero, and M. Pérez-Sánchez, "Objectives, keys and results in the water networks to reach the sustainable development goals," Water (Switzerland), vol. 13, no. 9, pp. 1268, 2021.

[55] S. Beygi, M. Tabesh, and S. Liu, "Multi-Objective Optimization Model for Design and Operation of Water Transmission Systems Using a Power Resilience Index for Assessing Hydraulic Reliability," Water Resour. Manag., vol. 33, no. 10, pp. 3433–3447, 2019.

[56] N. Mehzad and M. Tabesh, "Optimum Reliable Operation of Water Distribution Network Considering Pumping Station and Tank," Iran. J. Sci. Technol. Trans. Civ. Eng., vol. 43, no. s1, pp. 413–427, 2019.

[57] N. Palod, V. Prasad, and R. Khare, "Reliability-based optimization of water distribution networks," Water Supply, vol. 22, no. 2, pp. 2133–2147, 2022.

[58] C. Hwang and T. Yoon, *Multiple Attribute Decision Making: Methods and Applications*, Berlin-Germany, Springer-Verlag, 1981.

[59] L. K. Raminelli and D. Costa, "Hierarchy of hydraulic and energy conservation actions at water supply systems Hierarchy of hydraulic and energy conservation actions at water supply systems," Urban Water J., vol. 16, no. 10, pp. 727–737, 2020.

[60] F. Taillandier, S. M. Elachachi, and A. Bennabi, "A decision-support framework to manage a sewer system considering uncertainties," Urban Water J., vol. 17, no. 4, pp. 344–355, 2020.

[61] M. Ward, C. Poleacovschi, and M. Perez, "Using AHP and Spatial Analysis to Determine Water Surface Storage Suitability in Cambodia," Water (Switzerland), vol. 13, no. 3, pp. 367, 2021.

[62] T. L. Saaty, *Decision making with dependence and feedback: The analytic network process*, Vol. 4922. No. 2. Pittsburgh, RWS publications, 1996.

[63] G. Amantidis, "Energy climate policy framework EU 2020-2030," European Parliament, 2019.

[64] A. Casasso, T. Tiziana, C. Bianca, A. Bucci, and R. Sethi, "How Can We Make Pump and Treat Systems More Energetically Sustainable?," Water (Switzerland), vol. 12.1, pp. 67, 2020.

[65] A. Martin-Candilejo, D. Santillán, and L. Garrote, "Pump efficiency analysis for proper energy assessment in optimization of water supply systems," Water (Switzerland), vol. 12, no. 1, pp. 132, 2020.

[66] H. Kato, H. Fujimoto, and K. Yamashina, "Operational improvement of main pumps for energy-saving in wastewater treatment plants," Water (Switzerland), vol. 11, no. 12, pp. 2438, 2019.

[67] M. F. Pasha and K. Lansey, "Optimimal Pump Scheduling by linear programming," World Environ. Water Resour., pp. 1–10, 2009.

[68] D. Cohen, U. Shamir, and G. Sinai, "Sensitivity analysis of optimal operation of irrigation supply systems with water quality considerations.," Irrig. Drain. Syst., vol. 18, pp. 227–253, 2004.

[69] D. Ibarra and J. Arnal, "Parallel Programming Techniques Applied to Water Pump Scheduling Problems," J. Water Resour. Plan. Manag., vol. 140, no. 7, p. 06014002, 2014.

[70] L. A. Rossman, EPANET 2 User's Manual, Cincinnati OH-USA, September 2000.

[71] F. De Paola, N. Fontana, M. Giugni, G. Marini, and F. Pugliese, "Optimal solving of the pump scheduling problem by using a harmony search optimization algorithm," J. Hydroinformatics, vol. 19(6), pp. 879–889, 2017.

[72] S. Mohsen, A. Sadatiyan, and C. J. Miller, "PEPSO: Reducing electricity usage and associated pollution emissions of water pumps," Water (Switzerland), vol. 9, no. 9, pp. 640 2017.

[73] P. Wu, Z. Lai, D. Wu, and L. Wang, "Optimization Research of Parallel Pump System for Improving Energy Efficiency," J. Water Resour. Plan. Manag., vol. 141, no. 8, pp. 04014094, 2014.

[74] W. Zheng and Q. Zhu, "Scalable Parallel Computing Framework for Pump Scheduling Optimization," J. Water Resour. Plan. Manag., vol. Great Rive, pp. 1–11, 2009.

[75] Z. Rao and E. Salomons, "Development of a real-time, near-optimal control process for water-distribution networks," J. Hydroinformatics, vol. 9, no. 1, pp. 25–37, 2007.

[76] D. Nowak et al., "Decision support for the design and operation of variable speed pumps in water supply systems," Water (Switzerland), vol. 10, no. 6, pp. 734, 2018.

[77] C. León-Celi, P. L. Iglesias-Rey, F. J. Martínez-Solano, and D. Mora-Melia, "A methodology for the optimization of flow rate injection to looped water distribution networks through multiple pumping stations," Water (Switzerland), vol. 8, no. 12, pp. 575, 2016.

[78] C. F. León-Celi, P. L. Iglesias-Rey, F. J. Martínez-Solano, and D. Savic, "Operation of Multiple Pumped-Water Sources with No Storage," J. Water Resour. Plan. Manag., vol. 144, no. 9, p. 04018050, 2018.

[79] A. R. Simpson and A. Marchi, "Correction of the EPANET inaccuracy in computing the efficiency of variable speed pumps," J. Water Resour. Plann. Manag., vol. 139(4), pp. 456–459, 2013.

[80] A. R. Simpson and A. Marchi, "Evaluating the Approximation of the Affinity Laws and Improving the Efficiency Estimate for Variable Speed Pumps," J. Hydraul. Eng., vol. 139, no. 12, pp. 1314–1317, 2013.

[81] I. Sarbu and I. Borza, "Energetic Optimization Of Water Pumping in Distribution Sytems," Period. Polytech. Mec. Eng., vol. 42, no. 2, pp. 141–152, 1998.

[82] Coelho, Bernardete and Andrade-Campos A. G., "A new approach for the prediction of speed-adjusted pump efficiency curves," J. Hydraul. Res., vol. 54, pp. 586–593, 2016.

[83] Hydraulic Institute, Europump, and the US Department of Energy's (DOE) Industrial Technologies Program. "Variable speed pumping—A guide to successful applications—Executive Summary." pp. 1-14, 2004.

[84] N. Aranto, "Competitor: Variable speed drivers in pumping Application," M.S Thesis, University of Technology Lappeenranta, 2008.

[85] J. Conti, P. Holtberg, J. Diefenderfer, A. LaRose, J.T. Turnure, & L. Westfall. *International energy outlook 2016 with projections to 2040*. No. DOE/EIA-0484 (2016). USDOE Energy Information Administration (EIA), Washington DC-USA. Office of Energy Analysis, 2016.

[86] H. J. Tolvanen, "Life cycle energy cost savings and pump selection," World Pumps, vol. 2007, no. 490, pp. 34–37, Jul. 2007.

[87] S. Bunn, "Pump scheduling optimization in four US cities: Case studies," 8th Annu. Water Distrib. Syst. Anal. Symp. 2006, pp. 78, 2007.

[88] L. Cimorelli, A. D'Aniello, and L. Cozzolino, "Boosting Genetic Algorithm Performance in Pump Scheduling Problems with a Novel Decision-Variable Representation," J. Water Resour. Plan. Manag., vol. 146, no. 5, p. 04020023, 2020.

[89] C. X. Briceño-León, P. L. Iglesias-Rey, F. J. Martinez-Solano, D. Mora-Meliá, and V. S. Fuertes-Miquel, "Use of fixed and variable speed pumps in water distribution networks with different control strategies," Water (Switzerland), vol. 13, no. 4, pp. 479, 2021.

[90] P. S. Mahar and R. P. Singh, "Optimal Design of Pumping Mains Considering Pump Characteristics," J. Pipeline Syst. Eng. Pract., vol. 5, pp. 1–6, 2014.

[91] P. R. Bhave, Optimal design of water distribution networks. Pangbourne -England, Alpha Science International Ltd., 2003.

[92] T. M. Walski, "Planning-Level Capital Cost Estimates for Pumping," J. Water Resour. Plan. Manag., vol. 138, no. 3, pp. 307–310, 2012.

[93] J. R. Greco, Salvatore; Ehrgortt, Matthias; Figueira, *Multiple Criteria Decision Analysis*, Second edition, vol 37, New York (NY)-USA, Springer, 2016.

[94] T. L. Saaty, "Decision making with the analytic hierarchy process," Int. J. Serv. Sci., vol. 1, pp. 83–98, 2008.

[95] H. Ariff, M. Sapuan Salit, N. Ismail, and Y. Nukman, "Use of analytical hierarchy process (AHP) for selecting the best design concept," J. Teknol., vol. 49, pp. 1–18, 2009.

[96] M. Ahmed, M. N. Qureshi, J. Mallick, M. A. Hasan, and M. Hussain, "Decision Support Model for Design of High-Performance Concrete Mixtures Using Two-Phase AHP-TOPSIS Approach," Adv. Mater. Sci. Eng., vol. 2019, pp. 1696131, 2019.

[97] H. Al-barqawi and T. Zayed, "Infrastructure Management : Integrated AHP / ANN Model to Evaluate Municipal Water Mains ' Performance," Infraestructure Syst., vol. 14, pp. 305–318, 2008.

[98] I. Aşchilean, G. Badea, I. Giurca, G. Sebastian, and F. George, "Choosing the optimal technology to rehabilitate the pipes in water distribution systems using the AHP method," Energy Procedia, vol. 112, pp. 19–26, 2017.

[99] B. Karleuša, A. Hajdinger, and L. Tadić, "The application of multi-criteria analysis methods for the determination of priorities in the implementation of irrigation plans," Water (Switzerland), vol. 11, no. 3, pp. 501, 2019.

[100] T. L. Saaty, "Decision making with the Analytic Hierarchy Process," Sci. Iran., vol. 9, no. 3, pp. 215–229, 2002.

[101] M. Khamudkhanov, I. Abdullabekov, B. Khamudkhanova, K. Dusmatov, and K. Fayzullayev, "Controls of the modes of operation of the pumping station with application of frequency-controlled electric drive Controls of the modes of operation of the pumping station with application of frequency-controlled electric drive," IOP Conf. Ser. Mater. Scince Eng., vol. 862, no. 6, pp. 062048, 2020.

[102] T. L. Saaty, "Rank from comparisons and from ratings in the analytic hierarchy / network processes I," Eur. J. Oper. Res., vol. 168, pp. 557–570, 2004.

[103] P. L. Iglesias-Rey, F. J. Martínez-Solano, F. Arango-Gil, and V. Lozano-Cortés, "Methodology for the selection of pumping stations considering its mode of operation," 10th International Perspectives on Water Resources and The Environment (IPWE), vol. 13, 2018.

[104] K. Murugaperumal and P. A. D. Vimal, "Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification," Sol. Energy, vol. 188, no. February, pp. 1068–1083, 2019.

[105] V. Vilotijevi, U. Karadzic, R. Vujadinovic, V. Kovijanic, and I. Bozic, "An Improved Techno-Economic Approach to Determination of More Precise Installed Parameter for Small Hydropower Plants," Water, vol. 13, p. 2419, 2021.

[106] S. M. Bunn and L. Reynolds, "The energy-efficiency benefits of pump scheduling optimization for potable water supplies," IBM J. Res. Dev., vol. 53, no. 3, pp. 1–13, 2009.

[107] D. Torregrossa and F. Capitanescu, "Optimization models to save energy and enlarge the operational life of water pumping systems," J. Clean. Prod., vol. 213, pp. 89–98, 2019.

[108] P. Khatavkar and L. W. Mays, "Optimization-simulation model for real-time pump and valve operation of water distribution systems under critical conditions," Urban Water J., vol. 16, no. 1, pp. 45–55, 2019.

[109] L. M. Herstein, Y. R. Filion, and K. R. Hall, “Evaluating the Environmental Impacts of Water Distribution Systems by Using EIO-LCA-Based Multiobjective Optimization,” vol. 137, no. 2, pp. 162–172, 2011.

[110] L. J. Blinco, A. R. Simpson, M. Asce, M. F. Lambert, M. Asce, and A. Marchi, “Comparison of Pumping Regimes for Water Distribution Systems to Minimize Cost and Greenhouse Gases,” Water Resour. Manag., vol. 142, no. 6, pp. 04016010, 2016.

[111] M. Hajibabaei, S. Hesarkazzazi, M. Lima, and F. Gschösser, “Environmental assessment of construction and renovation of water distribution networks considering uncertainty analysis,” Urban Water J., vol. 17, no. 8, pp. 723–734, 2020.

[112] C. X. Briceño-León, D. S. Sanchez-Ferrer, P. L. Iglesias-Rey, F. J. Martinez-Solano, and D. Mora-Meliá, “Methodology for pumping station design based on analytic hierarchy process (AHP),” Water (Switzerland), vol. 13, no. 20, pp. 2886, 2021.

[113] T. L. Saaty and M. Sodenkamp, “The Analytic Hierarchy and Analytic Network Measurement Processes: The Measurement of Intangibles,” vol. 1, no. 1, pp. 91–166, 2010.

[114] E. Creaco and T. Walski, “Operation and Cost-Effectiveness of Local and Remote RTC,” J. Water Resour. Plan. Manag., vol. 144, no. 11, pp. 04018068, 2018.

[115] The European Union Comission, “Commission Regulation (EU) N0 547/2012,” Off. J. Eur. Union, vol. 04, pp. 178–183, 2012.

[116] Oficina Española del Cambio Climático (OECC), *Factores de emisión Registro de Huella de Carbono, Compensacion y Proyectos de Absorción de Dióxido de Carbono*, Ministerio para la Transición Ecológica y el Reto Demográfico España, 2022.

[117] S. Alvisi and M. Franchini, “A robust approach based on time variable trigger levels for pump control,” J. Hydroinformatics, vol. 19, no. 6, pp. 811–822, 2017.

[118] D. Fiorillo, G. Galuppini, E. Creaco, F. De Paola, and M. Giugni, “Identification of Influential User Locations for Smart Meter Installation to Reconstruct the Urban Demand Pattern,” J. Water Resour. Plan. Manag., vol. 146, no. 8, p. 04020070, 2020.

ANNEXES

Database of the pump models used in this work

The parameters that characterize the head curve and the efficiency curve of every pump model in the database are:

- η_0: The maximum efficiency of the pump model.
- H_1, *A, B*: Coefficients of the head curve of every pump model.
- $Q_{b,max}$: The maximum flow a pump model could deliver.
- Q_0: The nominal flow of every pump model.
- H_0: The nominal head of every pump model.
- *E, F*: Coefficients of the efficiency curve of every pump model.
- *Cost*: This cost includes the purchase cost of the pump and the installation cost.

N° Model	η_0	H_1 (m)	A	B	$Q_{b,max}$	Q_0 (L/s)	H_0 (m)	E	F	Cost (€)
1	56.00%	26.17	0.24	2	10.52	5.26	19.63	0.2128	0.0202	2361.83
2	47.00%	22.83	0.28	2	9.02	4.51	17.12	0.2084	0.0231	2442.90
3	50.00%	27.75	0.28	2	10.00	5.00	20.81	0.2000	0.0200	2534.86
4	56.00%	37.00	0.27	2	11.72	5.86	27.75	0.1912	0.0163	2644.97
5	58.00%	42.53	0.27	2	12.54	6.27	31.89	0.1851	0.0148	2742.98
6	50.00%	48.30	0.37	2	11.44	5.72	36.23	0.1748	0.0153	3154.38
7	53.00%	55.85	0.27	2	14.41	7.20	41.89	0.1472	0.0102	3468.98
8	54.00%	68.65	0.29	2	15.51	7.75	51.49	0.1393	0.0090	3703.72
9	39.00%	69.79	0.20	2	18.73	9.36	52.34	0.0833	0.0044	5450.96
10	43.00%	92.35	0.25	2	19.29	9.65	69.26	0.0891	0.0046	5862.36
11	45.00%	102.75	0.23	2	21.18	10.59	77.06	0.0850	0.0040	6202.37
12	78.00%	26.92	0.04	2	25.14	12.57	20.19	0.1241	0.0049	2896.65
13	52.50%	27.99	0.10	2	17.04	8.52	20.99	0.1232	0.0072	2884.55
14	62.50%	33.86	0.08	2	21.17	10.58	25.39	0.1181	0.0056	3005.55
15	66.20%	42.59	0.07	2	24.68	12.34	31.94	0.1073	0.0043	3496.81
16	56.00%	41.33	0.17	2	15.59	7.79	31.00	0.1437	0.0092	3718.24
17	59.00%	56.51	0.12	2	21.37	10.68	42.39	0.1104	0.0052	3965.08
18	61.00%	67.73	0.11	2	24.27	12.14	50.80	0.1005	0.0041	4988.74
19	49.00%	59.30	0.11	2	23.49	11.74	44.48	0.0834	0.0036	5544.13
20	53.00%	75.21	0.12	2	25.40	12.70	56.41	0.0835	0.0033	5954.32
21	55.00%	100.47	0.11	2	30.18	15.09	75.35	0.0729	0.0024	7042.11
22	73.00%	15.77	0.02	2	29.86	14.93	11.83	0.0978	0.0033	2598.99
23	74.00%	19.13	0.02	2	33.03	16.52	14.35	0.0896	0.0027	2819.21
24	75.50%	23.49	0.01	2	42.86	21.43	17.61	0.0705	0.0016	2952.31
25	76.00%	27.26	0.01	2	43.87	21.94	20.45	0.0693	0.0016	3539.16
26	74.00%	29.42	0.02	2	37.55	18.77	22.06	0.0788	0.0021	3831.98
27	76.00%	38.08	0.02	2	42.64	21.32	28.56	0.0713	0.0017	4152.63
28	76.50%	43.63	0.02	2	48.50	24.25	32.72	0.0631	0.0013	4882.26
29	68.00%	55.49	0.05	2	34.78	17.39	41.61	0.0782	0.0022	5050.45
30	69.50%	63.54	0.04	2	38.94	19.47	47.65	0.0714	0.0018	5459.43

N° Model	η_0	H_1 (m)	A	B	$Q_{b,max}$	Q_0 (L/s)	H_0 (m)	E	F	Cost (€)
31	70.00%	67.24	0.04	2	38.70	19.35	50.43	0.0723	0.0019	5805.49
32	61.00%	81.41	0.04	2	45.42	22.71	61.06	0.0537	0.0012	7056.63
33	63.00%	104.98	0.04	2	48.63	24.32	78.73	0.0518	0.0011	9356.84
34	70.00%	20.50	0.23	2	9.42	4.71	15.38	0.2973	0.0316	3637.17
35	73.00%	22.83	0.20	2	10.59	5.30	17.13	0.2756	0.0260	3917.89
36	76.00%	26.81	0.19	2	11.99	5.99	20.11	0.2536	0.0212	4884.68
37	76.00%	33.36	0.26	2	11.32	5.66	25.02	0.2687	0.0237	4997.21
38	81.00%	44.44	0.26	2	12.99	6.50	33.33	0.2494	0.0192	5407.40
39	72.00%	41.29	0.28	2	12.17	6.09	30.97	0.2366	0.0194	5667.55
40	73.50%	49.14	0.24	2	14.27	7.14	36.85	0.2060	0.0144	6009.98
41	75.00%	55.03	0.28	2	14.13	7.07	41.27	0.2123	0.0150	7048.16
42	77.00%	68.92	0.27	2	15.97	7.99	51.69	0.1928	0.0121	9053.13
43	73.00%	82.74	0.32	2	16.16	8.08	62.06	0.1807	0.0112	9278.19
44	75.00%	93.45	0.31	2	17.41	8.71	70.09	0.1723	0.0099	9552.86
45	77.00%	104.25	0.32	2	18.11	9.06	78.19	0.1701	0.0094	11157.32
46	75.00%	26.58	0.10	2	16.61	8.31	19.93	0.1806	0.0109	5225.90
47	78.00%	33.16	0.12	2	16.57	8.29	24.87	0.1883	0.0114	5637.30
48	82.00%	34.83	0.08	2	20.48	10.24	26.12	0.1601	0.0078	5979.73
49	84.00%	39.62	0.08	2	21.96	10.98	29.71	0.1530	0.0070	6725.09
50	78.00%	49.06	0.14	2	18.79	9.40	36.79	0.1660	0.0088	7230.87
51	79.00%	54.18	0.12	2	21.06	10.53	40.64	0.1501	0.0071	9297.55
52	80.00%	59.61	0.10	2	23.83	11.92	44.71	0.1343	0.0056	9655.71
53	80.50%	65.69	0.10	2	25.38	12.69	49.27	0.1269	0.0050	10845.14
54	82.00%	73.46	0.19	2	19.63	9.82	55.09	0.1670	0.0085	11260.17
55	82.00%	86.11	0.14	2	24.78	12.39	64.58	0.1324	0.0053	13745.51
56	80.00%	100.97	0.14	2	26.83	13.41	75.73	0.1193	0.0044	16492.21
57	78.00%	41.57	0.07	2	23.57	11.78	31.18	0.1324	0.0056	7627.75
58	80.50%	48.18	0.06	2	28.01	14.00	36.14	0.1150	0.0041	9405.24
59	81.50%	53.70	0.06	2	29.91	14.96	40.28	0.1090	0.0036	9758.56
60	82.50%	59.98	0.05	2	33.28	16.64	44.99	0.0992	0.0030	11108.92
61	83.00%	65.09	0.04	2	38.31	19.16	48.81	0.0867	0.0023	13597.89
62	82.50%	62.74	0.10	2	25.05	12.53	47.06	0.1317	0.0053	11365.44
63	82.75%	71.69	0.08	2	29.72	14.86	53.77	0.1114	0.0037	14119.40
64	83.00%	82.03	0.07	2	33.94	16.97	61.52	0.0978	0.0029	16866.10
65	70.00%	44.54	0.02	2	50.74	25.37	33.41	0.0552	0.0011	11490.07
66	72.00%	49.37	0.02	2	50.45	25.23	37.03	0.0571	0.0011	13486.57
67	74.00%	54.58	0.02	2	48.27	24.13	40.93	0.0613	0.0013	17258.14

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