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The use of Genetic Algorithm's in multi-objective optimization of Pump-as-Turbine Energy Recovery Systems

Extended Abstract

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Abstract: A major consequence of climate change is the drastic change in the weather patterns of already friable zones that lead to water scarcity in multiple regions of the world. It is essential to have a more controlled management of water resources. Excess of pressure in water networks is directly related to excess of water losses which not only are devastating from the water scarcity standpoint but also a waste of energy and resources in the treatment and distribution of the lost water. The use of Pump-As-Turbines (PATs) instead of the traditional pressure regulation systems, could allow for a recovery of the excess hydraulic energy to reduce the energy footprint of the water supply industry and at the same time control the water losses by an effective reduction in pressure.

This research aims to explore the option of applying a multiple PAT system in a water network with an integrated multi-objective optimization using Genetic Algorithm's (GA). The objective of the optimization is to ensure a better use and more effectiveness in the implementation of this resources. A methodology to approach this multi-objective problem and the interface between components of the optimization is presented. The evolutionary capacities of the optimization will be analysed, as well, the effects of the general convergence of the pareto front and the adaptation of the final solutions.

Key- Words: pump-as-turbines (PATs), genetic algorithm (GA), multi-optimization, water losses, Micro hydro production.

1 Introduction

A major consequence of climate change is the drastic change in whether patterns and the rise in global temperatures. Therefore, it creates more stress to the already scarce natural water resources. Multiple regions, especially in Europe in the Mediterranean countries, are already suffering from water scarcity, some even already produce artificial water with the use of desalination methods which is a very expensive and energy dependent process (2.5kW/h/^{m3}) that goes against the will of reducing and managing the natural resources (Craig R & Andes, 2015). The excess pressure in the water supply systems worldwide, and their level of deterioration, create an estimated average water loss, just in the delivery system, of 35%, being possible that in extreme pressure regions and very deteriorated systems it could reach up to 50-60% (Fields, 2015).

The use of PATs has been thoroughly studied, from the prediction of the behaviour of the turbomachine in inverse mode by analytical methods to the use of Computer Fluid Dynamics (CFDs). The position and definitions of an energy recovery system that used PATs as the main element is an extremely complex problem to solve. Several works have been done with the use of GAs regarding the location and pressure to be removed by a PRV in the water network, the same concept is to be applied to the PAT system designing taking into consideration the progressively more complex variables and objectives of the optimization.

The purpose of this work is to study the effects of the application of a GA in an all-variable approach to the implementation of an energy recovery system, with the use of PATs. The goal is to apply all the variables in one compact genetic form. The variables used are power curves and characteristic curves for multiple turbine speeds, implicating the use of electric regulation of the system conditions, different demand patterns throughout the day. Although this work is focused on the application of a system in the short term, it opens the way to a long-term approach that could include as variable the progression of the demand pattern throughout the live cycle of the system.

The work of developing the optimization is based in the NSGA-II GA (Deb et al., 2002) and was executed using MATLAB programming language in the correspondent computer software. It is intended to evaluate the use of EPANET-MATLAB Toolkit in this kind of optimization. This toolkit creates an interface between software's allowing for an easier data analysis from the hydraulic simulations done in the EPANET model. An EPANET model needs to be created prior to the optimization. This model will consist in one simple example network, made for the purpose of this work.

2 Pressure regulation in Water Supply Networks

There is a direct correlation between excessive pressure and water losses due to leakage in a network, therefore, a good pressure management is essential to regulate water losses (Clarke, 2010). Due to the reduced investment corrective interventions, better customer service by the water supply companies and savings in energy necessary to pump or treat the water this type of water losses management is also one of the most economical ones (Girard & Stewart, 2007).

There are multiple types of PRVs, spring, piston and diaphragm (Ramos et al., 2005) There are four main different types of operation condition for the valves. Extensive work has been done in the incorporation of GAs within the optimization of the position and definitions of PRVs applied to a water network. Initial studies started with the use of simple GA to predict the optimal locations of PRVs, with the objective on minimising water leakage

2.1 Pump as turbine (PAT) for energy recovery and pressure management

As previously mentioned, a reduction of pressure to ensure a reduction on water losses in the network is typically achieved with PRVs. These valves induce a local loss of energy in the water supply network that is dissipated within the valve. This dissipated energy could be harvested with the aid of hydropower devices that allow for energy production at the same time the pressure requirements are achieved. PATs are extremely simple machines that are readily available worldwide that can offer low maintenance costs and a fast payback period, that can be around two years or even less (Derakhshan & Nourbakhsh, 2007).

Multiple studies, such as Gonçalves & Ramos (2008) and Chacón et. al. (2019) concluded that this type of implementation could offer a feasible solution to both pressure regulation and economic viability by energy recovery. An obstacle to correctly implement pumps working in inverse mode, is the lack of data of each pump working in those conditions. The curves are generally not provided by the manufactures. This created a demand in the investigation of different methods to determine the curves of the pumps working in reverse from the original pump curves (Derakhshan & Nourbakhsh, 2007).

In the late century, many authors worked to achieve good predictions of turbine behaviour. Williams (1994) illustrated how a lack in precision in this procedure can have major consequences in the viability of the PAT implementation. Authors, like Stepanoff (1957) and Sharma (1985) advanced in analytical methods to predict the performance of the PATs. Derakhshan and Nourbakhsh (2007) developed a prediction method to determine the Best Efficiency Point (BEP) for low-specific-speed centrifugal pumps and concluded that centrifugal pumps can work in multiple rotational speeds.

2.2 CFD

With the objective of improving the methods that predict the behaviour characteristics of pumps working in inverse mode, studies and progress was done in using computers to create virtual simulations of the turbomachines behaving in multiple conditions. A performance improvement in CFD approaches to predicting turbomachines behaviour could allow for a fast and realistic simulation of different turbomachines, in different environments with a very high precision.

Multiple authors, like Carravetta et al. (2012), concluded that this type of technique could be very effective. Nevertheless, reported small errors in the prediction and suspect that an improvement in the grid model definition can offer a solution to the problem. On the other hand, Derakhshan & Nourbakhsh (2008) concluded after a comparison between experimental results of a PAT characteristics and the ones obtained in a computational model that the results are already viable in pumping mode, but in turbine mode there is still a considerable difference in results, the authors point out that in turbine mode a higher sensibility to the model grid complexity must exist.

2.3 Variable Operating Strategy (VOS)

When applying energy recovery systems in water networks, there are multiple operating conditions, in this case, with hourly, daily, and yearly variance that influence the system project and viability. Carravetta et al. (2012) proposed the procedure, named variable operating strategy (VOS), for the election of the most appropriate system. The authors based this method in a preliminary use of the plant overall efficiency.

Carravetta et al. (2012) proposed a method of regulation to achieve better efficiency from the overall system, the Hydraulic Regulation (HR). HR works by regulating the flow that enters the PAT with the use of a bypass regulating valve. The flow and head conditions are adapted to the PAT.

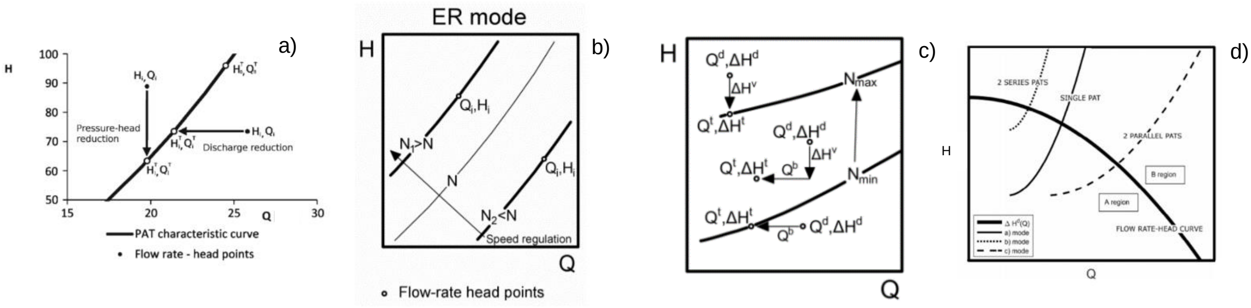

Figure 1 – a) Hydraulic Regulation, effects of the regulation system (Carravetta et al. 2012); b) ER, and the corresponding characteristic curves changes (Carravetta et al. 2013) (c) HER and (d) SPP operation diagrams (Carravetta et al. 2018)

Carravetta et al. (2013) extended their studies in regulating PAT operations in variable conditions by exploring Electrical regulated (ER) systems. In this method the PAT working conditions are adapted to the flow and head that exist in the system to optimize the energy production on the system without any other mechanical controller. The characteristic of the behaviour of turbomachine depends on the rotating speed it is working. When the rotational speed is higher, the head drop created by the PAT is also higher, with smaller flows. When the rotational speed is lower, higher flow goes throw the system with corresponding smaller head drop induced in the system.

A similar regulation method, uses both technique above described to ensure a better adaptability to the hydraulic conditions is the Hydraulic Electrical Regulation (HER), The same authors explored, later, a different regulating method, the single-serial-parallel regulation (SSP), this system eliminates the need of expensive control equipment offering by itself three different operation modes: Single Pat, Parallel PATs and tow PATs in series (Carravetta et al. 2018)

3 Genetic Algorithms

GAs are based on the dynamic system that make the theory of evolution in the natural world. Evolutionary algorithms are very well suited to problems that require a strong capability of adaptation, to allow to continue to perform adequately in changing environments, problems that require innovative solutions that don't fit the traditional progression of ideas and in problems where the size of the solutions space is extremely big, and with a very high complexity of variables that do not allow for a clear and reasonable approach "by-hand" in enumerative methods, neither by deterministic approach. (Mitchell, 1995).

When taken into account the available PAT models in the market, the multiple rotational speeds it can run, the multiple demand patterns that the system goes through every day and the projected variations in this demand during the life cycle predicted for the system, the total of possible solutions space reaches a very high dimension. For this reason, is clear that the decision maker for a PAT implementation needs at least some guidance to achieve desirable results.

NSGA-II is nondependent on previous information, are also nondependent on information related to the relative importance of a given parameter of the network in comparison to another. another. By using multiple point analyses at the same time and the construction of a Pareto Front, this kind of method allows a final decision, and final in-depth analysis by the decision maker without previous errors due to lack of correct information.

4 Methodology

The hydraulic simulation of the network to be improved is performed on EPANET 2.2. It has the capability to solve the system of flow continuity and headloss equations to achieve a desired level of accuracy for each time step, defined by its own demands and characteristics. EPANET-MATLAB Toolkit was used as an interface between the hydraulic solver and the GA optimization.

4.1 Objective functions

To select the best individuals in the solution space created by the genetic algorithm and the hydraulic simulation, a competition amid objectives must take place. The main objectives that should be achieved from the installation of a PAT in a water distribution network and utilized in this study are the regulation of pressure in the network, the production of electricity and the rentability of the system.

An initial approach to the pressure regulation function was made with an extrapolation of the methods used in multi-objective optimization of water networks with the implementation of Pressure Reducing Valves (PRV), the pressure function used was based on the *Root mean square error (RMSE)*

$$F.Pressure = [\frac{1}{n}\sum_{j=1}^{n}(h_j - h_{ref})^2]^{1/2} \quad \textbf{(5)}$$

In the approach used in this research the convergence only can occur from the high-pressure region to the low-pressure, not allowing for a convergence from both sides of the spectrum, and the low-pressure solutions are considered immediately out of bounds and do not have a reproductive chance.

On its own, energy production from PAT should not be viewed only as an alternative to PRVs that as the possibility to generate some extra income over the years. PAT recovery systems in water networks can have the possibility of being a productive investment that, besides regulating the water network, can stimulate investors outside the water supply companies to invest in this solutions. A cost per kW of energy produced was calculated for the fitness function. The cost function was imported from Novara et al. (2019), where the authors compiled the cost of 301 Radial and 42 Vertical Multistage pumps/PAT. A function of cost was broken into two regions: (i) from 0kW to 1kW; (ii) for > 1kW.

For region (i) from 0 kW to 1 kW:

$$Cost\left(\frac{€}{kW}\right) = -17512P^3 + 38193P^2 - 28846P + 9448{,}3 \quad (8)$$

For region (ii) from 1kW to 100kW:

$$Cost\left(\frac{€}{kW}\right) = 1498{,}4P^{-0.686} \quad (9)$$

The last fitness function measures the accumulated electric power produced in the network. During the procedure the power curve from each PAT at the correspondent velocity was incorporated in the input data received by the GA in the optimisation process. The curves were imported using a matrixial format. After locating the correct curves of the PAT model and rotational speed for a given time step, the fitness function defines the generated power by interpolating the PAT flow that came from the hydraulic simulation with the values on the power curve.

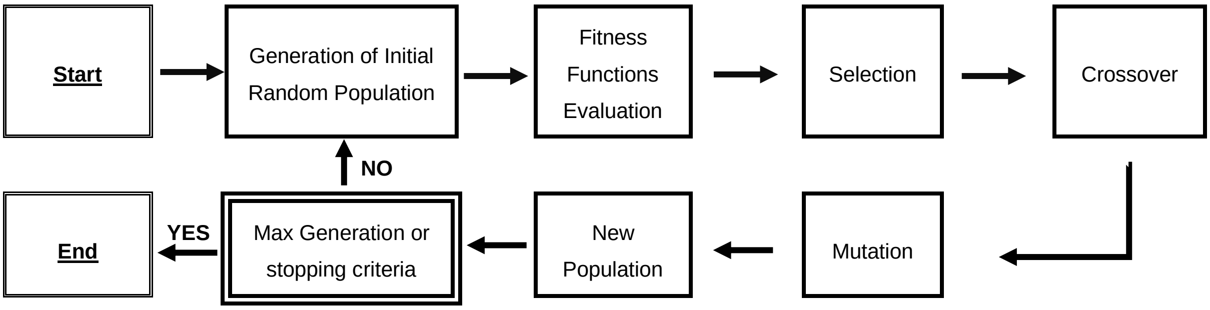

Figure 2 - Generic diagram of GAs methodology.

5 Case study

The first attempts to apply the algorithm used in this research were done in a stretch of a water distribution network, Figure 3, from a real-life scenario in Funchal, Portugal. Immediately, it was clear that the method used does not allow for quick enough speed in the resolution of big networks. It was created an example of a water supply system to simulate the concept and plausibility in a reduced and controlled environment. Multiple PATs were analysed and compiled into a data library to be used by the GA.

The supply network created aimed for a system with variable flow conditions and excess pressure. It was design in the EPANET workspace consisting initially in 20 base links connected to a reservoir on top of a hill. Three different district metered areas (DMA) existed in the network.

The DMAs selected in Figure 4 were supressed from the optimization because the flow conditions would not create suitable conditions for a PAT application. The correspondent demand was transferred to the

Figure 3 - Fuchal water supply network.

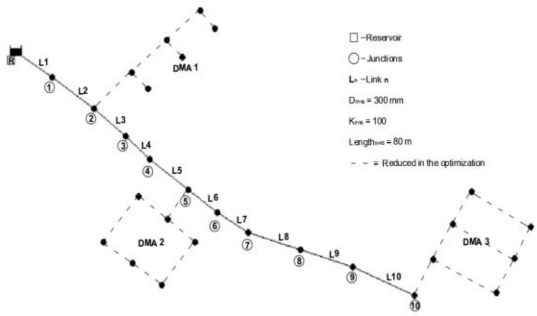

Figure 4 - Representation of the components and general structure of the network.

node in the main supply system. The optimal region for PAT application has therefore 10 links where a PAT may be installed by the optimization algorithm.

The headloss curve of a GPV valve is the respective characteristic curve of a PAT in the EPANET model. The bottleneck in this procedure is setting up the network conditions, consisting of mainly applying new valves in the water network.

The demand pattern was adapted to the constrains imposed by the hydraulic times of the simulation, and at the same time applying the variability that characterises WDN and the difficulty in applying a correct PAT that is required to have the most acceptable behaviour during these operational variable conditions. The variability, which is essential to validate the model is, therefore, preserved. The fundamental aspect of evaluating the adaptation of the PATs operating characteristics to the hourly demands is maintained with a decreased in optimization time.

5.1 Optimization process

Two main components in the process should be noted: (i) the genetic optimization algorithm, (ii) the hydraulic network edition and simulation. For an efficient interaction between the two simulation tools, the network morphology of each solution was comprised in one common matrix. By having every element of the population comprised in one matrix with a simple nomination of the characteristics, such as the binary or index connotation of the features to be stated in the network, not only it becomes easy to process the hydraulic network but allows for compatibility with simple evolution methods of mutation and crossover.

The GPV implementation and corresponding characteristics are the most critical step in the process, not only because is repeated multiple times (time steps*number of valves per generation*number of generations), for every time step and PAT (in form of valve), but also because it is dependent on the size of the network and the velocity of the interface toolkit.

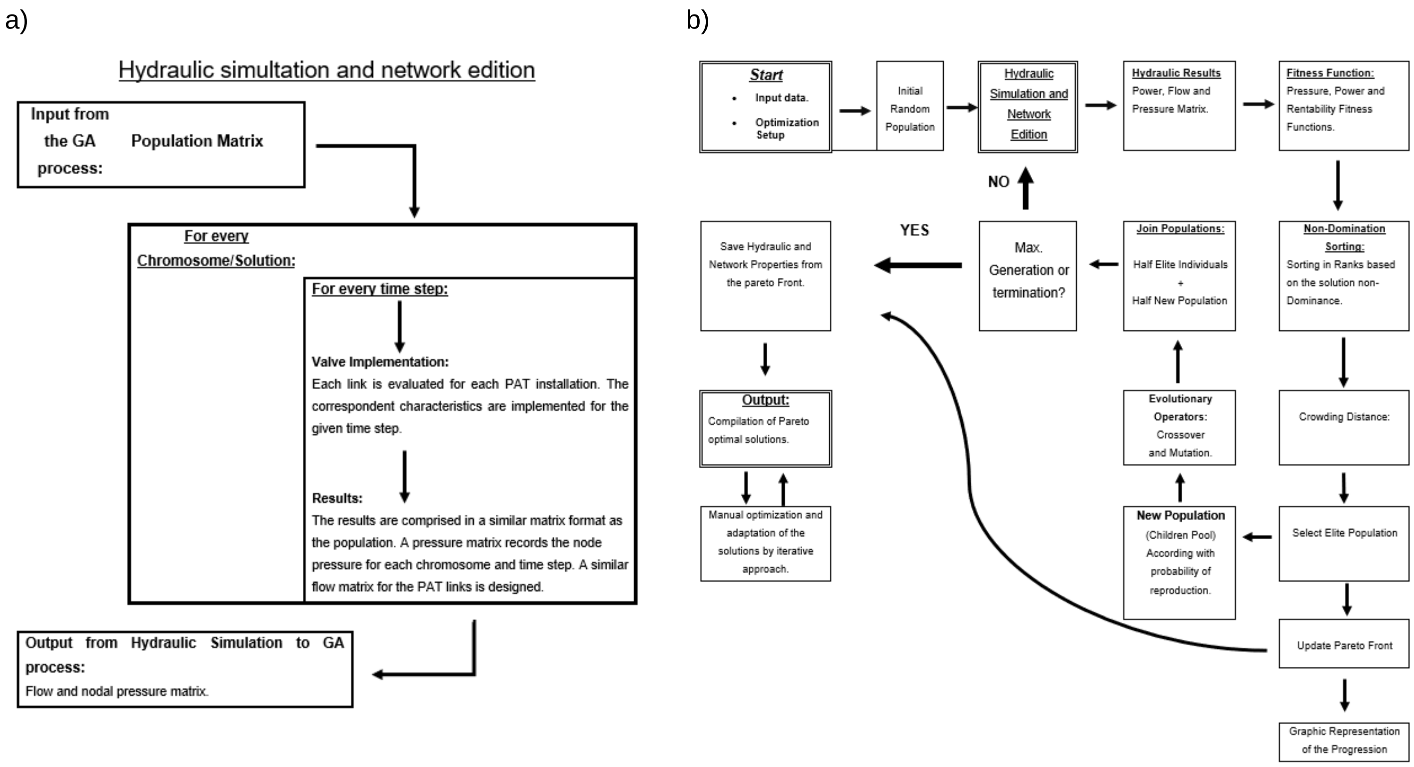

Figure 5 - a) Flow chart for the hydraulic simulation and network edition diagram and b) general workflow of the GA in the case study.

The simulations were made with an AMD Ryzen 7 3750H (2.3Ghz) CPU where only one core was dedicated to the processing. It is important to note that the apparent simplicity of this network is not representative of the level of possible solutions and combination of parameters that may exist in this problem. Taking in account the number of solutions permutations possible with the chromosome/solution matrix, the multiple PATs and operating conditions available and the time steps, the total number of possible solutions is **$4{,}12.10^{56}$**.

In Figure 5 is described the general methodology of the routines used in the present study. It is important to note that every major variable that impacts the system performance in the short term was incorporated in this optimization process. Meaning that the GA must deal with a complete simulation that takes into consideration not only a demand pattern but also a multitude of options in the PAT library. With this procedure a higher range of possible solutions exists and the difficulty to achieve good solutions is also inherently higher.

The space of solutions to be analysed, comes from a non-continuous function. A GA approach to a continuous function, where the changes in inputs can be smooth, offering a constant and gradual progression of results. In this kind of approach to a non-continuous solution space the resulting convergence is predicted to behave in a breakthrough-to-breakthrough evolution. The true pareto front is not made of continuous points, and each pareto solution may be very distinct from each other not only in terms of the fitness function output, but also in the true characteristics of the chromosomes. A geometrically imperfect pareto front is thereby expected.

6 Optimization results

In each generation of the GA convergence, the pareto front for that generation was saved and each solution represented as one circle with the corresponding fitness values associated. For Figure 6a), b) and c) only the better results at the time of the respective generation were selected. Solutions that remained dominant for multiple generations create a line made from constant points of the same pressure fitness. With the referred processing power, the analysed optimization took approximately 390 hours to achieve the results in Figure 6.

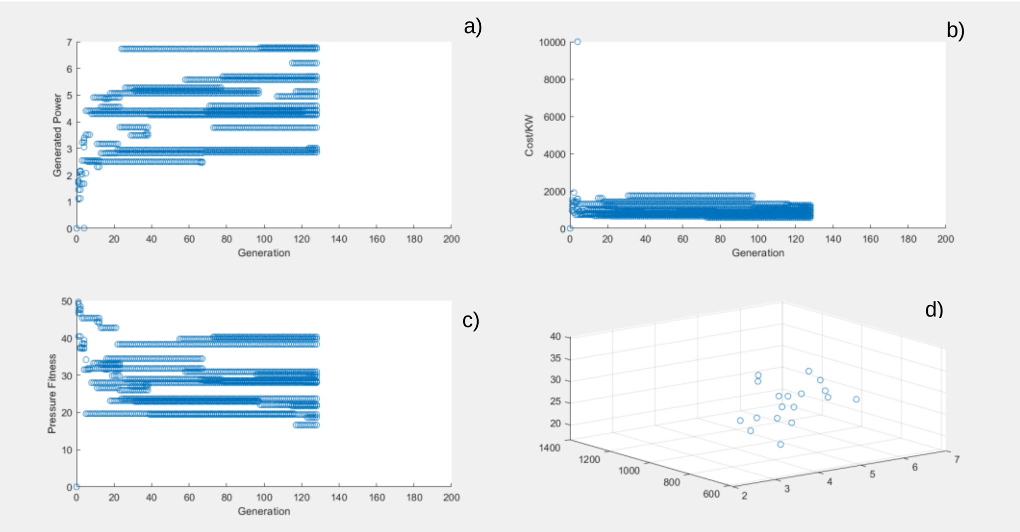

Figure 6 - Pareto Front representation and the corresponding results for each generation. a) Generated power (kW); b) Rentability (Cost/kW) c) Pressure Fitness d) Final representation of every solution in the pareto front.

A clear relation, that could be previously expected, is that with higher power generation the lower the fitness pressure is. It's a testimony of the correct behaviour of the optimization algorithm. Logically the reduction of pressure is equivalent to the reduction of potential energy in the water network. A refinement post optimization of the PAT characteristics was executed for the solution with the best pressure fitness. The pressure profile is represented in Figure 7.

By analysing the recovered data, the solutions that have better pressure regulation have followed the logical route of applying more small power PATs in more links of the network to create less accumulation of back pressure. Since the rentability fitness function used provides higher cost for low power installations the result is an inevitable reduction in the rentability potential.

The pressure results provided solely by the optimization algorithm provide a reduction to **78%** in the network pressure. Small enhancements were made in the PAT rotational speeds which are represented in Table 1. After the fast refinement of PAT speeds of the optimization results there is a reduction to a noticeable **59%** of the original pressure in the water network. A clear improvement was made regarding the original pressure conditions.

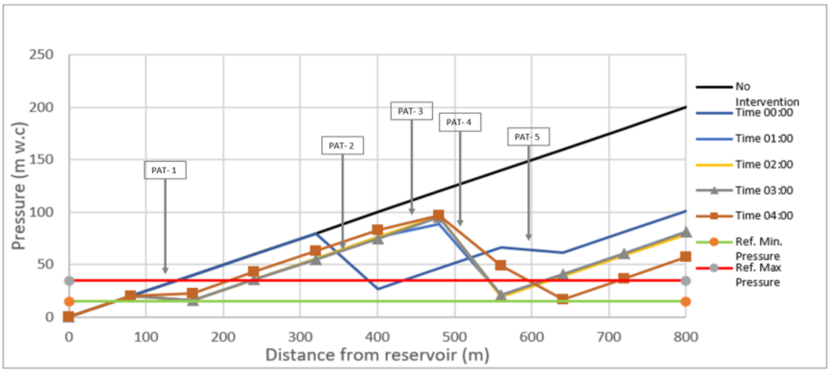

Figure 7 - Pressure profile in the refined network for each time step.

		Rotational speed (RPM) at time:				
	Model	Time 0:00	Time 01:00	Time 02:00	Time 03:00	Time 04:00
PAT – 1	80-200	1300	1900	2100	1900	1900
PAT – 2	80-200	1900	1100	1300	1300	1300
PAT – 3	80-200	900	1100	1500	1300	1100
PAT – 4	40-315	900	1500	1700	1500	1100
PAT - 5	32-200	900	1500	1700	1500	1100

Table 1 - Rotational speed of the optimized PATs at each given time period referent to Figure 7.

7 Conclusions

The use of an integral approach to optimize solutions that use PATs as the base element in a multi-objective problem show a feasible option that could allow for an efficient optimization of large water networks. The method of combining all the information in the proposed population matrix proved to be a robust option and the use of all fitness functions developed in this research showed an effective comparison between solutions and allowed for a competitive evolution of the pareto front and a convergence of the results. The use of a pareto front optimization is an excellent method to avoid unnecessary bias by the user of the system and allows it to have a stronger decision power.

The optimization results demonstrate a clear improvement in the pressure conditions. Besides offering adequate solutions that respect the limits of what is the acceptable solution space, it offers a direct improvement after the optimization to only **78%** of the original pressure and after a refining of the rotational velocities in the solution, pressure levels of **59%** the original pressure were achieved. even better results.

The use of EPANET-MATLAB Toolkit, despite being a good solution to analyse data from water networks using a powerful mathematical software like MATLAB, is not adequate in performance capabilities (with the available processing capabilities) to the number of network editions and the simulations needed.

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