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An optimization model for the energy management of the network of tanks in a water distribution system

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Abstract : "L'eau c'est la vie" is a well known french expression for "Water is life", which reflects the fact that water is undoubtedly the most vital resource in the world. The main mission for water utility companies is to convey and distribute water that is of acceptable quality to satisfy the demand of the population at any time of the day. In the recent years, achieving this mission has become very challenging for these companies. Indeed, the rapid growth of the population and of the expansion of urbanization have significantly increased the demand for water on the one hand. While on the other hand, natural phenomenon such as drought as well as the impact of climate changes are making it almost impossible for water distribution companies to be able to convey the right amount of water where and when it is needed. The presence of water storage tanks in a water distribution network is aimed at alleviating this pressure by storing water and distributing it later in response of the variability of the demand across the network. The management of the tanks of the network is done based on the assignment of three level set-points which allows to meet the outflow demand of water from each tank, while maintaining the adequate flow rate of through the network. The set-points define the level at which the valves that enable inflow and outflow of water to the tank have to be switched on or off. However, operating the valves during different periods of the day in order to meet the water demand, may yield extremely high operational cost, since opening some of the of the valves will induce the running of pumps to maintain an adequate flow rate of water in the network. We present a network optimization model for managing the network of storage tanks in a water distribution system while minimizing the total cost of electricity involved. Computational experiments have been conducted to show that the proposed optimization model can be used to reduce the operational cost of managing the network of storage tanks for a water distribution system, while still being able to maintain the right amount of water in the tanks.

Keywords : Water distribution systems, mathematical modeling, linear programming, network optimization model

1 Introduction

It is no secret to anyone that water is one of the most vital resources of the 21st century. May it be used for household consumption, agriculture, power generation, transportation or recreation, its value is priceless. From the underground stone water canals in Persepolis and aqueducts in Athens to advanced water distributions systems in large modern cities, supplying clean water with an affordable cost has always been a concern foe human societies. Water distribution systems are at the heart of this concern. The purpose of a water distribution systems is to convey and distribute water that is of acceptable quality to meet user demands.

A water treatment and distribution system is a complex infrastructure designed to ensure the supply of safe and clean drinking water to communities. It involves multiple stages and components to treat raw water from natural sources and deliver it to homes, agricultural farms, businesses, and other facilities. In general, the system begins by collecting water from a reliable source such as rivers, lakes, or underground wells. Intake structures are built to capture the raw water and direct it into the treatment facility. A treatment process, which includes activities such as coagulation, sedimentation, filtration disinfection, etc, then takes place in order to ensure that the water supplied will meet the specific quality requirements of the water demand. The treated water is stored in reservoirs or in tanks to maintain a constant supply and meet demands at any time of the day. A distribution network, consisting of pipes and pumping stations, is usually in place to make sure that the water can physically go from the intake sources to the end consumers.

In October 2011, the world population hit the 7 billion mark. This has come with an exponential expansion of urbanization and development that are driving water use like never before. In fact, it is reported that water usage in the last century has risen to higher than double the rate of population growth in the last century [34, 35]. It is even projected that by 2050, at least one in four people will suffer recurring water shortages [34]. Additionally, the impact of climate changes, droughts, and the increased demand for high-priced water supply sources such as desalination make long-term sustainability concerns a hard and daily economic reality for water distribution companies.

Storage tanks have, so far, played an important role in alleviating the above mentioned pressures on water distribution systems, in the sense that they have played a major role in reducing energy cost by storing water during low electric tariff and releasing it during high electric tariff. Additionally, they have supported demand variations, allowing for smooth operation of pumps, increasing water security, and breaking pressure in the network. Storage tanks have also served as providing emergency water storage for fires and system failures. In fact, without adequate storage, pumps must be operated to coincide with the occurrence of water demands, which may not be desirable when attempting to reduce pump energy usage [33]. With the upcoming above mentioned challenges of water distribution systems, storage tanks are expected to be even more critical in the future of water distribution systems [36, 37]. In fact, the use of storage tanks can enable the use of fewer pumps for a greater proportion of the day, which is one way to reduce GHG emissions.

The existing literature on pump scheduling problem focuses on general water distribution networks in which pipes connectivity, pump types and water demand pressure play the most important role [25, 26, 28, 32]. These considerations are certainly motivated by the topology of the existing water distribution network benchmarks. However, for future water distribution networks [36, 37] in which tanks are expected to play an equally important role, a good management of storage tanks will be able to help reducing the energy usage of water distribution. Thus contribute to reducing the cost of pumping as well as the emission of GHG in water distribution systems.

In this paper, we propose an optimization model for managing the network of storage tanks in a water distribution system while minimizing the energy cost of the pumps in this network. Indeed, for a network of storage tanks in a water distribution system, water is first extracted from its various sources (e.g., rivers, lakes, dams, water treatment plants, desalination stations) to storage tanks. This water will then be moved to other tanks located across the region and will be used when required in order to satisfy the water demand across the network. It should be noted that some of the tanks are interconnected to one another so that water can be used from one tank in order to balance the volume requirement of another tank. The water stored in the tanks are then used to satisfy the water demand of the population. Pumps have to be used to extract water from the various sources to the first level storage tanks. Then, for water to move between tanks or to supply demand points, valves have to be open. Opening some valves will automatically turn on some pumps in order to maintain the correct flow rate of water, while for other valves, pumps are not needed to maintain the flow rate, since the effect of gravity as well as the amount of water in the tanks will ensure the required flow rate. The purpose of our optimization model is to ease the complexity of maintaining good quality water in the tanks interconnected to one another in order to meet the demand at any time while minimizing the overall energy cost.

The remainder of the paper is organized as follows. Section 2 presents the background of the problem by giving a high level description and motivation for this study. In Section 3, we present a thorough literature review of the existing relevant water distribution models. In section 4, we present the proposed mathematical model. Section 5 discusses the results and analyses of some computational experiments. Finally, we provide some concluding remarks in Section 6.

2 Problem description

The main mission of a water distribution system is to convey and distribute water that is of acceptable quality to meet user demands. However, with the recent increase of the population in urban areas in addition to the effect of climate change and droughts, it is becoming more and more difficult for water utility companies to be able to satisfy the water demand with the existing facilities of the water distribution systems. For this reason, the future of water distribution system has been the subject of a couple of studies which attempt to propose viable solutions [36, 37]. It appears that a better management of water storage tanks can play an important role in alleviating the pressures on water distribution systems, by storing water when appropriate and releasing it when and where it is needed the most. Managing a water storage tank amounts to controlling the inflow and outflow of water in the tank as well as its three set points, which are the minimum and maximum levels of water that should be contained in the tank, and the amount of water in the tank that should be sufficient to meet the outflow demand of the tank. It should be noted that the minimum and maximum levels of water in a tank are usually determined by hydraulic simulations which will then guaranty the required flow rate when the valves are open as well as maintaining the quality of the water stored in the tank.

For a given planning period (for example one day), discretized into time periods, the manager of the network of storage tanks has to decide at what time period to open or close the valves connected to the tanks, either for inflow or for outflow of water, in order to ensure that the water demand for the overall network is met, while maintaining the required amount of water in each tank. It should be noted that when the valves are opened, the water can flow in the network at the required flow rate either aided by pumps or by the gravity. The profile management of storage tanks has so far been centered around low cost and peak electricity cost time periods [33]. This kind of approach can work well for the case of a single tank or water distribution system wherein the storage tanks do not connect to each other. Moreover, with renewable energy sources being more and more integrated into energy supply networks, electricity providers are beginning to offer dynamic electricity pricing, which varies in real time based on the realized supply and demand. Hence, forecasting electricity prices and optimizing the profile management of storage tanks accordingly is becoming essential to capitalize on dynamic pricing and reduce operational costs [25].

In this article we consider a network of tanks in a water distribution system, for which we aim to provide a profile management of each individual tank. In this network, the water is first pumped into reservoirs or tanks from natural sources. Then, it is carried across the network from tanks to tanks until the final demand point in order to be able to meet the required demand level of water.

Therefore, we aim to propose an optimization model which will: *i)* prescribe when to extract water from its various sources; *ii)* prescribe when to open and close each valve of the storage tanks network inflow or outflow of water; *iii)* decide of the amount of water to flow from one tank to another; *iv)* decide the amount of water to withdraw from each tank at each time period to satisfy part of the water demand. The objective of this optimization model is to minimize the total cost of electricity used by the pumps while having a better control of the three set points of each tank in the network.

3 Literature review

The development of optimization models for water distribution systems is at least five decades old. While some of the models focus mainly on the design of optimal water distribution systems [29], others target the operation of the systems instead [27]. Mala-Jetmarova et al. [3] present a comprehensive review of more than 200 research articles that mainly focus on optimizing the design of water distribution system. Interested readers are referred to [3] for the optimization of the design of water distribution systems. This paper is concerned with the operational aspect of the network of tanks in the system.

The primary goal of most water distribution companies is to be able to provide water to satisfy the demand of the consumers in terms of quality and quantity and at any time. In this process, electricity consumption is one of the largest marginal costs. With price of electricity rising globally over the past few decades, it has become more critical to water distribution companies to optimize their pumping operations in order to achieve a minimal amount of energy consumed. Zessler and Shamir [5] proposed a separable quadratic continuous optimization formulation to determine the optimal discharge level of water in the reservoirs for each time period, while ensuring that there is sufficient water to meet the forecasted demand. The discharge level of water is given by the operating level of the pumps between two reservoirs. Their formulation is then solved using a dynamic programming approach. Another model that uses dynamic programming for real time operations is proposed by Nitivattananon et al. [8]. Brion and Mays [6] presented a methodology which is based on an optimal control framework in which a nonlinear optimization model interfaces with a hydraulic simulation model to implicitly solve the conservation of flow and energy equations. Pasha and Lansey [9] proposed the linearization of the relationship between the consumed energy of the pumps, the water level in the tanks and water demand, which resulted in a linear programming model. A mixed integer linear optimization model, wherein, the integer variables represent the number of time period for which the pumps can stay on, and while the start/end time of the pumps are modeled as continuous variables is proposed by Bagirov et al. [19].

The problem of determining when to turn on or off the pumps in a water distribution network is often refer to as the Pumps Scheduling Problem (PSP). Most of the existing literature on this problem have modeled the problem as mixed integer non-linear optimization problem. For example, non-linear PSP models have been proposed in the literature and solved using Lagrangian decomposition approaches [25], branch-and-bound [26], simulation based optimization approaches [28], as well as metaheuristic methods [20, 21, 22, 23]. Nevertheless, some linear programming models can also be found in the literature, see [30, 31]. These linear models are obtained though by linearizing the non-linear energy cost functions as well as the non-linear hydraulic properties of the water distribution network.

Most of these models are designed for water distribution systems, which only include reservoirs that receive water from the sources and from where water will go directly to the various demand points of the network via the pipes. Nowadays, due to the growth of the population in the major cities around the world, most water distribution systems are having to include more tanks as intermediary sources of water, which allow to meet the increasing demand. These tanks are interconnected to form a network so that water can easily be conveyed to every demand point upon request without having to be necessarily drawn from the natural sources. The flow of water to and from the tanks is either commanded by low power pumps (using switches) or by gravity (using valves). For all the existing optimization that we could find in the literature, less attention have been placed on the role of storage tanks in water distribution systems. The main contribution of this paper is therefore to propose an optimization model which is able to support the management of the network of storage tanks in a water distribution system. The paper also offers some insights in analyzing the movement of water from tanks to tanks in a water distribution. It should ne noted that the model is adapted to the current and future reality of water distribution systems.

4 Problem formulation

In this section, we present the proposed mathematical formulation of the problem described in Section 2. The model takes the form of a mixed integer network flow problem. In this model, we use binary decision variables to represent the ON/OFF status of the pumps (used to draw water from their natural sources), and implicitly, the open and close status of the valves. The continuous variables are the control variables for the amount of water in each tank as well as the amount of water taken from each tank to satisfy part of the water demand at each demand node. It should be noted that for the proposed model relies on a couple of hypothesis. First, it is assumed that the distribution network water can only flow in one direction. Secondly, we assume that the pumps in the network can only be ON at their optimal power level or OFF. It is also assumed that the speed of distribution of the water is instantaneous. We therefore start by defining the parameters and the decision variables used in the model.

The parameters of the model:

$\mathcal{I}$ is the set of all the pumps in the water system network that are connected to the various sources. This set does not include the pumps that enable the flow of water between two tanks.

$\mathcal{J}$ is the set of all the tanks in the water system network.

$\mathcal{K}$ is the set of all the water demand points of the network.

T is the total number of time periods in the discretization of the planing horizon.

$\mathcal{J}_j^-$ and $\mathcal{J}_j^+$ are the set of tanks that can respectively supply water to and receive water form tank $j \in \mathcal{J}$.

J^k is the set of tanks that can supply water to the demand point $k \in \mathcal{K}$.

L_j, U_j are, respectively, the lowest and highest level of water to be kept in tank $j \in \mathcal{J}$

C_t^i is the cost of electricity for running the pump $i \in \mathcal{I}$ during period $t \in \{1, \ldots, T\}$.

$C_t^{jj'}$ is the cost of electricity induced by opening the valve between tanks $j \in \mathcal{J}$ and $j' \in \mathcal{J}_j^+$ is opened during time period $t \in \{1, \ldots, T\}$. Note that this cots is 0 if the flow of water between the two tanks is induced by the gravity.

P^{ij} is the mount of water pumped in tank j from pump i during one period of time

$S^{jj'}$ is the amount of water pumped from tank j to tank j' during one period of time

The decision variables of the model:

$$y_t^i = \begin{cases} 1 & \text{if the pump } i \in \mathcal{I} \text{ is turned on during time period } t \in \{1, \ldots, T\} \\ 0 & \text{otherwise} \end{cases}$$

$$x_t^{jj'} = \begin{cases} 1 & \text{if the valve between tanks } j \in \mathcal{J} \text{ and } j' \in \mathcal{J}_j^+ \text{ is opened during time period } t \in \{1, \ldots, T\} \\ 0 & \text{otherwise} \end{cases}$$

$Q_j(t)$ is the amount of water in the tank $j \in \mathcal{J}$ at the end of time period $t \in \{1, \ldots, T\}$

D_t^{jk} is the amount of water from tank $j \in \mathcal{J}$ needed at the demand point $k \in \mathcal{K}$ during the time period $t \in \{1, \ldots, T\}$

The model:

$$\min \sum_{i\in\mathcal{I}}\sum_{t=1}^{T} C_t^i y_t^i + \sum_{j\in\mathcal{J}}\sum_{j'\in\mathcal{J}_+^j}\sum_{t=1}^{T} C_t^{jj'} x_t^{jj'} \tag{1}$$

$$\text{s.t. } L_j \leqslant Q_j(t) \leqslant U_j, \quad \forall j\in\mathcal{J}, t=1\ldots,T, \tag{2}$$

$$Q_j(t) = Q_j(t-1) + P^{i_j j} y_t^{i_j} + \sum_{j'\in\mathcal{J}_j^-} S^{jj'} x_t^{jj'} - \sum_{j'\in\mathcal{J}_j^+} S^{jj'} x_t^{jj'} - D_t^{jk}, \quad \forall j\in\mathcal{J}, t=1\ldots,T, \tag{3}$$

$$D_t^k = \sum_{j\in J^k} D_t^{jk}, \quad \forall t=1,\ldots,T, k\in K, \tag{4}$$

$$x_t^{jj'}, y_t^i \in \{0,1\}, \text{ and } Q_j(t), D_t^{jk} \geq 0, \quad \forall i\in\mathcal{I}, j\in\mathcal{J}, \tag{5}$$

$$j'\in\mathcal{J}_j^+, t=1\ldots,T. \tag{6}$$

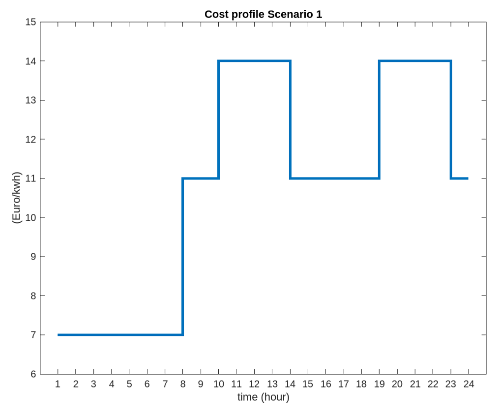
It should be noted that in Equation (3), $y_t^{i_j}$ represents the ON/OFF status of the specific pump that enables the flow of water directly from the source to tank j. In this model, the objective function (1) represents the cost of electricity for moving the water from the natural sources to the demand points via the various tanks. The first component is the explicit cost of pumping water from the source, while the second term represents the implicit cost of moving water from tanks to tanks. In fact, when the valve between two tanks is open, it may induce a pump to go on in order to maintain the appropriate flow rate of water. Whereas if the valve that is open for the outflow of water is driven by the gravity, then this cost is negligible. The constraints (2) ensure that the amount of water in each tank never goes beyond the maximum and the minimum required levels. The constraints (3) are the flow conservation constraints for each tank, which require that the amount of water in the tank at a given time period is calculated as the amount of water in the tank in at the end of the previous period, plus the inflows of water, which may come from the natural sources or from other tanks, minus the total outflow of water, which is the amount of water going to other tanks or serving part of the demand. The constraints (4) then ensure that the total demand of water at each demand point is always met by collecting portions of this demand from different tanks. Finally, the nature of the decision variables are specified in constraints (5).

5 Computational experiments

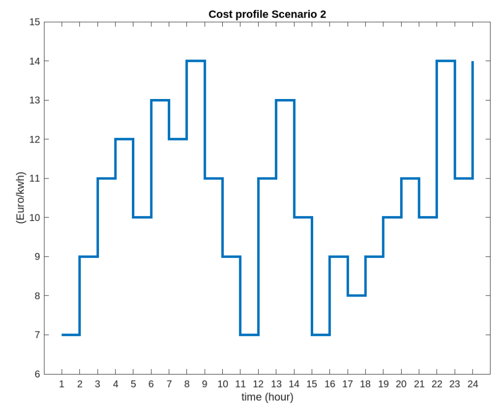
In this section, we present and discuss the results of the computational experiments carried out to show the usefulness of our proposed network optimization model. All the computations were run on an Intel Core i5 Desktop with processor at 2.50 GHz and 8 GB of memory. The codes were written in Python and the optimization model was solved using the GUROBI MIP solver, version 10.0.2 ([38]). We have conducted three sets of experiments for which some part of the data had been obtained from the Granollers water distribution system in the North East of Barcelona in Spain. In the first set of experiments, we consider the case of a single tank and a single demand point and we compare our results with the managerial decision observed. In the second set of experiments, we consider a network of the four tanks and two demand points in order to show the effectiveness of our model in helping in the decision making process. The third set of experiment considers the full network of the Granollers water distribution system with 12 tanks, 5 water sources and 8 demand points.

5.1 A single tank case study

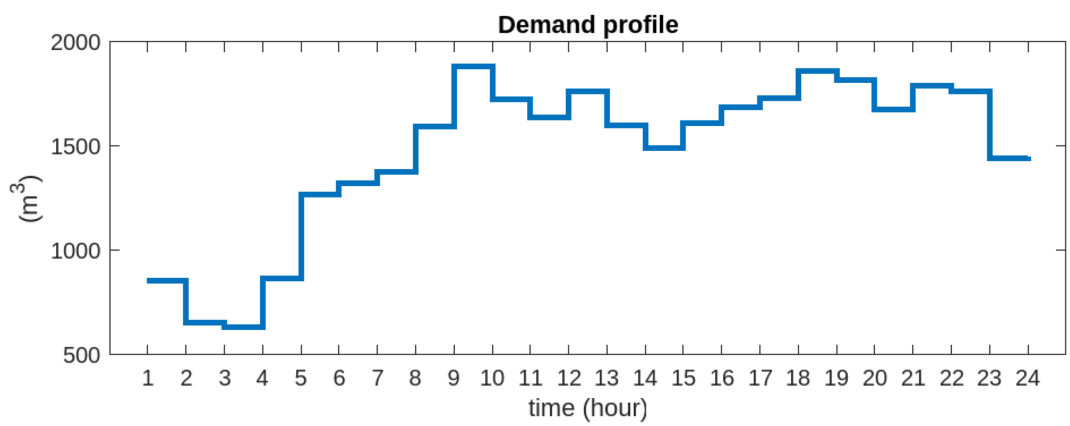
In this experiment, we consider a network consisting of a single tank and a single demand point. We experimented two scenario obtained by varying the electricity cost profile of the pump. In the first scenario, the electricity cost profile is a real data set obtained from a water distribution research group based at the University of Girona in Spain. This cost profile, shown in Figure 1a, varies with three different prices (low, medium and high) depending on the time of the day. In the second scenario we have generated the cost profile of electricity randomly, as shown in Figure 1b, to reflect the fact that the effect of the 'demand-respond' in electricity market can sometimes have abnormal impact on the price of electricity. We have used the same demand profile for one day in both scenarios, as shown in Figure 1c. It can be seen in the latter figure that the demand starts at a low level at the beginning of the day, then rises up to a steady level for the rest of the day. This demand data were also provided to us by the water distribution research group based at the University of Girona.



(a) Cost profile in Scenario 1



(b) Cost profile in Scenario 2

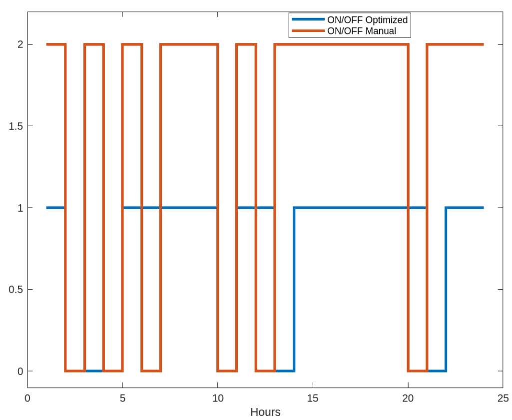


(c) Water demand (m^3) for one day

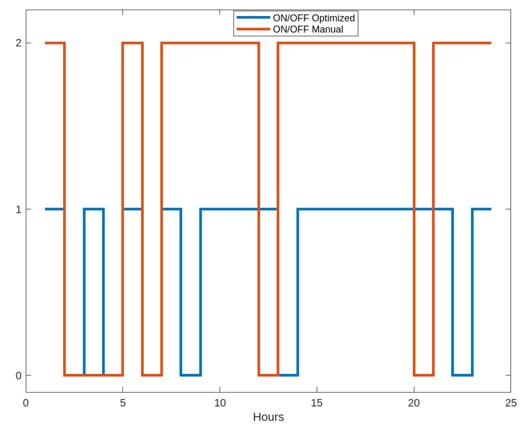
Figure 1: Cost profile scenario and water demand profile for one day

For this test example, since the data are realistic, we could obtained an insight of the real managerial planning i.e., the time period at which the pump was open or close as well as the level of water the tank for each time period. It is understood that this managerial planning is based filling the tank as much as possible during the low and medium electricity cost periods of the day, and only open the pump during the high period if there is not enough water to meet the demand. We have therefore replicated this approach even for the second scenario in order to mimic the managerial planning results, which is done manually.

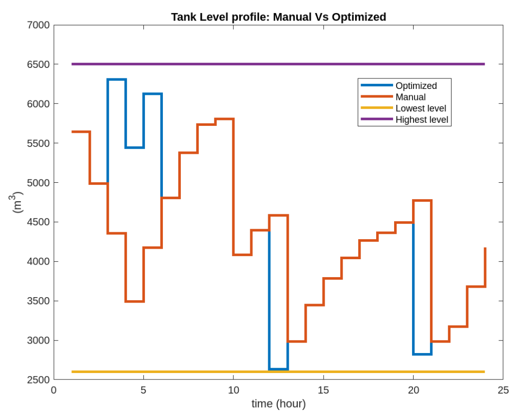
The output of this first experiment is shown in Figure 2 for both scenarios. In these graphs, we plot the ON-OFF status of the pump as well as the level water in the tank throughout the day for both the results obtained by our optimization model and the manual (managerial) planning process. It should be noted that in Figure 2a and in Figure 2a we have scaled the values plotted in order to render the ON-OFF profile of each solution visible. Therefore, a value of 2 or 1 on the y-axis respectively simply means that the corresponding pump is turned ON in the corresponding solution for that specific time period.



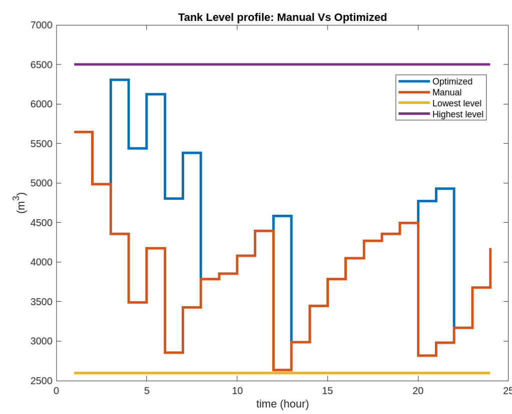
(a) Pump's ON/OFF status in Scenario 1



(b) Pump's ON/OFF status in Scenario 2



(c) Tank level profile in Scenario 1



(d) Tank level profile in Scenario 2

Figure 2: Tank level profile and the ON/OFF profile of the pump in the two scenarios

In Figure 2a, it appears that the ON/OFF statuses of both the manual solution and the optimized solution are almost completely synchronized, with only four differences. The associated cost of electricity during the time periods of difference do coincides and thus leads into the same objective function values. Which could thus be seen as a case of two alternative optimal solutions. However, when it comes to the second scenario, Figure 2b shows that there are six differences in the ON/OFF statuses of the two solutions. The evaluation of the objective function values shows that the manual planning solution is improved by nearly 5% by the solution from the optimization model. The latter observation suggests that the proposed optimization model can already bring some improvement to the industrial practice even for the most simplistic case of a water distribution system with only one tank. This improvement can only be expected to be more interesting in the case of a network, wherein the manual planning becomes even more complex due to connectivity between the tanks in the network and the need of keeping the right amount of water in each tank.

5.2 A multiple tanks case study

In this second case study, we consider a network of four tanks and two demand points. The configuration of the network is shown in Figure 3. It should be noted that the configuration of this network has been extracted from the full network of the Granollers water distribution system, which is part of the Barcelona water distribution system in Spain, the full conceptual version of the network can be found in [39]. In this network, the tanks are labeled j_5, j_6, j_7 and j_8. The water sources are labeled i_1 and i_2 (the pumps used for drawing water from these sources will use the same labels) that are respectively connected to tanks j_5 and j_6 and require pumps for water flow. The two demand points are k_3 and k_4. The connectivity between the tanks as well as between the tanks and the demand point are shown in the Figure 3. The flow of water from tank j_5 to the tanks j_7 and j_8 is gravity driven and does not require electricity. Whereas the flow of water from tank j_6 to the tanks j_5 and j_7 is induced by pumps and therefore uses electricity.

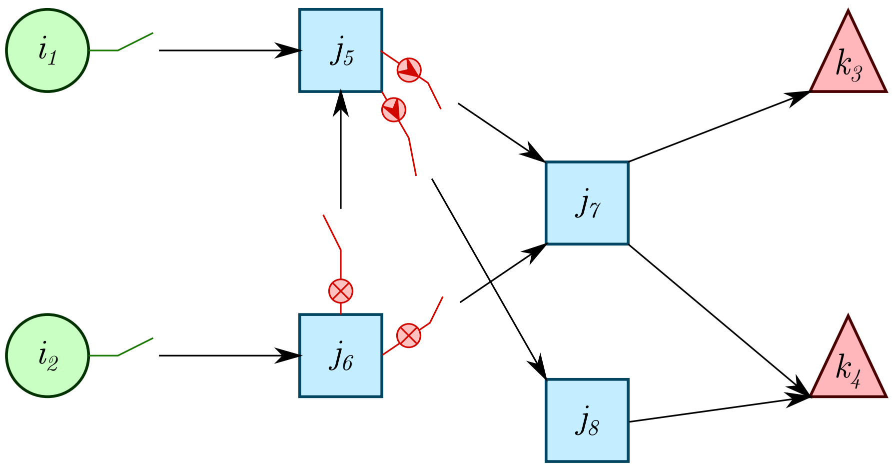


Figure 3: A multiple tank network example

For this example, we used the characteristics of the tanks obtained from the Granollers water distribution system. We generated the cost of electricity randomly. The idea is to avoid the usual profiles of peak and off-peak electricity price period and to consider any random cost structure. The water demand profiles for each demand point, shown in Figure 4 for this example are also taken from the data obtained from the Granollers water distribution system.

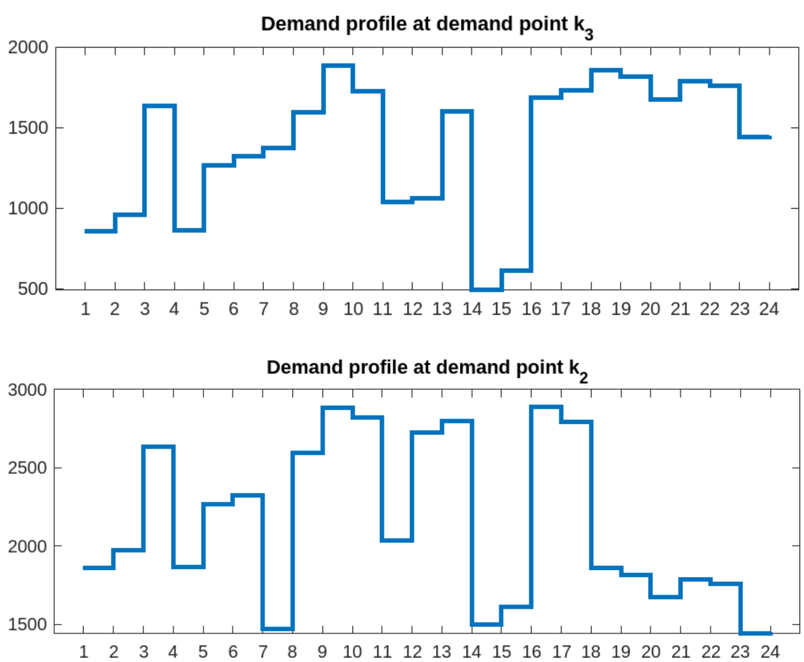


Figure 4: The water demand profiles for the demand points k_3 and k_4

In terms of the results for this example, we will first show the pumps' (i_1 and i_2) scheduling profiles for drawing water from the natural sources to tanks j_5 and j_6. These scheduling profiles are shown in

Figure 5. Secondly, we will show the ON/OFF profiles of the valves between the tanks. These results are presented in Figure 6. Finally, we show the amount of water in each tank during each time period of the day. These tank levels are shown in Figure 7.

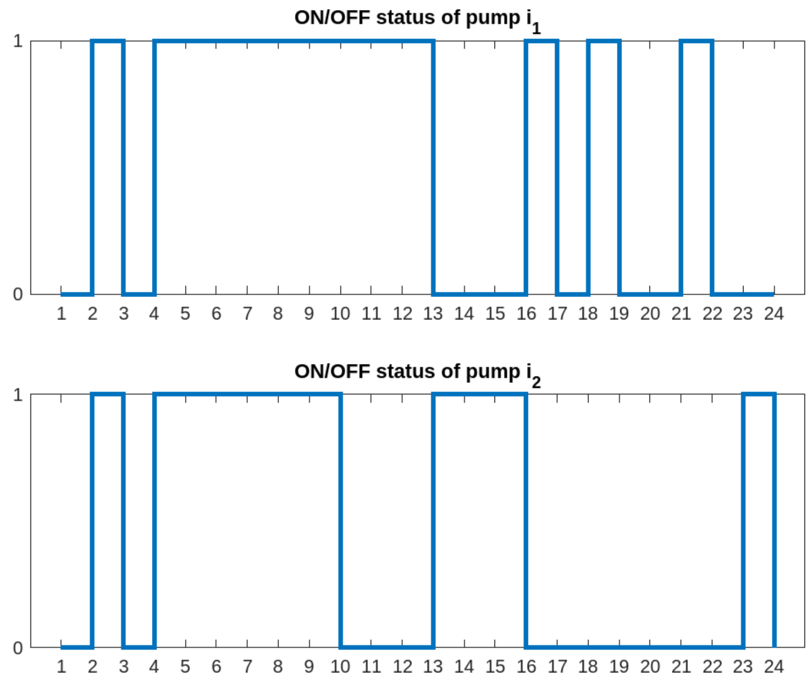


Figure 5: The pumps scheduling profiles at sources i_1 and i_2

The pump scheduling profiles in Figure 5 show that the Tank j_5 receive water from the natural source (through pump i_1) mainly from the early hours of the day until early in the afternoon, then the pumps are open again during three time periods in the evening. While for the Tank j_6, the connected pump i_2 is turned ON in the early hours of the day, then in the afternoon and for the last time period of the day. This shows that the tanks j_5 and j_6 are very busy accumulating water in the early hours of the day, and much less in the evening, despite the high demand for water at the demand point k_3 during the later hours of the day.

In Figure 6, there are two main intriguing facts. Firstly, the valve between Tank j_6 and Tank j_5 is only open once during the day. Secondly, the valve between Tank j_6 and Tank j_7 is almost always kept opened. In fact, the flow of water from Tank j_6 is gravity driven and does not require electricity. So, it makes more sense to convey water from Tank j_6 more often to Tank j_7 in order to satisfy the demand at both points k_3 and k_4. On the other hand, opening the valve between Tank j_6 and Tank j_5 will mean that this water needs to transit through pump-induced valves in order to get either demand points, which in most cases will be a needless use of energy.

In Figure 7, one can notice that between the two tanks that are connected to the natural sources, Tank j_6 often accumulates more water than Tank j_5. In fact, the slow increase in the tank level profile of Tank j_5 between 8.00 am and 6.00 pm means that this tank receives water and discharges it almost suddenly. Whereas for Tank j_6, it can be seen that there is always some fair amount of water accumulated throughout the day. The accumulation really starts in the early evening. It can also be noted that the variation of the amount of water in Tank j_8 also stops at around 6.00 pm as for Tank j_5. This means that for the remaining hours of the day, the demand of water at node k_4 is mainly satisfy by water coming from Tank j_7. Indeed, with a low demand at the latter node after 6.00 pm, it makes sense to ship water for free from Tank j_6 (which has accumulated enough water) to Tank j_7 in order to satisfy the demand at both nodes k_3 and k_4.

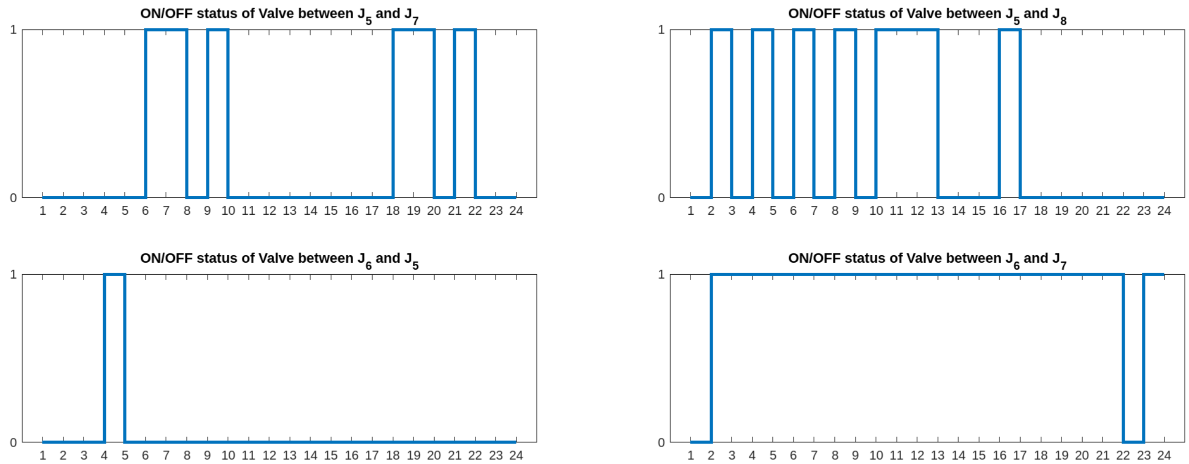


Figure 6: The scheduling profile of the valves between the tanks

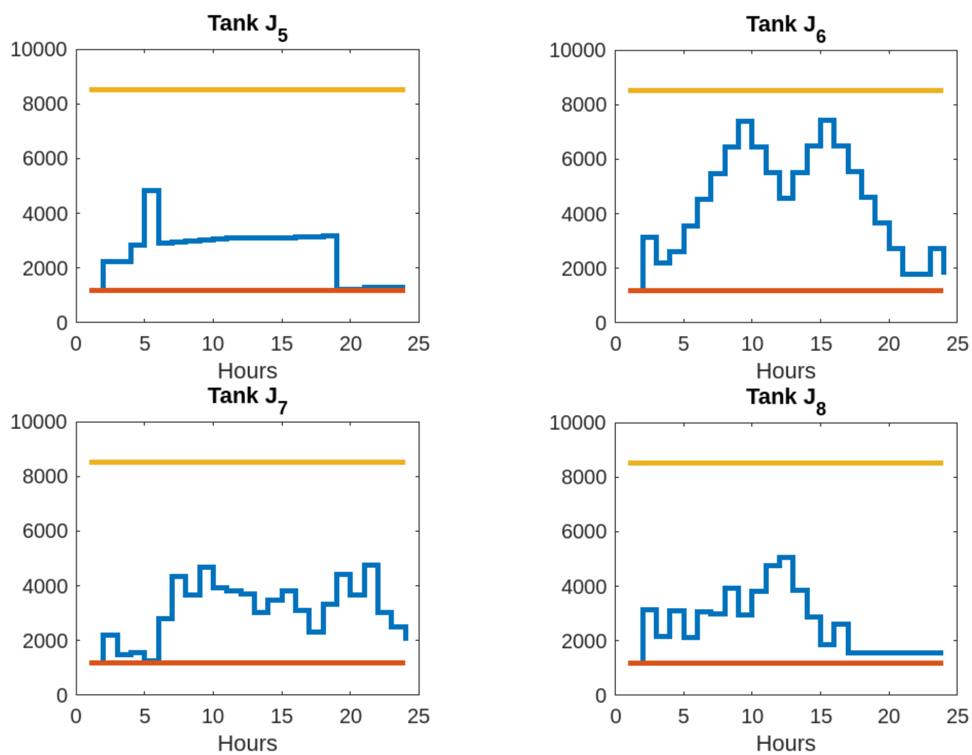


Figure 7: The amount of water in the tanks: the horizontal lines are the lower and upper levels of the tanks

5.3 A large network example

We carried out a third set of experiments on a large network in order to assess the scalability of our optimization model. For this purpose, we have used an adaptation of the full network of the Granollers water distribution system. This network of tanks is shown in Figure 8. The network consists of 12 water storage tanks represented by the rectangles, 5 water sources (rivers, lakes, reservoirs) represented by the circles, with each having a connected pump to draw water, and 8 demand points represented by the triangles. The data about the demand profiles, the cost of electricity usage by each pump as well as the other parameters of the problem have been generated randomly. In this network, the water flow between the tanks as well as between the tanks and the various demand points of the upper level of the graph is commanded by pumps which yield direct cost of electricity. While, in the lower level of the graph, everything is gravity driven, thus no electricity cost involved.

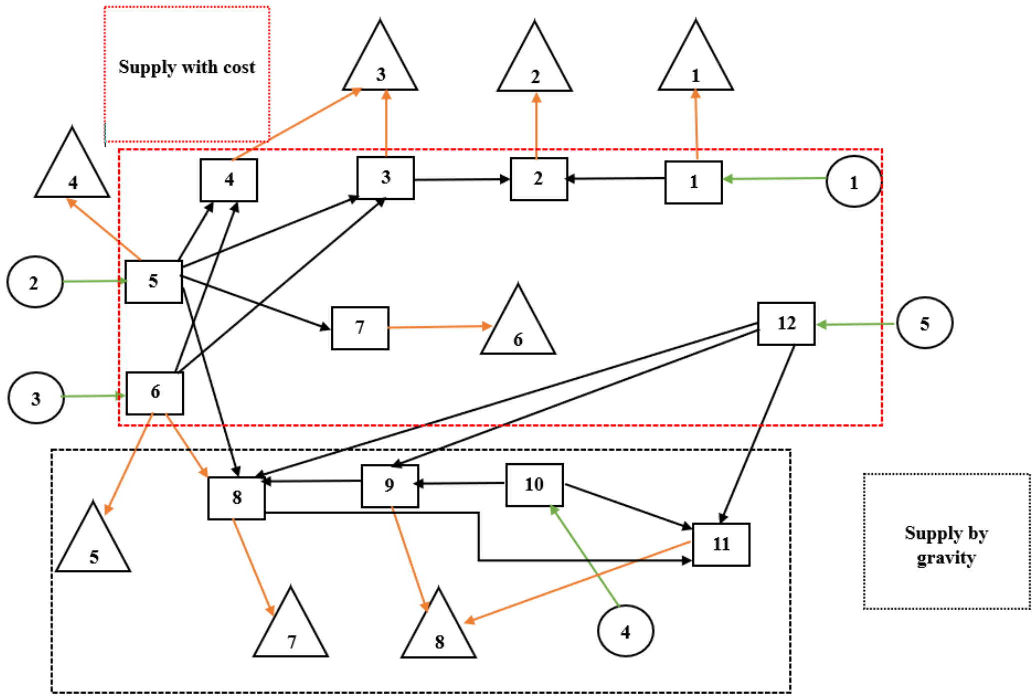
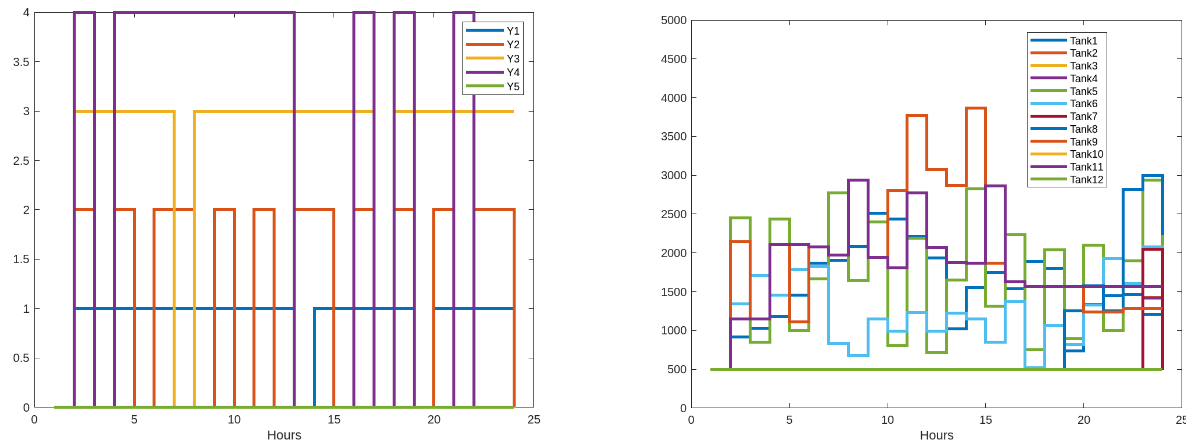


Figure 8: An adaptation of the Granollers tanks network [39]. The rectangles are the tanks, the triangles are the water demand points, the circles are the water sources

Some of the results of this third set of experiments are presented in figure 9. In this figure, we show the ON/OFF profile of the pumps that are directly connected to the water sources in Figure 9a and the water level profile of the tanks in Figure 9b. Figure 9a displays the time periods of the day for which each pump is switched ON or OFF in order to satisfy the various demands at minimum cost. In this Figure, $Y1$, $Y2$, $Y3$, $Y4$ and $Y5$ correspond respectively to the statuses of Pump 1, Pump 2, Pump 3, Pump 4 and Pump 5. It should be noted that in this Figure 9a we have scaled the values plotted in order to render the ON-OFF profile of each pump visible. Therefore, a value of 4, 3 or 2 on the y-axis of Pump 2, Pump 3 and Pump 4, respectively simply means that the corresponding pump is ON. It can be seen in this graph that Pump 5 is kept OFF for the full day, while the other four pumps have are turned ON and OFF at different periods during the day. In fact, Pump 5 is directly connected to Tank 12, which supplies water to Tank 8, Tank 9 and Tank 11, who in turn are in charge of supplying water to the demand points 7 and 8. These demands have probably been satisfied by water pumped in the same tanks by the effect of gravity (Pump 4) in the lower part of the network.

Elsewhere, Figure 9b provides the water level profile of all the 12 tanks present in the network. It can also be noticed that Tank 12 has no inward or outward water flow at all during the day, which reflects the fact that Pump 5 is kept OFF the entire day. Although, the graph shows the profile of all the pumps at the same time, which may make it slightly difficult to read or to read, it is still possible to make individual profile for each tank or for each pumps to better inform decision making. The outcome of this computational experiments shows that our optimization model could well be used to analyzed large water distribution network of tanks in order to improve decision making for this industry.



(a) On/Off status of the pumps at water sources **(b) Tanks water level profiles**

Figure 9: Some results for the large network example

6 Conclusion

In this paper, we have studied the problem of managing the network of storage tanks in a water distribution system with the aim of minimizing the energy cost of the pumps in this process. Indeed, with the growth of the world population combined with the impact of climate changes as well as droughts, it is becoming more challenging for water distribution companies to achieve their primary goal, which is to convey water that is of acceptable quality to meet users demands. Storage tanks are expected to play a more important role in alleviating these pressures on water distribution companies, in the sense that they can be used to store water, which is later used to respond to the demand of the users at any time. We have proposed an optimization model for managing the network of storage tanks in a water distribution system while minimizing the energy cost of the pumps in this network. The model is a mixed integer network optimization model wherein the binary variables represent the ON/OFF statuses of the pumps and the valves, while the continuous variables are the variable allowing to control the amount of water in tanks throughout the planning horizon, as well as controlling the amount of water to collect from each tank in order to meet the full demand of the network.

A first set of computational experiment with real data collected from the Granollers water distribution system the North East of Spain for simple network with one tank and simple cost profile shows that the proposed optimization model is able to match the managerial decision making. Whereas, for a slightly complex cost structure, the manual managerial planning can be improved by nearly 5% using our proposed optimization model. Furthermore, the optimization model is able to adapt for contexts in which the cost structure is more complex and for more general network as shown in our second and third sets of experimentation. Indeed, the computational results show that our proposed model can serve as a based optimization model to use in running the simulations for determining the adequate set points of the tanks in a water distribution network in the quest of rendering these systems more autonomous as foreseen for the future water distribution systems.

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