- ALGORITHMS AND TOOLS FOR OPTIMUM SCHEDULING OF ON-DEMAND IRRIGATION FOR EFFECTIVE ENERGY COST REDUCTION

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ABSTRACT

To reduce the unfavourable impact of energy cost in irrigation there are numerous strategies, ranging from the use of water application systems with lower pressure requirements (e.g. drip irrigation, low pressure sprinklers, etc.) to the optimized design and management of collective distribution networks and their pumping stations, which can include renewable energy sources. Of these, we found optimising the scheduling of irrigation demands according to energy cost (combined with pumping station pressure modulation when different energy requirements at hydrants are present) the most effective measure in collective distribution networks, because of its high benefit/cost ratio. These strategies can only be implemented effectively with the help of ICT, especially software which is highly sophisticated but easy for network designers and managers to use, such as the programme presented in this contribution

Keywords: pressurised irrigation, software, energy cost, savings …

1. Introduction.

The large amounts of water used in agricultural irrigation, in comparison with urban or industrial demands, also mean significant energy consumption. Pressurized networks can save water and help preserve water quality in distribution systems. However, these require pumping facilities which can have a significant impact on energy consumption. This problem affects not only water-scarce and arid countries, but also those where intensive agriculture is already practised, and where water productivity has to be increased and/or diffuse pollution impacts must be reduced. For example, in the case of Spain, with 35% of the irrigated area of the EU-27, irrigation agriculture uses 2.37% (6,873 GWh) of the country's total electricity consumption (Corominas, 2013), (Berbel et al., 2014).

In order to reduce energy consume and cost in irrigation collective distribution networks the water requirements of crops, which are determined by farmers or integrated in automated forecasting systems, can be optimally scheduled to fulfil water demands in a timely manner, considering the physical and hydraulic restrictions of the network and maximising the irrigated plots, taking advantage of the times when energy prices are lower (or even non-existent in the case of gravity fed systems or renewable energy sources).

The latest versions of the software package GESTAR 2014 (www.gestarcad.com) include innovative solutions, the result of long-term research, which provide the tools needed to meet these requirements for energy efficiency and saving energy costs. These resources enhance this engineering platform, which has been under continuous development in the Fluid Mechanics Department of Zaragoza University since 1995, and was specifically created for designing pressurised irrigation systems and managing their water and energy use, both in collective distribution networks and in drip or sprinkler networks for individual plots. Figure 1 shows the programme home screen with a collective distribution network.

Unlike other existing tools which focus on modelling water drinking distribution systems, such as EPANET and its commercial extensions, GESTAR 2014 especially considers energy, with advanced functions which are the result of scientific contributions followed by technology transfer. As well as optimal sizing of networks with Direct Pumping Stations (DPS), functioning on demand (Aliod et al., 2007) or by rotational turns (García et al., 2011), we find the modelling resources described in section 2, and other resources for the integrated optimisation of DPS and the distribution network, such as optimising regulation for a given composition to achieve a given operating point with the best possible performance, or determining the pressure conditions needed in pumping stations to reach the required pressures at every point in the network (Paño et al., 2012).

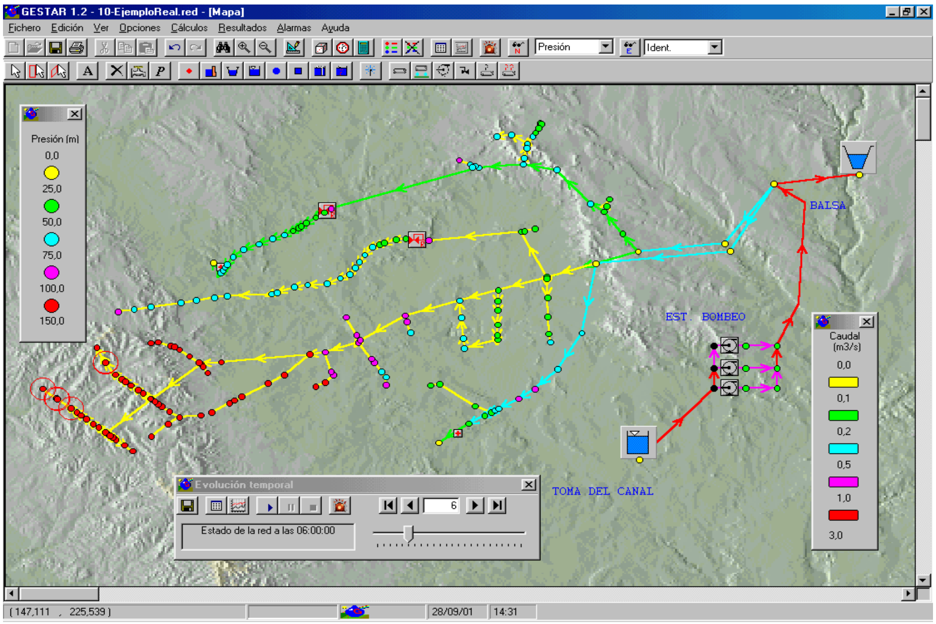

Figure 1. GESTAR software package home screen

In this contribution we also present a new optimisation function, PRORIEGO-TeleGESTAR, recently extended (Fací 2014), which uses evolutionary algorithms to manage the irrigation requests of the hydrants in a pressurised irrigation network over a certain period (a day, a week, a month, etc.), taking into account the different energy prices and contracted power, reorganising them so that the irrigation schedule minimises the energy cost of the electricity powering the pumping stations, while satisfying demand with sufficient pressure and catering to other restrictions (e.g., periods when irrigation is enabled) or preferences (e.g., a preference for less sunny or windy periods).

The solutions found in the case of DPS will tend to concentrate irrigation sessions to the cheaper time bands, running the pump station at full capacity at those times, and minimising irrigation in other periods (see Figure 2). As the prices of consumed and contracted power can vary a great deal from one period to another, these are treated as the main restriction, and therefore there is a very notable cost saving, as well as minimising malfunctions due to low pressure.

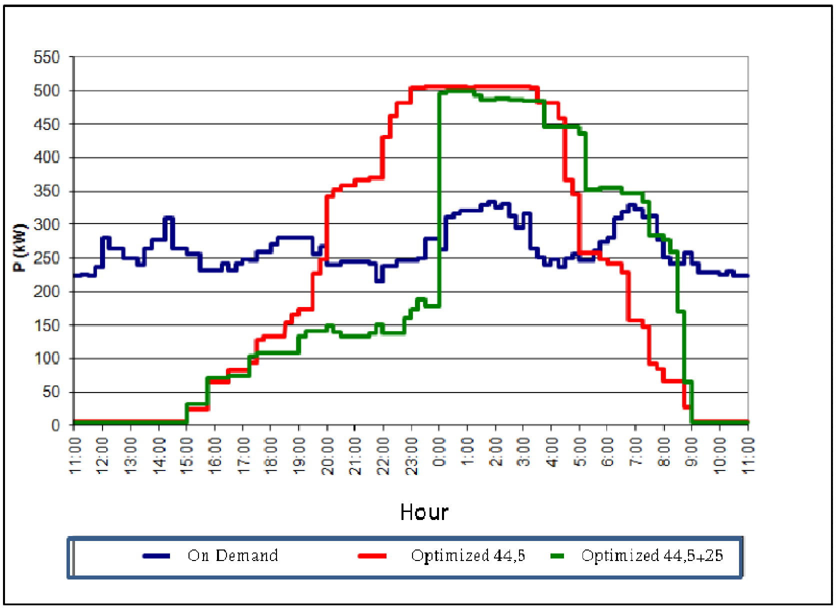

Figure 2. Example of distribution of power consumed in a direct pumping station over one day in an on-demand irrigation network (blue), optimally organised to minimise energy costs, with one pressure level (44.5 mH2O, red) and two pressure levels (44.5 and 25 mH2O, green)

2. Advanced pumping station modelling tools.

1. Modelling pumps using splines and uncoupled nodal equations.

To assess the energy aspects we first need to accurately reproduce the behaviour of pumps over the whole range of flow rates, an important aspect given that a faulty approximation of the characteristic curves of the pump head (H) vs flow rate (Q) can produce errors of 15% in calculating energy costs when there are variable speed groups. Spline fitting techniques (Paño et al., 2012): overcome the limitations of simple linear adjustments between H-Q points, or exponential or parabolic interpolations throughout the flow domain, with a better representation of the underlying curves of each pump and achieving greater numerical stability.

Thanks to this and the uncoupled treatment of the equations constituting the pumps in the Nodal Algorithms (Paño et al., 2012) used in the GESTAR Hydraulic Solver, pumps can be modelled with rising head-flow rate characteristic curves (which is not possible with the EPANET Solver), a key factor enabling the compact modelling described below.

2. Synthetic modelling of Direct Pumping Stations (DPS) and their regulation with virtual characteristic curves.

The key to the modelling strategy consists of assimilating each DPS to a “virtual pump” with assigned pressure head-flow rate and energy consumed-flow rate (“Operating Curves”) resulting from the composition and setting of the pumps installed in the DPS. These “Operating Curves” (OC) of the “virtual pump” contain the information needed for the hydraulic and energy analysis of the system.

3. Automatic configuration of joint DPS characteristic curves.

GESTAR provides tools for automatically constructing the Operating Curves (OC) of pumping stations to follow a predefined System Curve (SC), in any conditions of number, composition or size of the pumps and type of setting (considering one or more variable speed pumps) through a user-friendly interface linking to databases.

The tool for generating DPS-OC is based on establishing the operating point of each individual pump integrated in the DPS, for each pair of head-flow rate values of the System Curve, including running VSPs, for which it evaluates the RPM needed to supply the head specified by the SC. With this information it calculates the power consumed by each pump at each point of the SC, telling us the power and net performance of the DPS for each flow rate, provided as a DPS-OC.

3. Description and implementation of the hydraulic-energy optimisation algorithm of PRORIEGO-TeleGESTAR irrigation schedules

The first operating version of the PRORIEGO function dates from 2013, and was reinforced by (Fací 2014). The function uses the tools described above and reuses them to construct an optimisation process designed to reorganise irrigation requests from hydrants in a pressurised irrigation network over a given period (daily, weekly, bi-weekly, etc.) taking into account the different energy prices and contracted power, so that the reorganised irrigation schedule minimises the energy cost of the electricity powering the pumping stations, while satisfying demand with sufficient pressure and catering to other restrictions or preferences. The problem to be solved is complex due to its multiple decision variables, the objective function is not explicit and cannot be differentiated. There are different types of restriction (contracted power, irrigation periods, etc.) so the problem can be solved using evolutionary algorithms.

3.1 Basic principles

After evaluating our options, we chose the family of algorithms known as ACO (Ant Colony Optimisation) (Dorigo et al., 2010) to tackle this type of problem, as it allows for great flexibility when formulating restrictions and obtains consistent results more quickly. ACO reproduces the behaviour of ants in nature looking for food as a heuristic for resolving combinatorial optimisation problems, consisting of marking their routes with volatile pheromones which reinforce successful paths and evaporate in unfavourable ones.

In this case, each ant is an entity which chooses different times to begin irrigation for each request. The paths are graphs which the ants will follow. Each irrigation period to be scheduled is considered as a node on the graph. Each irrigation period or “node x” is the starting point for as many possible paths (edges) as there are feasible irrigation start times, towards the next “node y”, with the graph ending at the last irrigation period to be optimised. Each ant travels the graph such that at the end it will have generated an irrigation schedule, which will be evaluated according to its energy cost and penalised for failing to comply with the restrictions of the hydraulic and energy variables obtained in the hydrodynamic simulation of that schedule.

The generic algorithm schema is shown in Figure 3 (Faci 2014).

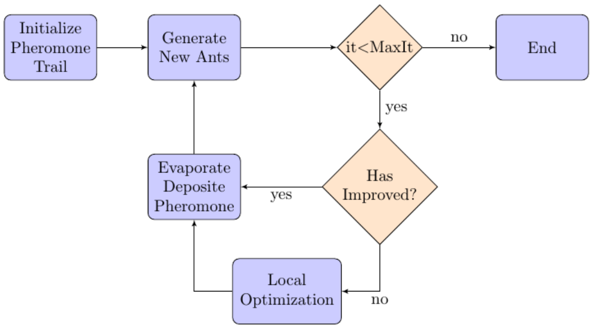

FIGURE 3. Schema of the Ant Colony Optimisation algorithm

3,2 Implementation

The algorithm and all the required auxiliary functions have been programmed in the .NET environment for the TeleGESTAR platform, the web service which allows GESTAR functions to be run remotely by client applications, communicated via the SOAP protocol and XML format for data exchange, allowing it to be integrated easily into Telecontrol and SCADA systems, adding simulation and hydraulic-energy optimisation features. At the same time, a user interface has been created for handling the function in the GESTAR 2014 environment, which can be used as an alternative to SCADA integration. The data needed for the optimisation process are:

- Database with a hydraulic model of the network and pumping stations, modelled with their set point curves and joint performance curves, depending on the composition and regulation of each station, and control set points for the network components.

- Times enabled for irrigation and excluded times (e.g., peak energy cost times), Restrictions on irrigation start times, Time enabled for irrigation but disincentivised (due to strong sun or wind).

- Prices applied to consumed and contracted power according to the time of day. In gravity-fed irrigation or with solar or wind-powered pumps, the energy cost is null.

- Partition conditions and irrigation requests if these are for long periods.

- Listing the requests with extremely flexible configurations: each hydrant can request one or more irrigation sessions, and for each request the flow rate may be variable over time. Each request can be restricted so it can be placed in a given time band, or executed at a given time (forced requests). Periodical requests can be established, with a given duration and gap between irrigation sessions, or periodical requests with variable gaps, above a minimum period in order avoid solutions with irrigation sessions too close together.

- Finally, the parameters associated with the optimisation algorithms must be configured, with the weights and penalisation of the control variables (pressure in hydrants, velocity in pipes, etc.) and initial conditions, convergence and calculation speed. This block of parameters is pre-set and adjusted in advance to provide the best solutions.

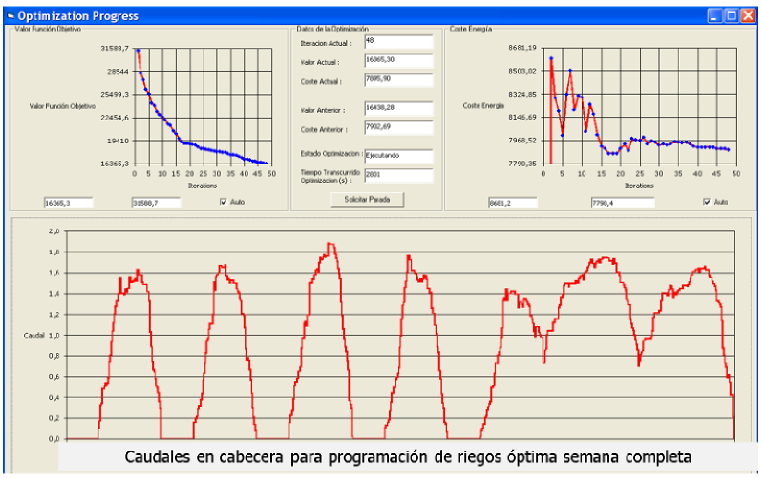

Figure 4. Timeline of flow rates in the pumping station for a schedule optimised for a full week, showing the hydraulic and energy convergence indicators

The results obtained consist of a list of the optimal sequences for opening and start times for each request and the resulting temporal pattern, in XML format readable by GESTAR 2014, enabling an immediate hydraulic and energy simulation of the solutions obtained, in order to check the level of compliance with the restrictions (pressures, velocities, maximum power) and make individual adjustments to the obtained schedule. During the schedule optimisation process, managers can control the process of fine tuning the solutions found, Figure 4.

4 Results

4.1 Savings on energy costs in application cases

To test the technology, quantify its impact, explore its operational limits and extend its usability, the PRORIEGO-TeleGESTAR function was applied to a set of real systems (see Table 1), under construction or in use, with the participation of affected communities of irrigators in the Spanish region of Aragón.

Name of the network with DPS	Irrigators' community	Area (ha) (n.º of hydrants)	Nominal pressure on demand (m)	Total energy costs on demand (€/year)	Saving achieved using PRORIEGO
Laviolada	(Almudevar)	1,335 (106)	66	231,000	32%
NETWORK 3	(Mequinenza)	1,000 (101)	65	88,000*	16 %
NETWORK A NETWORK B	(Callén)	1,135 (89)	70-44.5	216,000	18%
PHASE II	(Molinar)	3,644 (273)	68	963,000	16%-20% (Estimated)

Table 1. Examples of potential savings in energy costs for on-demand irrigation communities if they organise their irrigation requests using the PRORIEGO-TeleGESTAR function.

The last column in Table 1 shows the percentage saved on energy costs in relation to the value in the preceding column, corresponding to the probable annual energy cost (including energy and power, except for Mequinenza, which is energy consumed only), in a best case scenario, with a purely on-demand network, demonstrating the indisputable effectiveness of this technology. The time required to reach convergence is around 15 minutes for a daily schedule, and 2 hours for a weekly schedule, with 15-minute minimum intervals between requests.

4.2 Compliance with pressure requirements

The optimisation model implemented in PRORIEGO-TeleGESTAR, which integrates the hydraulic simulation of the organised period, penalises solutions which do not meet the minimum pressure requirements. This eliminates or minimises the pressure deficits which tend to appear when energy cost saving strategies based on concentrating irrigation sessions in cheaper periods are implemented manually or with the help of simple calculations which just limit flow rates in branches and in the pumping station.

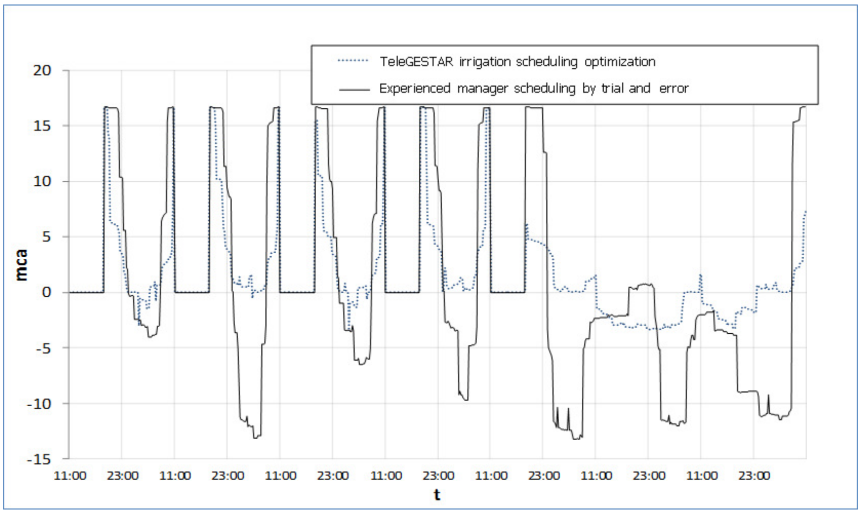

Figure 5. Pressure excess/deficit over the minimum required pressure at critical points over a week: As arising from an optimum demand scheduling by TeleGESTAR (dotted line) and from a trial and error manager solution (solid line).

Figure 5 shows the evolution of the pressure margin (existing pressure minus the required minimum pressure) in a representative hydrant from the most critical area of the first case in Table 1 (Laviolada), obtained by simulating the irrigation schedules for one of the weeks with the greatest water needs in the irrigation campaign, performed heuristically by the manager (solid line) based on the requests received, with the help of a flow rate measurement tool, and the pressure margin corresponding to the schedules generated automatically by PRORIEGO-TeleGESTAR (dotted line).

We see that the schedule created without optimisation resources leads to large pressure deficits for long periods, while for the same requests organised by the PRORIEGO-TeleGESTAR, there are no deficits over 3 m. It should be noted that if PRORIEGO-TeleGESTAR is allowed to subdivide the longest requests into shorter intervals (using the “Split” option), these occasional pressure deficits disappear.

4.3 Other management advantages

As well as minimising energy costs and satisfying demands in the requested period with guaranteed pressure, the optimal irrigation scheduling system offers other advantages: It avoids inefficient trial-and-error processes which also take up a great deal of managers' time, freeing them to attend to other tasks, and it gives optimal results regardless of their level of expertise or available time. The system adapts immediately to changes such as new prices or different maximum flow rates, and can be integrated with automated irrigation systems and with precision agriculture. It can be used with and without telecontrol, and can adapt to telecontrol at the hydrant level or within each irrigation sector.

5 Conclusions

Managing irrigation demand is an effective strategy for reducing energy costs in systems pressurised by pumps, but ICT tools are needed to implement it effectively, given the many different variables and restrictions, which make it a complex problem. The adaptation and extension of an algorithm in the ACO family, implemented in the PRORIEGO-TeleGESTAR function, has been shown to be effective and quite flexible, with savings of 15 to 35% and faster execution than other alternatives. To make the most of this strategy, we need to consider this new paradigm in the design of irrigation networks, making it advisable for all future projects to be conceived or revised with this in mind.

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