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# Phased Methodology for the Optimal Rehabilitation of a Network with an Intermittent Water Supply Based on Hydraulic Criteria

Juan Saldarriaga, A.M.ASCE<sup>1</sup>; Jessica Bohorquez<sup>2</sup>; Camilo Salcedo, S.M.ASCE<sup>3</sup>; Alexander Garzón<sup>4</sup>; David Celeita<sup>5</sup>; Laura Enriquez<sup>6</sup>; Juana Herrán<sup>7</sup>; Andrés Ariza<sup>8</sup>; María Alejandra González<sup>9</sup>; Santiago Gómez<sup>10</sup>; Laura Serje<sup>11</sup>; Laura González, S.M.ASCE<sup>12</sup>; Danna Velásquez<sup>13</sup>; and Catalina Ortiz<sup>14</sup>

**Abstract:** The intermittent supply of drinking water represents a major technical and social challenge, affecting more than 1 billion people worldwide. This paper proposes a methodology with three stages to rehabilitate a deteriorated system with intermittent service in a time horizon of five years as part of the Battle of Intermittent Water Supply problem. First, the initial assessment stage identifies vulnerable areas and critical supply hours. The network is analyzed to establish whether it is possible to deliver the desired demand in a scenario without any leaks. The latter is to set a baseline scenario for the upcoming stages. The sectorization stage defines the optimal district metered areas to reduce water losses and increase supplied water through the improved control of flows and pressure. This stage is divided into clustering, by means of the Girvan–Newman algorithm, and partitioning by defining the location of valves. Finally, the third stage determines the optimum investments for asset rehabilitation. The *optimization process* is performed individually and sequentially for valve settings, pump replacements, storage tanks upgrade, pipe rehabilitation, leakage repair, frequency inverter installation and pumping operation modification, and simple controls. The final solution validates how hydraulic criteria, in combination with optimization techniques and engineering judgment, can significantly improve the operation of an intermittent water distribution system. DOI: 10.1061/JWRMD5.WRENG-6143. This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <https://creativecommons.org/licenses/by/4.0/>.

**Practical Applications:** It is very common that the normal dynamics and performance of drinking water distribution systems are affected by the availability of water resources, either for lack of large enough sources or for low maintenance and operation, which result in high losses or very low pressures in some part of the network. In such cases the operation could become intermittent, a common problem in some cities. Therefore, an adequate rehabilitation of the existing infrastructure is essential to mitigate the socioeconomic impact generated by the lack of opportune maintenance. This study proposes a methodology for the rehabilitation of systems through three stages: (1) identification of the most vulnerable areas according to hourly consumption peaks; (2) sectorization of the network with the aim of having a better control of flows and pressures to reduce leaks; and (3) optimal investment for rehabilitation. During this work, technical knowledge and engineering criteria are integrated to provide integral solutions. These include favorable operating conditions, such as simple controls, valve status, and operation of pumping systems with frequency variators. Finally, a series of indicators is established to measure the progress of the improvement of the network over a chosen period.

**Author keywords:** Intermittent water supply; Water distribution systems (WDS); Multiobjective optimization; Network rehabilitation.

<sup>1</sup>Professor, Dept. of Civil and Environmental Engineering, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia (corresponding author). ORCID: <https://orcid.org/0000-0003-1265-2949>. Email: jsaldarr@uniandes.edu.co

<sup>2</sup>Ph.D. Researcher, School of Civil, Environmental, and Mining Engineering, Univ. of Adelaide, North Terrace, Adelaide 5005, Australia. ORCID: <https://orcid.org/0000-0001-5071-8676>. Email: jessica.bohorquez@adelaide.edu.au

<sup>3</sup>Ph.D. Student, Dept. of Civil and Architectural Engineering and Mechanics, Univ. of Arizona, Tucson, AZ 85721. ORCID: <https://orcid.org/0000-0002-0248-7276>. Email: csalcedo@email.arizona.edu

<sup>4</sup>Ph.D. Student, Faculty of Civil Engineering and Geosciences, Dept. of Water Management, Delft Univ. of Technology, Stevinweg 1, Delft 2628 CN, Netherlands. ORCID: <https://orcid.org/0000-0002-0012-7293>. Email: j.a.garzon@tudelft.nl

<sup>5</sup>Ph.D. Student, Département de Génie Civil et de Génie des Eaux, Université Laval, Pavillon Adrien-Pouliot 1065, av. de la Médecine, QC, Canada G1V 0A6. Email: david.celeita@ulaval.ca

<sup>6</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. ORCID: <https://orcid.org/0000-0002-9628-118X>. Email: lv.enriquez@uniandes.edu.co

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<sup>7</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. Email: jm.herran10@uniandes.edu.co

<sup>8</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. Email: ad.ariza@uniandes.edu.co

<sup>9</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. Email: ma.gonzalezml@uniandes.edu.co

<sup>10</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. Email: s.gomez3@uniandes.edu.co

<sup>11</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. Email: l.serje@uniandes.edu.co

<sup>12</sup>Ph.D. Student, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. ORCID: <https://orcid.org/0000-0002-3929-5817>. Email: lk.gonzalez@uniandes.edu.co

<sup>13</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. Email: dc.velasquez@uniandes.edu.co

<sup>14</sup>Researcher, Water Distribution and Sewerage Systems Research Center, Universidad de los Andes, Bogotá 111711, Colombia. ORCID: <https://orcid.org/0000-0002-3833-2188>. Email: pc.ortiz@uniandes.edu.co

## Introduction

Intermittent water supply occurs when a water distribution system (WDS) is not able to deliver water to all consumers continuously. Many people around the world are affected by this problem, especially in developing countries. Half of the customers connected to WDSs in Asia, two-thirds in Latin America, and one-third in Africa deal with intermittency in water supply (Klingel and Nestmann 2013). Users are exposed to issues such as inequitable water distribution, questionable water quality, and fire hazards. It is noteworthy that developed countries may also face intermittency and the related consequences due to droughts, pollution accidents, natural disasters, or system maintenance (Simukonda et al. 2018).

Demographic and economic dynamics, unplanned system extension, poor system management and operation, hydrological regime changes, and lack of customer awareness have been previously described as causes for intermittent water supply (Simukonda et al. 2018). The rapid increase in water demand due to population growth and urbanization forces the expansion of WDSs (Galaitis et al. 2016). Expanding water systems in an unplanned manner can lead to poor pressure conditions when the original hydraulic capacity is surpassed (Simukonda et al. 2018), inducing intermittent supply. In addition, private (frequently illegal) connections to the network and private storage in households are common coping mechanisms used by customers to imitate a continuous water supply (Klingel 2012). Storage at households deteriorates water quality, causes pressure surges in the system, and promotes consumer overdrawn (Galaitis et al. 2016). In intermittent systems, the natural deterioration of infrastructure is triggered by these unstable pressure conditions (Galaitis et al. 2016; Klingel 2012). Hence, the system's functioning is restricted due to an augmented pipe break rate and the related water losses through leakages (Klingel 2012). These conditions aggravate the network performance, which reinforces the system intermittency, developing a negative feedback loop (Galaitis et al. 2016).

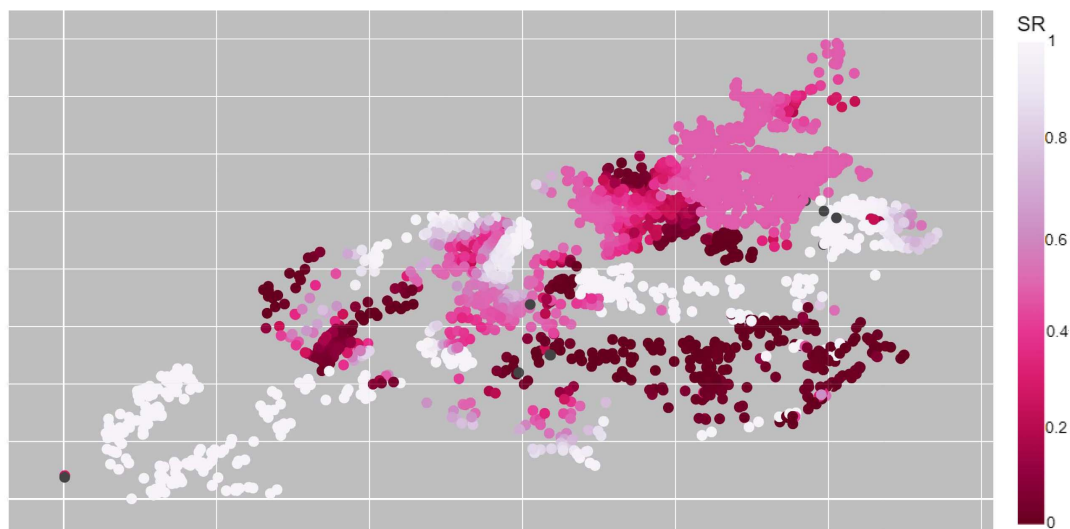
Two alternatives can be found in the literature to diminish the adverse effects of intermittency: developing tools to design and operate intermittent systems or converting them into continuous supply systems (Simukonda et al. 2018). The first approach addresses the operational problems of intermittent systems designed

to work in a continuous mode (Simukonda et al. 2018), which are often planned assuming unlimited water availability. In contrast, converting the system means that all intermittent modes of operation are temporary while investments in the network are made to achieve continuous water supply (Klingel and Nestmann 2013; Simukonda et al. 2018). As part of the 2nd Water Distribution System Analysis & Computing and Control in the Water Industry (WDSA/CCWI) Joint Conference, the objective of the Battle of Intermittent Water Supply (BIWS) is to recover a deteriorated network so continuous supply is ensured 24 h a day with adequate pressure at all nodes.

The water distribution network under study fails to satisfy water demand and to guarantee enough pressure at all nodes. The original design considered only one main reservoir to feed the network through gravity. However, due to the deterioration of the network and the increase in demand, it has been necessary to use five underground wells. Nevertheless, the amount of available water is still limited, and users are not receiving water continuously. Fig. 1 demonstrates the poor performance of the network through the supply ratio (SR), where a value of 1 represents continuous supply. The SR is the average relation between supplied and expected demand, which is one of the nine indicators proposed by the Battle Organizing Committee for evaluating the performance of the network (Battle Organizing Committee 2021).

The BIWS invites participants to propose a strategy for rehabilitation of the network in a time horizon of five years. The rehabilitation can be attained with annual improvements to the network's infrastructure and operation settings, all with an associated cost and considering budget constraints. The possible investments include repairing leaks, replacing pipes, replacing pumps, adding frequency inverters on existing pumps, installing isolation or control valves, and increasing the capacity of the network's tanks (Battle Organizing Committee 2021). These changes aim to increase water availability per user, improve supply pressure, and reduce leaks, energy consumption, and the amount of air in the pipes.

This paper proposes a methodology composed of three stages to rehabilitate the deteriorated system: initial system assessment, identification of hydraulic sectors, and optimal investment for asset rehabilitation. EPANET software (Rossman 2000) has been used to develop the solution through a Python Integrated



**Fig. 1.** Network initial performance represented through the supply ratio indicator (SR). The SR is calculated as the supplied over the expected water demand.

Development Environment. Multiple Python libraries have been used, mainly the Water Network Tool for Resilience (WNTR) (Klise et al. 2020) and specialized statistical and optimization packages. The obtained results for the final solution are presented, demonstrating that hydraulic criteria in combination with optimization techniques can significantly improve the operation of an intermittent WDS. Lastly, conclusions are presented on the most effective ways of improving the performance of an intermittent system considering hydraulic measures to determine the prioritization of investments.

## Methods

The developed methodology for rehabilitating the BIWS network is presented in Fig. 2. Each stage is represented in a dashed square, and it presents all the required steps of the proposed rehabilitation strategy. The initial assessment stage provides a baseline to understand the current state of the network and urgent requirements for improving intermittency in supply. The sectorization stage defines hydraulic sectors following clustering and partitioning procedures explained in literature using the Girvan–Newman algorithm (Di Nardo et al. 2014; Liu and Lensey 2020).

The last stage consists of sequential optimization procedures through NSGA-II deciding the best modifications to the network each year. The optimization sequence has been defined considering that users' water demand is constantly changing, so the network requires gradual improvement since the demand is modeled as pressure-dependent (Páez et al. 2014). Hence, the optimization procedures have been performed repeatedly every year. The process includes identifying essential investments, expanding tanks, replacing pipes and pumps, installing and operating frequency inverters in pumps, repairing leaks, and deciding the optimal settings of the valves over time.

### Initial Assessment

To mimic the effect of household tanks in the network, the demands have been represented as pressure-dependent using EPANET. The Battle Organizing Committee provided the current state of the network, including the location and emitter coefficients of all leakages. It is not possible to rely solely on emitters to simulate leakages because the flow rate is dependent on the pressure at the node. This would result in an unrealistic source of inflow when negative pressures occur due to the demand exceeding the maximum available flow in the system. Hence, simple controls have been implemented

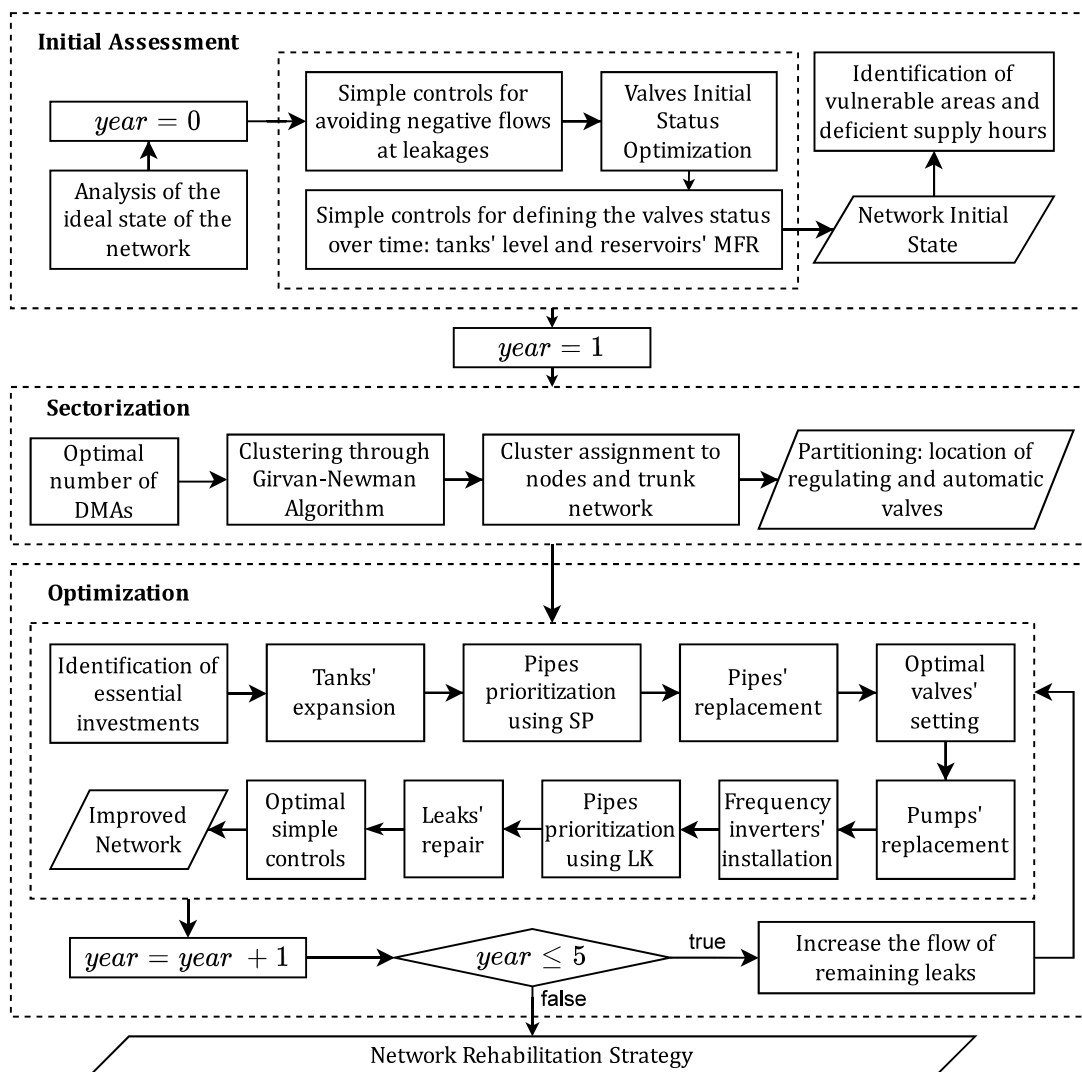


Fig. 2. Network rehabilitation methodology.

for leak modeling. A node has been added at the location of each leakage, while an emitter has been connected to the former through a dummy pipe. The negative flows through those pipes have been controlled by closing the pipelines when the pressure drops below zero in the corresponding node.

In addition to the scheduled rehabilitation of the network, the BIWS also encourages participants to propose an initial mode of operation that enables the system to supply water to the largest quantity of users during the most prolonged period of time (Battle Organizing Committee 2021). The status of the existing valves in the network has been modified, and the time to change this status has been defined. To decide the initial status of the 24 existing valves, an optimization procedure has been conducted employing genetic algorithms using *py moo* (Blank and Deb 2020) and WNTR (Klise et al. 2020). The optimization problem consisted of maximizing the SR by changing the status of each valve. The SR indicator has been used since it relates to five more indicators, so its maximization ideally would improve them all. In addition, solutions that did not comply with the maximum flow rate (MFR) of all reservoirs have been penalized proportionally to the exceeding extracted flow at each reservoir.

To define the changes in valves' status over time, EPANET simple controls have been added to the model with two more objectives: complying with the maximum and minimum allowable levels in all tanks and with the MFR of all reservoirs. The controls for the level of tanks have been used to comply with a safety margin of five centimeters to avoid the tanks overflowing or running dry during the simulation. Also, simple controls, jointly with the closings of some valves and pipes, have been used to limit the flows to the respective MFR at each source.

The resulting initial state of the network was the baseline for analyzing which investments are required annually to recover the system from intermittency. Also, it was used to study the hydraulic behavior of the system and to identify vulnerable areas, namely, those experiencing low pressures or lack of supply, as well as critical hours during the simulation.

### Sectorization

District metered areas (DMAs), or hydraulic sectors, are discrete areas of a WDS fashioned by closing valves or disconnecting pipes (Saldarriaga et al. 2019). Supply sectors simplify the hydraulic system functioning and monitoring by means of mass balance since the amount of water entering and leaving each area is measured through flow meters (Laucelli et al. 2017). Therefore, DMAs involve improved control of flows and pressure, allowing for the identification and reduction of leakages (Saldarriaga et al. 2019). Other advantages include the control of the spread of contaminants and operational flexibility. However, sectorized systems also have some disadvantages. The use of DMAs decreases network resilience because the pressure at nodes drops since gate valves affect the topologic and energetic redundancy (Di Nardo et al. 2015). Also, the resilience is affected due to fewer available paths from supply sources to demand nodes (Saldarriaga et al. 2019). Nonetheless, water utilities often sectorize the networks since it provides valuable tools for improving WDS performance. DMAs are often used for supplying water intermittently when a continuous service is unfeasible. A scheduled supply can be planned by feeding hydraulic sectors in turns so that the demand is limited to the water available at certain times.

An initial grouping of elements has been performed to optimize the rehabilitation of the network. Since the main problem of the network is a prominent presence of leaks, sectorization allows us to proactively manage them improving the system's performance

(Saldarriaga et al. 2019; Di Nardo et al. 2014). The usual methods for establishing DMAs involve two phases: clustering and network partitioning (Di Nardo et al. 2014, 2015; Liu and Lensey 2020). With the clustering phase, the objective is to define the dimensions and shape of the sectors based on graph theory (Di Nardo et al. 2015). It is necessary to consider that leaks are more detectable when small DMAs are designed due to permanent pressure control (Saldarriaga et al. 2019). However, it would be more expensive and inconvenient, so it is important to establish an optimal number of DMAs.

The proposed methodology determines first the optimal number of sectors using the K-means clustering algorithm. K-Means is one of the simplest unsupervised learning algorithms that solve the well-known clustering problem (Kodinariya and Makwana 2013). This algorithm works by grouping nodes according to their proximity. The elbow method has been used to determine the optimal number of DMAs by looking for a reasonable trade-off between a measure of error and the number of clusters (Kodinariya and Makwana 2013). In addition to the proximity criteria for establishing DMAs, granting network connectivity is necessary as it is the primary driver of hydraulic behavior (Laucelli et al. 2017; Liu and Lensey 2020). The Girvan–Newman algorithm has been applied to identify the boundaries of sectors based on the *edge betweenness* metric (Girvan and Newman 2002). The use of this metric ensures the connectivity of nodes because it allows identifying edges that lie between communities, namely, the edges that would separate two sectors and leave a minimal number of connecting edges between DMAs. Hence, the algorithm progressively removes these edges to form the sectors according to the established number of DMAs (Di Nardo et al. 2015).

The second phase of sectorization focuses on the hydraulic performance of the network in order that operative areas are defined (Laucelli et al. 2017). The partitioning considers the installation of valves and flow meters to isolate sectors from each other and establish inflow points. This phase creates optimal sectors by choosing the location and minimizing the number of valves and flow meters to reduce investments and operational costs, as well as to simplify the water balance to identify leaks (Di Nardo et al. 2015). The procedure is usually based on genetic algorithms or iterative techniques (Laucelli et al. 2017; Di Nardo et al. 2014, 2015; Liu and Lensey 2020). However, the location of valves for this problem has been established manually when analyzing the result from the clustering phase since the size of the network allows for it. Hence, pressure reducing valves (PRVs) have been placed at the inflow points of each sector. Isolating valves have been installed on the resulting edges from the Girvan–Newman algorithm and on those pipelines connected to the trunk network that do not obstruct inflow points.

### Optimization Process

The optimal design of a WDS is an NP-hard problem where the diameters of the pipes that satisfy hydraulic conditions in the network need to be selected (Saldarriaga et al. 2012; Páez et al. 2020). The rehabilitation of a network is a related problem; thus, deterministic approaches are not viable for obtaining optimal solutions in real systems. Metaheuristic approximations, such as genetic algorithms, should be employed to achieve near-optimal solutions (Páez et al. 2020). Therefore, to solve the BIWS problem, the nondominated sorting-based multiobjective evolutionary algorithm (NSGA-II) has been used to find the optimal investments that would improve the network's performance. This algorithm has been widely employed for solving similar problems since it allows for the exploration of multiple optimization criteria at once.

The objective functions selected to solve WDS optimization problems represent different aspects of the network performance, such as reliability-based indices (Páez et al. 2020). For instance, NSGA-II has been used to simultaneously minimize costs and maximize network resilience (Páez et al. 2020), to minimize leaks and the number of installed valves (Salcedo and Saldarriaga 2017), and to minimize costs and hydraulic head deficit, among others.

For the application presented in this paper, the parameters of the NSGA-II have been defined according to literature recommendations. The size of the initial population should be large to increase the chance of identifying key genes from the beginning, and a large number of generations ensures better convergence of the algorithm (Páez et al. 2020; Wang et al. 2019). Several optimization procedures have been executed, as detailed in the following paragraphs. Thus, a fair trade-off between results and computational costs has been considered employing populations of 100 individuals and a minimum of five generations per decision variable.

Seven different optimization procedures have been identified for the rehabilitation of the BIWS network, some involving investments and some involving the modification of the status of the elements on the network. The investment optimization included upgrading storage tanks, replacing pipes, repairing leaks, replacing pumps, and installing frequency inverters on pumps. Additionally, to deal with intermittency and increase the water supplied to users, the operation has been optimized by modifying the initial setting of valves and establishing simple controls for adapting the valves' status over time. Each of these optimization procedures has been performed individually and sequentially, as Fig. 2 presents. The sequence has been established giving priority to investments with significant influence on the network's performance. Changes in the demand flows are expected every time an investment or operational change is made because the demand is a function of the pressure in the system (Páez et al. 2014). Therefore, this approach allows for a near-optimal rehabilitation plan since the network requires progressive improvement.

The objective functions used for the BIWS problem match the indicators proposed by the Battle Committee. Energy consumption of pumps ( $i_8$ ) has been employed for tanks' expansion, the percentage of subscribers with continuous service ( $i_2$ ), pressure level at consumption nodes ( $i_5$ ), or the level of equity in supply ( $i_9$ ) for replacing pipes and pumps, and the proportion of water supplied to users ( $i_4$ ) or  $i_5$  for installing and operating frequency inverters in pumps. These actions involve optimizing the chosen indicator and minimizing the costs while restricting the solutions to a limited budget. Hence, the cost has been considered an objective function and a constraint. Regarding the operational optimizations,  $i_2$  or  $i_5$  and leaked water volume ( $i_3$ ) have been chosen as objective functions because an equilibrium between these measures is desired. The decrease of leaked volume would ideally increase the volume supplied to users. However, as the demand is a function of the pressure in the system, the improvement of supplied flow rates implies higher pressures in the system and probably more water losses through leakages.

The yearly rehabilitation plans have been performed repeatedly and following the same sequence, with some exceptions for Year 1. As Fig. 2 shows, the identification of essential investments has been the first approach of the procedure every year. The first-year optimization differs particularly from the rest of the years due to the urgent need for flow control valves (FCVs) at the exit of supply sources and PRVs and isolating valves for DMA definition. Hence, the initially reduced budget has been exclusively destined for the essential investments identified after the initial state analysis, prioritizing the replacement of unusable pumps. The exceeding capital has been destined to expand tanks and repair

leakages, which have also been identified as crucial initial improvements.

Further, the first optimization conducted has been the expansion of tanks, which considers one tank at a time based on a capacity assessment. The analysis consists of doubling each tank's diameter, adjusting its initial level, and estimating the indicators. As a result, the tank that shows the most significant improvement is optimized. In this process, the NSGA-II looks for the most convenient volume upgrade, considering the simultaneous adjustment of simple controls. In addition to the available budget, this optimization problem is constrained by the minimum pressure requirement at all nodes and a 5-cm margin for the upper and lower levels of the tank.

The following step decides which pipes should be replaced in the network. Given the complexity of the problem, the solution space has been reduced using hydraulic criteria to increase the algorithm's efficiency. Hence, specific power ( $SP$ ) has been used to determine the relative importance of pipes on the hydraulic behavior of the network.  $SP$ , calculated using Eq. (1), quantifies the power losses in unit weight across the network as a consequence of the flow passing through each pipe (Saldarriaga et al. 2014, 2016). For each one of the pipes  $SP$  is

$$SP = Q(h_f + h_m) \quad (1)$$

where  $Q$  = flow rate of the pipe; and  $h_f + h_m$  = sum of friction and minor losses in the pipe, respectively. The pipes with the highest  $SP$  indicate primary importance for being replaced with a new one with a larger diameter since that is where the most significant pressure losses are located (Páez et al. 2020). Additionally, according to their replacing cost and a certain price threshold, pipelines have been classified as "cheap" or "expensive." From the "expensive" group, a priority subgroup based on  $SP$  has been identified using the K-means clustering algorithm. These prioritized pipelines represent the decision variables for the optimization procedure, which could take values between 0 and 16. A value of 0 means no replacement, while the numbers from 1 to 16 represent one diameter of those specified in the problem. The NSGA-II algorithm identifies which pipes should be replaced, considering that a pipe cannot be substituted for one with a smaller diameter.

The next step is to define the optimal initial settings of the PRVs in the network. High pressures have been identified during certain hours of the initial state simulation, generating increased water losses and a decrease in the supplied water. Hence, the initial settings of the valves have been decided between 10 and 50 m to find the most optimal combination in all PRVs that would produce acceptable pressure levels at consumption nodes while preventing the pressures from reaching extreme values.

The fourth set of yearly optimizations is the replacement of pumps. This optimization step considers one decision variable per pump, ranging between 0 and 153. Each decision variable represents every possible pump model according to the problem description. Pumps that are not powerful enough to overcome the elevation difference or surpass the MFR at each source are not contemplated. Subsequently, the installation of frequency inverters is optimized, together with the definition of their operation. For the installation, binary decision variables per pump have been considered, determining whether to install an inverter. For the operation, each pump with an inverter requires a pattern that indicates the speed percentage at each hour. To reduce the search space, the simulation hours have been classified as high, medium, or low demand according to the pattern in the network. Demand multipliers higher than 1.4 have been classified as high and under 0.5 as low. In this way, each inverter only requires three decision variables.

The NSGA-II has been implemented with seven binary variables and  $7 \times 3$  multipliers between zero and one to optimize the installation and use of these inverters, adding 28 decision variables.

The last set of investments is to repair leakages. As well as with pipes replacement optimization, the asset choices have been reduced using hydraulic criteria. Leaked Flow rate (LK) has been used in this case. *SP* and *LK* have shown satisfactory results for narrowing down the solution space and reducing the computational effort while strategically optimizing the network (Saldarriaga et al. 2009, 2012, 2014; Salcedo and Saldarriaga 2017). Pipes with high *LK* indicate the urge to repair leaks since the total water volume lost through leakages during the simulation is large. Hence, the same procedure previously explained has been conducted to prioritize pipes whose leaks must be repaired, but this time within the “cheap” group. The “cheap” group has been chosen since it allows us to tactically upgrade the network while complying with a limited budget. This process does not involve an optimization algorithm. Therefore, only leakages in priority pipelines have been repaired within the remaining budget each year.

Finally, a pattern of settings for each PRV is optimized using NSGA-II with two different settings for every PRV. These variables are expressed as percentages of the optimal valves’ setting found in a previous step, ranging between 0 and 2. The simulation hours have been classified as high and low demand, defined by a limit of 1.1 in the hourly multiplier of the demand pattern. According to the demand classification, one of the two settings for each valve is assigned through simple controls. Next, a status pattern for each isolation valve that is not required to define DMAs has been optimized using the same method and parameters. In this way, 11 isolation valves have been considered, resulting in 22 variables deciding whether to open or close each valve.

After the optimization sequence is finished, the last state of the network is analyzed to verify its improvement and compliance with restrictions. If any restriction has been violated, simple controls have been added manually to limit the level of tanks between safety margins and to guarantee the MFR at each supply source. Additionally, before the initialization of the following year’s optimization, the flow rate of the remaining leaks was exponentially increased to represent what would occur in a real network, as the problem description states.

## Results

### Network Rehabilitation

The first approach of the initial assessment stage has determined if the network can deliver the desired demand without any pipe breaks, with maximum pumping power and use of the available water from all reservoirs. After a hydraulic execution with these ideal conditions, results have revealed that the demand cannot be completely satisfied in continuous operation. In fact, even surpassing the MFR in some sources, the supplied demand cannot meet the expected demand completely. Nevertheless, these findings provided an upper bound of the best conceivable performance of the network so that at the end of the five-year investment plan, the resulting network would be as similar to this system as possible.

For defining the initial mode of operation of the network in Year 0 (where no investments could be made), the status of the existing elements on the network has been modified. Firstly, two pumps have been closed (*B\_RI* and *B\_SM*) because the head required by the network surpasses their shutoff heads, inducing them to close automatically. Consequently, these pumps have been identified as essential initial investments for Year 1. Regarding the setting

of valves, 13 out of 24 valves have been closed to improve the hydraulic behavior of the network. The *SR* indicator has been maximized for deciding these settings, influencing an improvement in other indicators as well.

Simple controls have been added to the model to prevent water from entering the network through leakages. Nevertheless, there are still some leaks in which the flow rate is negative. Although the magnitude of these flows is low, this situation is not ideal and should be revised in further research related to intermittent systems and pressure-dependent water demand modeling. Additionally, controls for complying with restrictions in all reservoirs and tanks have been added. Controls for tanks *T3\_MO* and *T4\_CU* have been particularly difficult to define since these tanks have only one inlet–outlet pipe. The limits for all controls to tanks’ water level and pressure in the adjacent nodes to sources have been established empirically and iteratively. Therefore, FCVs at the outlet of supply sources were also crucial initial investments so that the flow from reservoirs would not be controlled solely through simple controls.

The minimum pressure requirements in the resulting network for Year 0 were not met in some zones of the system, especially in areas with high elevation differences. These locations have been considered vulnerable zones. A solution would be adding new pumping stations; nevertheless, due to BIWS restrictions, no new pumps could be added. Therefore, it is necessary to shift water supply by zones so that users are supplied at different times, prioritizing equity even if the demands are not completely satisfied. For this reason, the definition of DMAs is key for improving the performance of the network. Seven DMAs have been identified and defined according to proximity and connectivity criteria using the Girvan–Newman algorithm. In this way, 29 new PRVs and 17 isolating valves have been added. Additionally, seven of the existing valves in the network have been used to define DMAs due to their convenient location. Therefore, as Fig. 3 shows, the initial budget for investing in Year 1 has been reduced by 35.8% after purchasing FCVs, PRVs, and isolating valves.

Moreover, Fig. 3 presents the yearly distribution for the budget directed to the different interventions on the network. These investments have been defined in the last stage of the methodology,

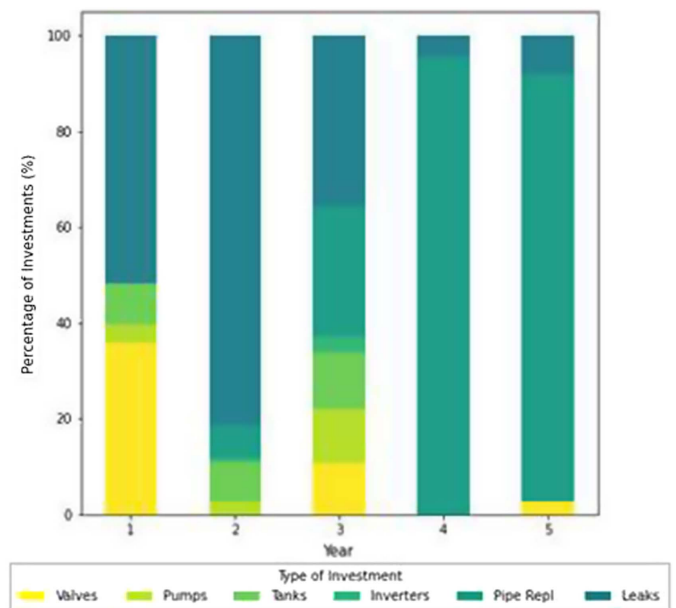


Fig. 3. Distribution of investments along the five-year rehabilitation plan.

consisting of sequential optimization procedures. Engineering judgment has been fundamental as a first step of the optimization chain to detect essential investments at the beginning of each year. Further, the employed algorithms have revealed satisfactory results for optimizing the WDS. A brief description of the most relevant findings for each intervention is now presented.

### Tank Expansion

The expansion of tanks has been considered a priority since Year 1 to regulate the water availability in the system. However, the regulating effect of any tank has not shown a considerable change when performing the capacity assessment. Therefore, only one tank of the four in the network has been considered every year, looking for the most influential tank and its optimal expansion to improve water level behavior.

Tank T4\_CU has been upgraded in Year 1 because it showed a significant influence in the selected indicators. Tank T1\_CO has been upgraded in Year 2 as it has shown the greatest improvement potential among the three-remaining nonoptimized tanks. Further, the capacity assessment for tank T3\_MO has enhanced the indicators and water levels in Year 3, so it has been optimized. The optimization of these tanks resulted in a volume increase of almost 905 m<sup>3</sup>, and the final associated cost has not resulted in major investments, as Fig. 3 shows.

The only tank that has not been modified after Year 3 is the largest of all, so optimizing it involves a very high investment. The optimization of T2\_PL has been skipped in Year 4 because duplicating its volume does not enhance the network performance. In contrast, the regulating effect has slightly improved in Year 5. Therefore, T2\_PL was initially optimized, and the optimal volume result took 63% of the annual budget. Nevertheless, the expansion of this tank has not impacted the network at the end of the optimization chain. For this reason, it has been possible to reverse its volume and, instead, invest that budget in replacing pipes. These findings demonstrate that it is not possible to automate the optimization process completely. Engineering knowledge and judgment is fundamental for evaluating the optimization results' potential and distributing the annual resources adequately.

### Pipe Replacement

Pipe replacement has not been considered in Year 1 as replacing pumps, expanding tanks, and eliminating leaks have been prioritized. However, there has been a gradual but sustained increase in the budget destined for pipe rehabilitation because pipe replacement proved to be one of the interventions with the highest impact on the network, along with operational optimizations. In fact, pipe replacement was preferred before upgrading tanks in Year 5. Consequently, almost 8 km of pipes have been replaced overall, representing 2.4% of the network's total length.

Not many pipes have been replaced in total—two in Year 2, four in Year 3, five in Year 4, and five in Year 5. However, pipe replacement has been the most expensive intervention, counting up to 43.5% of the total budget spent over the five years. This is due to the behavior of the optimization solutions, as the indicators employed as objective functions performed significantly better when expensive pipes were prioritized for rehabilitation. Pipes with high *SP* have been considered most-likely-replaced pipes because they concentrate the energy losses in the WDS, requiring urgent rehabilitation. Results have shown that these pipes are usually part of the trunk network, so their costs are high as they are long and have large diameters.

### Valves Settings

At first, the number and location of valves were decided exclusively according to the definition of DMAs. However, further in the

optimization process, it was necessary to add more PRVs since the pressure in the system was progressively recovered. For instance, new valves have been added after replacing all pumps in Year 3 since the system requires controlling pressure so that water losses would not increase. The location of these valves has been defined through engineering knowledge and understanding of the hydraulic behavior of the network.

The settings of all PRVs in the WDS must be wisely selected to obtain an acceptable hydraulic gradient line in each path of the network. NSGA-II has shown outstanding performance for choosing the optimal settings of all valves since this optimization procedure has been one of the most influential for improving the service indicators. After replacing pipes, the performance of the WDS varies significantly. Hence, adjusting the initial setting of PRVs has been selected after this intervention. The result works as a first approximation to adequate pressure levels in the system, allowing the definition of the optimal pattern operation of pumps and the prioritization of leaks that should be repaired in the following stages.

### Pump Replacement

The essential investments in Year 1 included the replacement of pumps B\_RI and B\_SM. The NSGA-II looked for the best replacements for these pumps to make them suitable for the system. The selected pumps were low-tier pump models. For Year 2, pumps B\_SA and B\_PL have been optimized out of the five nonreplaced pumps. The optimal solution suggested replacing them with pump models that utilized the total capacity of each borehole. When identifying essential investments in the introductory step for Year 3, it was noted how several pumps were not enough to supply the sectors they were serving. Also, the available water from some reservoirs was being wasted. Thus, pumps that have not been optimized, B\_PT1, B\_PT2, and B\_AB, were considered critical improvements to the network on Year 3. New investments in pumps B\_RI, B\_SM, and B\_SA have also been considered, even when they were already replaced in previous years. A manual selection of pumps has been made to take advantage of the water available in each well while satisfying the maximum flow rate restrictions and providing enough head. Thus, all pumps have been upgraded in Year 3, and no further optimization has been performed.

These findings showed that using an optimization algorithm for pump selection does not deliver the expected results. It was necessary to review the suggested pumps and use good engineering judgment to finally decide which pump models could better serve each area. In addition, selecting new pumps is not an easy task because the behavior of the network changes with selected investments each year. Thus, it would be necessary to replace pumps constantly. However, this is not realistic. Therefore, the best approximation was the immediate replacement of all pumps with the best available models.

### Frequency Inverter Installation and Operation

The NSGA-II has shown satisfactory results for deciding the installation and operation of frequency inverters in pumps. This procedure was skipped in Year 1 because almost all the pumps had old models; therefore it was not worth investing in frequency inverters. In contrast, two frequency inverters were installed in Year 2, one in an old pump (B\_PT1) and one in a replaced pump (B\_SA). In this way, the operation of the network was significantly enhanced. Nevertheless, as explained in the previous section, these pumps have been replaced all over again in Year 3. Therefore, pumps B\_PT1 and B\_SA have been optimized again, installing and operating frequency inverters in the new models. Additionally, the optimal solution also suggested the installation of inverters in three more pumps (B\_PT2, B\_SM, and B\_PL). Pumps B\_PT1 and

B\_PT2 work in parallel at the outlet of tank T2\_PL, so the use of frequency inverters in both pumps enables a better and more flexible operation.

No more inverters were installed after Year 3, even when two pumps do not have inverters. These pumps, B\_AB and B\_RI, are located in vulnerable areas; thus, NSGA-II identified how the network requires its total capacity at all times. In contrast, the operational optimization of the installed frequency inverters has been optimized every year. In this way, it has been possible to provide enough head and capacity according to the hourly multipliers of demand. Therefore, more efficient use of the pumping power in the network has been obtained while optimizing the pressure levels at consumption nodes.

### Leak Repair

As was previously discussed, it is more efficient to replace pipes than any other intervention, especially compared to repairing leaks. Thus, the number of leaks to be fixed year after year progressively decreased considering that most resources were destined to replace pipes. The leak repair procedure has been left at the end of the optimization sequence because it has been noted that it does not have a significant influence on the network. Prioritizing the group of “cheap” pipes in this process allowed us to employ the precise amount of resources so that the annual budget would be spent entirely. As the cost of detecting leaks is higher than fixing them, a combination of large and small leaks has been chosen to match the associated costs and the available budget. However, large leaks were preferred so that a more significant number could be repaired.

### Optimal Simple Controls

The controls for PRVs and isolation valves have been crucial as a last step of the optimization sequence. In this way, only operational changes are suggested with the current state of the network and looking for the best conceivable pressure and flow conditions. As well as with the definition of the initial setting of PRVs, optimizing simple controls for adjusting these settings over time has allowed balancing the system’s pressure levels, but this time considering the demand variations during the entire simulation time. Therefore, the optimization algorithm looked for the optimal pressure conditions that regulated the hydraulic necessities of the network and reduced water losses. This result is attained since the percentage of subscribers with continuous service ( $i_2$ ), or the level of pressures at consumption nodes ( $i_5$ ), has been maximized while minimizing the total leaked volume ( $i_3$ ).

Similarly, closing and opening isolation valves in the network allowed us to define different flow pathways over time to serve

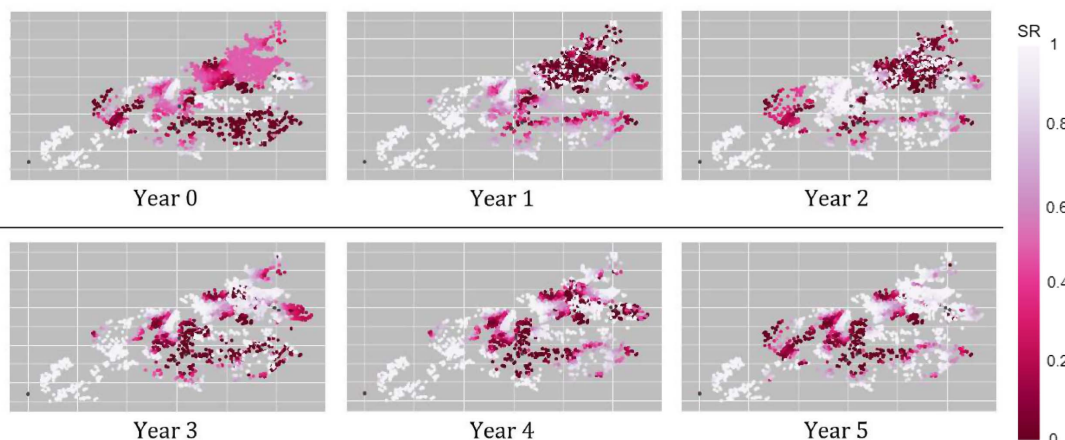
various areas in the system. Thus, customers would be supplied at different times, prioritizing equitable water access. These controls in the settings of PRVs and isolation valves along the simulation time proved to be one of the most effective modifications to the network. Nonetheless, no optimal solution has been found for controls of isolating valves in Year 4, meaning that the system requires all flow pathways at all times. It is noteworthy that controls for isolation valves must guarantee the complete connection of the network, so no valves that disconnect the WDS must be considered in the optimization process.

### Yearly System Improvement

The final models for every year have been obtained after checking all restrictions. Simple controls for avoiding negative flows in leaks, controlling the level of tanks, and complying with the MFR of reservoirs have been revised as in Year 0. To better control water levels in tanks T3\_MO and T4\_CU, which have only one inlet–outlet pipe, dummy check valves and isolation valves have been included as interventions in Year 5. Nevertheless, there were instabilities in all models, and it was not always possible for simple controls to restrict the network in the intermediate moments between one reporting time step and another. Likewise, even though FCVs have been included to restrict the flow extracted from supply sources, the MFR in the final optimized models was not always satisfied because the system was unbalanced. For this reason, the number of trials had to be increased, meaning the number of iterations EPANET performs to find a hydraulic solution for each moment in time.

These manual modifications altered the solutions obtained after the optimization sequence, deteriorating its performance for Years 1 to 4. The final model for Year 4 presents high instabilities, implying a worsening in some of the indicators compared to Year 3 (see Fig. 5). However, these modifications to the models are essential to satisfy the restrictions so that a fair analysis of the intermittency problem can be performed. Otherwise, more water than the actual available would be extracted. In contrast, the optimized system for Year 5 only violated the maximum level of one tank, which was fixed through simple controls. Surprisingly, this final model did not get worse, showing an enhanced performance of the final rehabilitated system.

The SR indicator ( $i_4$ ) in every consumption node for each year’s final network is presented in Fig. 4. With all the interventions, the supplied demand increased from 48.2% in Year 0 to 70.6% in Year 5. Thus, the optimization outcomes implied a satisfactory



**Fig. 4.** Supply ratio indicator (SR) from Years 0 to 5. The SR is the supplied over the expected water demand.

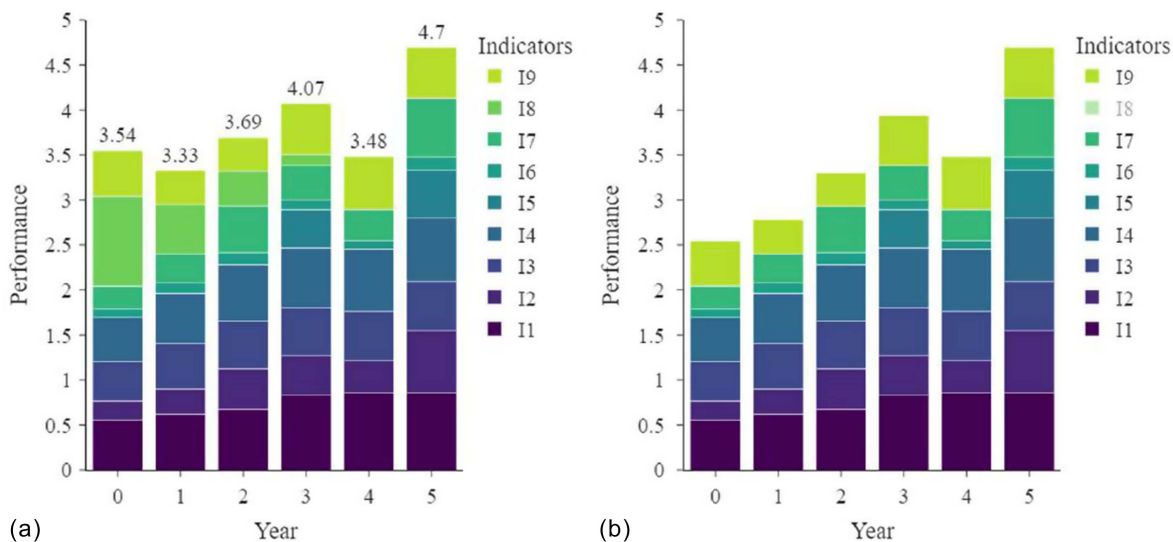


Fig. 5. Evolution of normalized performance indicators. (a) All indicators; and (b) only service indicators.

improvement of the WDS, but further rehabilitation is still missing. In fact, the vulnerable zones identified since the beginning, which are the darker nodes in Year 0, could not be served entirely in any year. New pumping stations are necessary to supply water in these zones without affecting the rest of the network.

Even though the system does not get to supply all the customers, the network's general performance measured through all the indicators showed a significant improvement. Indeed, results from the optimization sequence revealed satisfactory outcomes when performing each optimization procedure with different indicators. In this way, Fig. 5 shows how it has been possible to obtain an optimal combination of the nine BIWS service indicators.

Fig. 5(a) presents the performance of the nine indicators over the five-year rehabilitation period. All indicators have been adjusted so that their optimal is one, representing the best performance. Hence, the graph shows a gradual improvement for indicators 1, 2, 3, 4, 6, and 9. These are related to the proportion of effective hours when a customer is served, the percentage of customers with continuous service, the leaked water volume, the proportion of water supplied to users, the percentage of users supplied continuously, and the level of equity in supply. In contrast, the two indicators related to negative pressures in the system have an unstable behavior and presented a worsening in Year 4: the level of pressures at consumption nodes ( $i_5$ ) and the pipe length with negative pressures ( $i_7$ ). Note that  $i_5$  is 0 for all years except in Years 3 and 5, and  $i_7$  has been normalized relative to the total network length. This deterioration is related to the already mentioned instabilities in the model. Additionally, the indicator for the energy consumption of pumps ( $i_8$ ), which has been normalized using the min-max method, has worsened over time since more pumping power has been used to distribute more water in the system. When this operational indicator ( $i_8$ ) is excluded, Fig. 5(b) shows that there is a clear improving trend in the overall performance of the network. Therefore, service has improved at the expense of increasing pumping costs.

### Validation of Results and Comments on the Hydraulic Modeling

The BIWS organizing committee evaluated the service indicators modeling all the optimal solutions using a list of interventions that did not correspond to the files produced by the optimization

algorithm. They created network files based on a yearly list of interventions and then validated the magnitudes of the service indicators. However, when the BIWS organizing committee calculated the service indicators, they differed from the values reported in this study. The reasons for this situation rely on the hydraulic modeling of the presented solutions and the calculation methodology of the BIWS.

In the first place, the BIWS organizing committee calculated the service indicators globally. Their methodology considered that all the optimal outcomes from Years 0 to 5 were equally relevant as solutions to the intermittency of the water network under study. However, this research considered that the studied water network achieved further optimality in a year if the sum of its service indicators in that year was higher than that of its previous years' service indicators. This approach made it possible to employ the service indicators directly as objective functions of the NSGA-II optimization methodology used each year to determine the investments contemplated by the BIWS. Therefore, through this year-by-year methodology, the final optimal water network corresponds to the outcome of the optimization algorithm of Year 5.

Applying the global approach of the BIWS for calculating the service indicators of the water network outcomes through Years 0 to 5 would have been computationally expensive. Through the BIWS approach, it would have been necessary to choose a less direct, more time-consuming optimization strategy that simultaneously investigated six water network arrangements that maximized or minimized a global service indicator of interest for each intervention in a year. Furthermore, a yearly adaptation of the service indicators allowed the inclusion of computational cost reduction strategies in the optimization algorithm, such as *SP* for prioritizing pipe replacements and *LK* for repairing leakages. Finally, a yearly approach facilitated the application of engineering judgment in a way that it was possible to consider the effects that all the possible interventions had in a single water network as informers of the best intervention algorithm for a particular year of analysis.

In the second place, the service indicators reported by the BIWS diverged because the modeling of the leakages of the solutions presented in this study was addressed differently. Water entering the network at the nodes is a physically impossible situation. However, water entered the network when the emitters were placed in nodes directly at the leakage locations. Therefore, leakages were modeled

as emitters in the network, with a frictionless dummy pipe connecting a node at a leakage location to its emitter node. Also, simple controls were implemented to close a dummy pipe when water was entering the network. In contrast, the BIWS did not use simple controls but placed check valves that closed when water entered the network through any dummy pipe.

The two leakage modeling approaches were investigated. Adding the dummy pipes at the location of the leakages and initializing the emitter coefficients in the initial assessment water network (Year 0) produced 523 nodes with negative mean demands. On the other hand, 148 emitters had negative mean demands with the addition of check valves, and none of the emitters had negative mean demands using simple controls. Hence, leakages were modeled using dummy pipes with simple controls, as this arrangement prevented water from entering the water network. Nevertheless, the disadvantage of the employment of simple controls relies on the instability of the hydraulic executions of the final solutions, as was discussed previously.

In third place, the modeling of tanks followed the recommendations of the BIWS. However, this approach produced instabilities in the water tank levels, which were corrected by changing the number of trials of the hydraulic executions. Changing the number of trials also helped to address the instabilities in the pumps and valves of the water network. Also, increasing the number of trials allowed the hydraulic calculations to converge to a single solution. To further guarantee convergence of the hydraulic calculations, the accuracy of the water networks of this study was also modified, as it was changed 0.0001 to 0.001 m.

In conclusion, all service indicators were calculated using the final solution of each year and the global expressions proposed by the BIWS, but they reached different magnitudes from those reported by the organizing committee. Nevertheless, even if the approach was different, the methodology proposed in this study allows obtaining an optimal, computationally adequate outcome in Year 5 that solves a real-life scenario of intermittency, as all the constraints were met, the sum of the normalized service indicators reached a high magnitude, and the behavior of the hydraulic modeling represents the actual physical environment.

As existing distribution networks may encounter issues due to unplanned DMA densification or expansion, this phased methodology aligns well with the practical realities of water utilities by recognizing the need for gradual improvement rather than pursuing a perfect performance in the long term. In fact, when the minimum pressures are not met, the conventional response of utilities is to “reinforce” the network by changing some pipes, usually those close to the pressure regulating valves at the inlet. This early solution generates a poorly resilient network with elevated pressures, leading to increased undetected leaks and requiring many man-hours per subscriber for its operation and maintenance. Contrary to this reactive approach, leveraging the *SP* concept, hydraulic modeling, and optimization algorithms to prioritize deficient pipes offers a proactive solution to stabilize the pressures in the network, enhancing its resilience and facilitating its operation.

## Conclusions

The implemented methodology revealed satisfactory outcomes for the rehabilitation strategy of an intermittent system. However, it is not possible to apply a completely automatic optimization process. Engineering judgment is required for decision-making between each step and adequately distributing the annual resources. Additionally, NSGA-II proved not to be entirely efficient for deciding interventions related to tank expansion and pump replacement.

The optimal solutions suggested by the algorithm did not meet the overall network requirements. However, it must be considered that the chosen objective functions were related to costs and efficiency; thus, better solutions might make use of unexpected interventions to achieve similar results in the network, such as reducing the capacity of a pump.

In contrast, the NSGA-II results for replacing pipes, deciding the optimal operation of frequency inverters in pumps, and the setting of valves showed outstanding outcomes. The results suggested prioritizing the replacement of pipes using the specific power as a fundamental hydraulic criterion to decide which pipes to substitute. For this reason, the annual budget has been preferably destined to replace pipes rather than any other investment. Further, even though installing frequency inverters has an associated cost, these represent minimal resources, and their operation considerably enhances the system’s performance. In this way, enough head and flow are supplied according to the hydraulic requirements in the network at each time. Likewise, deciding the optimal setting of valves over time, bearing in mind the simultaneous use of objective functions for pressure levels and water losses, allows for an adequate counterbalance between the delivered water to users and the leaked volume.

## Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. Items available: the code of the optimization algorithm of the first year (Year 1).

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