Genetic Algorithms for the Optimal Operation of Sprinkle Irrigation Systems under Deterministic Loading Conditions

Matteo Nicolini

Abstract—**The paper presents a methodology developed for the optimal management and operation of sprinkle irrigation networks. Some typical problems are presented and solved through Genetic Algorithms (GAs), assuming that the loads (demands) at nodes are cyclic and deterministically established. In particular, an algorithm for model calibration is first introduced, aimed at the minimization of the maximum errors between measured and calculated values. Since the operation of such systems is highly water and energy demanding, two algorithms for controlling pressure and pumps are described: the first is aimed at finding the optimal location and control of a set of devices (pressure reducing valves and/or closed gate valves) in order to maintain a desired range of pressure throughout the network, while the second is focused at finding the optimal regulation of inverters for variable speed pumps in order to minimize energetic costs. An application to a real system is finally presented.**

Index Terms—**Energy, variable speed pumps, water distribution networks.**

I. Introduction

The demand of water for irrigation accounts for the largest percentage of water consumption in the world, with an average value of 70% and ranging between 30% in industrialized nations up to 90% in countries under development [1]. The most widespread method is still surface irrigation, but in these last decades the scarcity of resources has led governments and regulatory bodies to finance many projects of reconversion from surface to sprinkle systems, because of the large amount of water that can be saved (50 – 60%).

Sprinkle systems are particularly energy demanding, since energy is required for pressurizing the pipelines and sprinkler units. The energy to pump water from groundwater (or surface) sources is usually given by centrifugal pumps. Thus, two order of problems have to be faced when dealing with the management of such systems: the first is to provide an adequate level of pressure in time and space (there is actually a direct relationship between pressure and flow at active sprinklers); the second is related to optimal pump operation, in order to maintain high levels of efficiency in the irrigation season.

In these last decades, genetic algorithms (GAs) have been adopted as powerful stochastic alternatives to classical deterministic optimization techniques, and have proven their robustness in many engineering application areas, even for multimodal, highly nonlinear and not-differentiable problems [2]-[5]. Moreover, they are particularly suitable to multiobjective optimization, because they simultaneously deal with a population of solutions [6], [7].

Many research papers have focused on the application of single-objective GAs for the optimization of water distribution systems [8]-[16]. Multi-objective GAs are receiving ever-increasing attention in the field of water resources, and these last years have seen an increasing number of applications in water distribution systems optimization: generally, only two-objective problems have been considered, the first criterion being the total cost of the system and the second representing a measure of the network performance [17]-[26].

Despite the large literature related to the optimization of water distribution systems, few studies have been dedicated to the optimal design and operation of irrigation systems with GAs [27]-[29].

The paper presents a methodology for the optimal operation of sprinkle irrigation systems in which sprinkler activation at nodes is cyclic and a-priori established. The procedure relies on a coupling between EPANET simulator [30] and a set of GAs developed for water distribution systems optimization.

The paper is organized as follows. In Section II, the basic equations of the problem are presented, describing the conservation principles applied to a pressurized irrigation network. In Section III, a review of GAs adopted in water networks optimization is illustrated, particularly focusing on the difference between single and multi-objective GAs. In Section IV, model calibration is described, while in Sections V and VI, optimal pressure management and variable-speed pump operation are presented, respectively. Section VII describes the application to a real system, while Section VIII draws some concluding remarks.

II. Basic Equations

Optimal management of sprinkle irrigation systems can be achieved starting from a simulation model which represents the behavior of the network under different loading conditions. By loading condition we mean a set of sprinklers which are active at the same time and for a fixed duration, called ‘turn’. A complete cycle of all turns is typically performed in one week, with each turn characterized by a duration of four hours. The physical constraints describing the mass and energy conservation principles for a pressurized

Manuscript received March 10, 2012; revised April 6, 2012.

M. Nicolini is with the Department of Chemistry, Physics and Environment, University of Udine, Via Cotonificio, 114, 33100 Udine, Italy (e-mail: matteo.nicolini@uniud.it).

water network are, respectively, the continuity and head-loss equations, which can be written as

$$\sum_j Q_{ij,k} - \ell_{i,k} = 0 \quad \forall \text{ node } i \tag{1}$$

$$H_{i,k} - H_{j,k} = h_{ij,k} = \begin{cases} \dfrac{10.6668 Q_{ij,k}^{1.852} L_{ij}}{C_{ij}^{1.852} D_{ij}^{4.871}} & \text{pipe} \\ -\omega_{p,k}^2 \left[A_p - B_p \left(\dfrac{Q_{ij,k}}{\omega_{p,k}} \right)^{C_p} \right] & \text{pump} \end{cases} \quad \forall \text{link} ij \tag{2}$$

In (1), $Q_{ij,k}$ indicates the flow from node i to node j at turn k; $\ell_{i,k}$ is the flow at turn k delivered at node i (when active), which depends on pressure according to

$$\ell_{i,k} = c_i \; p_{i,k}^{\gamma} \tag{3}$$

where $p_{i,k}$ is the pressure at node i and c_i and γ are two coefficients quantifying the relationship between flow and pressure (the coefficient c_i is dependent on the type of sprinkler unit, while usually $\gamma = 0.5$). In (2), $H_{i,k}$ and $H_{j,k}$ are the total head at nodes i and j at turn k, while L_{ij}, D_{ij} and C_{ij} are the length, diameter and Hazen-Williams friction factor for pipe connecting nodes i and j, respectively. If a pump is present in link ij, its characteristic curve is described by coefficients A_p, B_p and C_p, while $\omega_{p,k}$ represents its relative speed setting for turn k.

III. Genetic Algorithms

A. Single-Objective GAs

Genetic algorithms are derivative-free search procedures based on the mechanics of natural selection and natural genetics. They have been introduced by [2], who explained the adaptive processes of natural systems and laid down the two main principles of GAs: the ability of a simple bit string representation to encode complicated structures, and the power of simple transformations to improve such structures; [3] gave a decisive thrust in GA research field.

Traditional GAs evolve a population of solutions through several operators. Encoding converts given parameter values (e.g. diameter sizes) to a string of bits (0 or 1), also called *individual* or *chromosome*. Decoding maps back the string to the corresponding parameter values. Each individual is evaluated according to its objective function, which plays the role of the environment (i.e. every individual is characterized by a *fitness*). After evaluation, selection, reproduction, crossover and mutation take place. Selection consists in choosing the individuals which are going to form a new generation, and in placing them in the *mating pool*; it is often proportional to fitness values: the higher the fitness, the higher is the probability for the individuals to be selected. Reproduction is the mechanism by which a string is copied in the subsequent generation: it may be copied with no change, but it may also undergo crossover and/or mutation, with prescribed probabilities. With crossover, two individuals are randomly selected and put in the mating pool; then, a position along the string is chosen, according to a uniform random law; finally, the paired individuals exchange all characters following the cross site. Mutation is a random alteration of a bit at a string position; in general, it enhances population diversity and enables the optimization process to get out of local optima. The procedure is iterated until a stopping criterion is met (in terms of total number of generations or convergence percentage).

The procedure outlined above can be regarded as the basic form of a GA. Many techniques have been added in order to improve the performance of such algorithms, and several selection, reproduction, crossover, mutation, and scaling operators have been proposed.

B. Multi-Objective GAs

Multi-objective genetic algorithms, also denoted as Pareto GAs, are receiving increasing attention in the field of water resources and pipe network optimization.

The goal of an algorithm for multi-objective optimization is not to return one design, but to generate a set of designs representing all optimal tradeoffs. To define what constitutes an optimal trade-off, the concepts of Pareto dominance and optimality are used. Though in this work only a two-objective problem is considered, such concepts can be applied to design problems with any number of criteria. Let $F = [F_1(x), \ldots, F_G(x)]$ be the vector of a maximization problem with G objective functions, $x \in \Re^n$, and x_1 and x_2 two possible configurations. We say that configuration x_1 *dominates* configuration x_2 $(\text{or } x_1 >_P x_2)$ if, for all $i \in \{1, 2, \ldots, G\}$, $F_i(x_1) \geq F_i(x_2)$, and there exists at least one i such that $F_i(x_1) > F_i(x_2)$. A configuration is said to be non-dominated if no feasible design exists in the entire solution space which dominates it.

IV. Model Calibration

One of the most important steps in building a decision support tool for planning future management and rehabilitation strategies is to implement an accurate simulation model, which allows to analyze the behavior of the system under different scenarios. However, the predictive ability of a numerical model is strongly dependent on its calibration.

Model calibration may be regarded as an optimization problem characterized by specific objective function and constraints; in particular, conservation laws (mass and energy) have to be included, resulting in a nonlinear optimization problem that has to be solved.

The issue of model calibration was investigated by many authors: typically, roughness coefficients are included as decision variables [31], but also water losses have been also considered as an unknown parameter [32]. In addition, several examples exist in the literature which address the sampling design for water distribution systems through the determination of the optimal choice of calibration test locations [33]-[35].

In this paper, the objective function for model calibration is defined as [36]

$$\min: f_1 = w_H \max_{n,k}\left|H_{n,k}^{meas} - H_{n,k}^{calc}\right| + w_Q \max_{p,k}\left|Q_{p,k}^{meas} - Q_{p,k}^{calc}\right| \quad (4)$$

where $H_{n,k}^{meas}$ and $H_{n,k}^{calc}$ represent, respectively, the measured and calculated head at turn k in node n, while $Q_{p,k}^{meas}$ and $Q_{p,k}^{calc}$ the measured and calculated flow at turn k in pipe p. w_H and w_Q are weighting factors for heads and flows.

Model calibration is based on a single-objective GA, characterized by real-coded decision variables representing pipe friction factors (according to conduit material). The GA was developed in C++ starting from GAlib library [37], and has been extended to a set of multi-objective GAs in order to solve also multiple criterion decision making problems [38], like optimal design of water distribution systems or optimal location and control of pressure reducing valves in water networks [39].

V. Optimal Pressure Management

The problem of optimal pressure management in a sprinkle irrigation network is addressed through the placement and regulation of pressure reducing valves and/or the insertion of closed gate valves. The determination of the number of such devices, together with their location and setting, is formulated as a two-criterion optimization problem, and is based on a multi-objective genetic algorithm previously developed [39].

Several examples exist in the literature which address the problem of optimal location and/or optimal setting of control valves in water distribution systems, solved with mathematical programming techniques [40]-[45], or with genetic algorithms [46], [47]. These studies were usually characterized by focusing only on optimal placement or setting, with the exception of [47], who were the first to address both the problems of optimal location and regulation of control valves, although in a single-objective context. For a given scenario representing a load condition in the system, they optimized the best placement and regulation of a fixed number of valves.

This paper adopts a different approach: the total number of installed pressure reducing or closed gate valves (first objective) and the total delivered water in the system (second objective) are considered independent of each other, and the multiobjective NSGA-II (Nondominated Sorting Genetic Algorithm, [48]) was implemented in order to optimize the two conflicting criteria. In addition, the particular coding of the real variables allows the determination of both the location and the regulation of the valves, according to a number of predefined demand conditions.

In this way, in one simulation run the optimal trade-off solutions representing different level of compromise between the number of valves installed and the related total delivered water in the system can be determined. The great advantage resides in the fact that a single combination of valves is found for different load conditions, thus giving the possibility of providing the rule curve for each valve, for example the setting-versus-discharge relationship.

The problem may be mathematically formulated as follows:

$$\min: f_1 = n_v \quad (5)$$

$$\min: f_2 = \sum_{k=1}^{N_T}\sum_{i=1}^{N_N} w_k\ \ell_{i,k} \quad (6)$$

subjected to:

$$H_{i,k} \geq H_{req,i} \quad (7)$$

$$n_v \leq N_v \quad (8)$$

In (5), n_v is the number of valves in a generic solution, while in (6) N_N represents the number of nodes in the network and w_k the weight associated to load condition k. In (7), $H_{req,i}$ represents the required head at node i (usually fixed), while in (8) N_v is the maximum number of pressure reducing or closed gate valves allowed.

VI. Optimal Operation of Variable-Speed Pumps

The aim of the algorithm developed for inverter optimization is to determine the values of the setting of each speed controller for the time horizon of a complete irrigation cycle, in order to minimize energetic consumption and with the constraint of satisfying the required pressure at every node in the system (7).

The objective function can be expressed as:

$$\min: f_1 = \sum_{p=1}^{N_P}\sum_{k=1}^{N_T} C_{e,k}\frac{Q_{p,k}H_{p,k}}{\eta_{p,k}}\Delta T_k \quad (9)$$

In (9), N_P is the total number of variable speed pumps, N_T is the total number of turns (there are usually 42 turns each lasting 4 hours, to complete a week), $C_{e,k}$ is the cost of energy at turn k, $Q_{p,k}$ and $H_{p,k}$ are the flow, head and efficiency of pump p at turn k, and ΔT_k is the duration of the turns.

VII. Application to a Real Network

The methodology has been applied to the system illustrated in Fig. 1. The network serves nearly 600 ha with a water demand of 500 l/s on average. To this end, five pumping wells are operated: three of them (Pump 1, Pump 2 and Pump 3 of Fig 1) are fixed speed pumps delivering water to a booster station (actually two equal pumps in parallel, R.1 and R.2) controlled by a variable speed drive, while Pump 4 and Pump San Giusto are operated with variable speed controllers. Objective of the study was to optimize the network operation in order to reduce energy costs.

The model of the network has been calibrated through a series of measurement campaigns of pressure and flow in some nodes (shown in Fig. 2). Table I and Table II report the maximum error between measured and calculated values.

The application of the multi-objective pressure management algorithm resulted in an optimal location of 7 closed gate valves and 2 pressure reducing valves, as illustrated in Fig. 3. In particular, such results have been obtained assuming the critical point in the system as depicted in Fig. 2, and a desired pressure range between 3.1 and 3.6 bar (actually not satisfied at present condition).

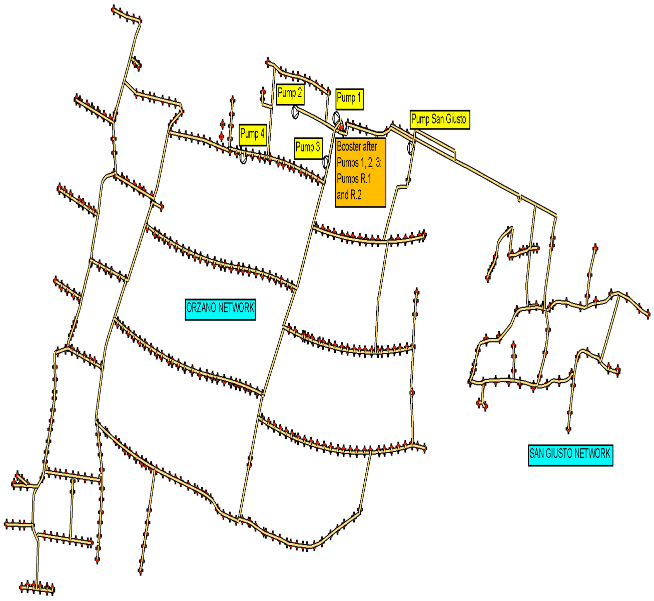

Fig. 1. Layout of the system under analysis. The booster pumping station after pumps 1, 2, 3 is made up of two equal pumps in parallel, named R.1 and R.2.

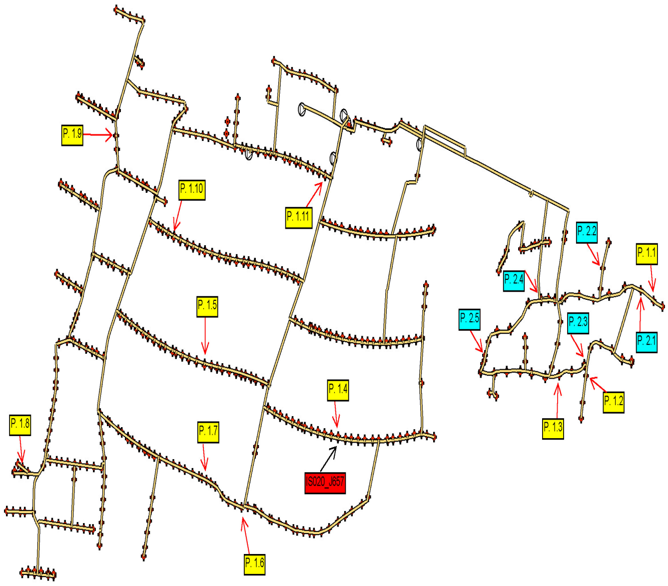

Fig. 2. Localization of pressure gauges for field surveys and of the critical node for orzano irrigation network (IS020_J657).

By critical point, we mean the hydrant in the network which is characterized by the lowest values of pressure, thus constraining the setting of pressure reducing and closed gate valves or the inverter operations.

Table III reports the values of pressure for the different turns at the critical point in the system, both for the present situation and after the proposed optimizations.

The application of the algorithm for the optimization of variable speed drive settings has lead to a 10% of savings in energetic consumption and operational cost, as reported in Table IV.

TABLE I: MAXIMUM DIFFERENCES BETWEEN MEASURED AND CALCULATED PRESSURES

Location	p^{meas} (bar)	p^{calc} (bar)	Location	p^{meas} (bar)	p^{calc} (bar)
P 1.1	4.8	4.6	P 1.9	5.5	5.6
P 1.2	4.8	4.9	P 1.10	5.1	5.3
P 1.3	4.7	4.8	P 1.11	5.3	5.5
P 1.4	5.1	4.8	P 1.12	3.0	2.9
P 1.5	5.2	5.1	P 1.13	3.0	2.9
P 1.6	4.9	5.1	P 1.14	3.0	3.1
P 1.7	4.6	4.9	P 1.15	3.8	3.6
P 1.8	5.5	5.4	P 1.16	4.1	3.8

TABLE II: MAXIMUM DIFFERENCES BETWEEN MEASURED AND CALCULATED PRESSURES AND FLOWS AT MAIN PUMPING STATIONS

Location	p^{meas} (bar)	p^{calc} (bar)	Q^{meas} (l/s)	Q^{calc} (l/s)
Booster after pumps 1,2,3	5.4	5.4	293	299
Pump 4	5.6	5.6	104	100
Pump San Giusto	5.0	5.5	57	56

TABLE III: VALUES OF PRESSURE FOR THE CRITICAL NODE IN THE SYSTEM (IS020_J657) AT PRESENT CONDITION (p^{now}) AND AFTER THE PROPOSED OPTIMIZATIONS (p^{after})

Turn	p^{now} (bar)	p^{after} (bar)	Turn	p^{now} (bar)	p^{after} (bar)
1	3.5	3.3	22	4.0	3.6
2	3.9	3.6	23	3.6	3.2
3	3.8	3.6	24	3.9	3.4
4	3.9	3.6	25	3.7	3.3
5	3.9	3.6	26	3.6	3.1
6	3.9	3.6	27	3.6	3.2
7	3.9	3.6	28	3.6	3.3
8	3.7	3.5	29	3.6	3.1
9	3.7	3.3	30	3.6	3.2
10	3.7	3.3	31	3.7	3.2
11	3.7	3.4	32	3.7	3.4
12	3.7	3.5	33	3.7	3.4
13	3.7	3.4	34	3.6	3.2
14	3.7	3.5	35	3.6	3.4
15	3.7	3.3	36	3.6	3.3
16	3.7	3.3	37	3.7	3.5
17	3.7	3.3	38	3.7	3.5
18	4.0	3.6	39	3.7	3.6
19	3.8	3.4	40	3.7	3.6
20	4.0	3.5	41	3.8	3.6
21	3.9	3.5	42	3.6	3.3

TABLE IV: ENERGETIC CONSUMPTION AND ASSOCIATED COST FOR THE SYSTEM AT PRESENT CONDITION AND AFTER THE PROPOSED OPTIMIZATIONS

Condition	Present	After optimizations
Energetic consumption (kWh/week)	114253	103156
Energetic cost (€/week)	18280	16505

Fig. 4 and Fig. 5 show, respectively, the flows and related heads through all the pumps at the present condition and after the proposed optimizations, for the different turns. From the comparison of the figures, it can be noted that a global saving in flow and head is achieved.

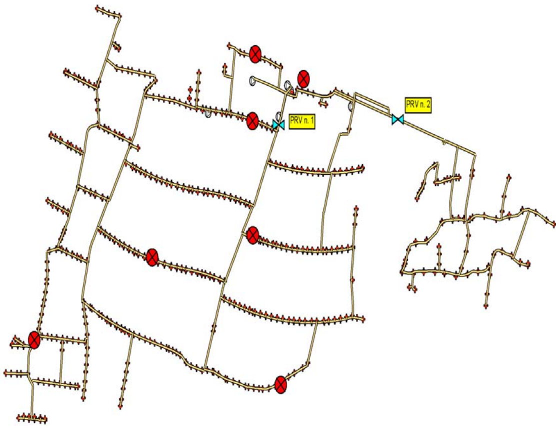

Fig. 3. Optimal locations for 7 closed gate valves and 2 pressure reducing valves as found by the multi-objective genetic algorithm.

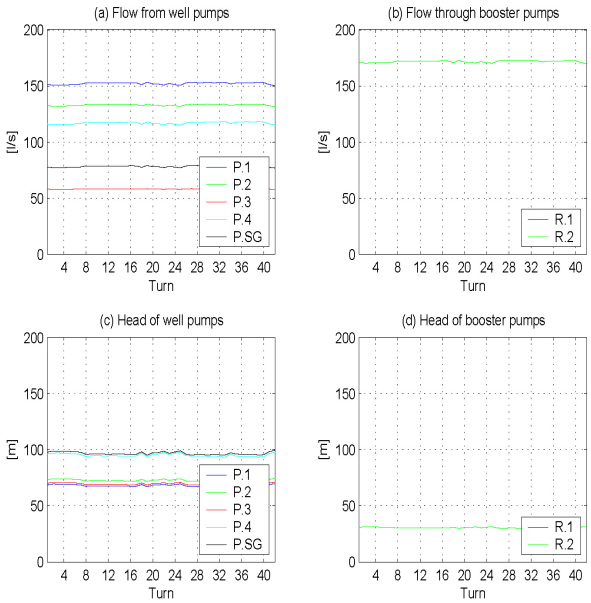

Fig. 4. Present condition: graphical representation of pump flows and heads with varying turn number.

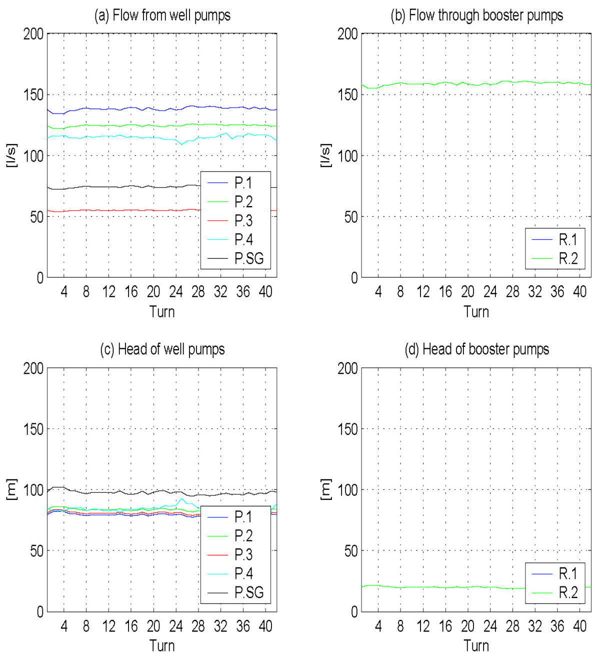

Fig. 5. After optimizations: graphical representation of pump flows and heads with varying turn number.

Concluding Remarks

The paper has presented a methodology for optimal management of sprinkle irrigation networks, based on a coupling between a calibrated model for system simulation and some optimization algorithms focused at the minimization of energetic consumption of pumping stations. The application of the multi-objective pressure management and of the algorithm for optimizing variable speed drive settings to a real system proved the effectiveness of the procedure.

Acknowledgment

The author wish to thank Dr. Massimo Canali, managing director of Consorzio di Bonifica Ledra-Tagliamento, for providing the support and the staff necessary for the measurement campaigns, which made possible the implementation of the whole project.

References

[1] P. Gleick, *The world's water*, Volume 7, Washington: Island Press, 2011.

[2] J. H. Holland, *Adaptation in natural and artificial systems*, Cambridge, Mass.: MIT Press, 1975.

[3] D. E. Goldberg, *Genetic algorithms in search, optimization, and machine learning*, Reading, Mass.: Addison-Wesley, 1989.

[4] Z. Michalewicz, *Genetic algorithms + data structures = evolution programs*, 3rd ed. New York: Springer, 1996.

[5] M. Michell, *An introduction to genetic algorithms*, Cambridge, Mass.: MIT Press, 1998.

[6] K. Deb, *Multi-objective optimization using evolutionary algorithms*, New York: Wiley, 2001.

[7] C. A. Coello Coello, D. A. Van Vendhuilzen, and G. B. Lamont, *Evolutionary algorithms for solving multi-objective problems*, Dordrecht, The Netherlands: Kluwer Academic, 2002.

[8] G. A. Walters and T. Lohbeck, "Optimal layout of tree networks using genetic algorithms", *Eng. Optim.*, vol. 22, no. 1, pp. 27-48, 1993.

[9] A. R. Simpson, G. C. Dandy, and L. J. Murphy, "Genetic algorithm compared to other techniques for pipe optimization," *J. Water Resour. Plann. Manage* vol. 120, no. 4, pp. 423-443, 1994.

[10] J. W. Davidson and I. C. Goulter, "Evolution program for the design of rectilinear branched distribution systems," *J. Comp. Civil Eng.*, vol. 9, no. 2, pp. 112-121, 1995.

[11] G. C. Dandy, A. R. Simpson, and L. J. Murphy, "An improved genetic algorithm for pipe network optimization," *Water Resour. Res.*, vol. 32, no. 2, pp. 449-458, 1996.

[12] D. A. Savic and G. A. Walters, "Genetic algorithms for least-cost design of water distribution networks," *J. Water Resour. Plann. Manage.* vol. 123, no. 2, pp. 67-77, 1997.

[13] D. A. Savic and G. A. Walters, "Evolving sustainable water networks," *Hydrological Sciences J*, vol. 42, no. 4, pp. 549-564, 1997.

[14] P. Montesinos, A. Garcia-Guzman, and J. L. Ayuso, "Water distribution network optimization using a modified genetic algorithm", *Water Resour. Res.* vol. 35, no. 11, 642-652, 1999.

[15] A. Babayan, Z. Kapelan, D. Savic, and G. Walters, "Comparison of two methods for the stochastic least cost design of water distribution systems," *Eng. Optim.*, vol. 38, no. 3, pp. 281-297, 2004.

[16] R. Olsson, Z. Kapelan, and D. Savic, "Probabilistic building block identification for the optimal design and rehabilitation of water distribution systems," *J. Hydroinf*, vol. 11, no. 2, pp. 89-105, 2009.

[17] D. Halhal, D. Walters, D. Ouazar, and D. Savic, "Water network rehabilitation with structured messy genetic algorithm," *J. Water Resour. Plann. Manage.* vol. 123, no. 3, pp. 137-146, 1997.

[18] P. B. Cheung, L. F. R. Reis, K. T. M. Formiga, F. H. Chaudry, and W. G. C. Ticona, "Multi-objective evolutionary algorithms applied to the rehabilitation of a water distribution system: a comparative study," in *Evolutionary Multi-Criterion Optimization*, C. M. Fonseca et al, Eds., LNCS 2632, New York: Springer, pp. 662-676. 2003.

[19] K. T. M. Formiga, F. H. Chaudry, P. B. Cheung, and L. F. R. Reis, "Optimal design of water distribution system by multi-objective evolutionary methods," in *Evolutionary Multi-Criterion Optimization*,

C. M. Fonseca et al, Eds., LNCS 2632, New York: Springer, pp. 677-691. 2003.
[20] B. A. Tolson, H. R. Maier, A. R. Simpson, and B. J. Lence, "Genetic algorithms for reliability-based optimization of water distribution systems," *J. Water Resour. Plann. Manage.* vol. 130, no. 1, pp. 63-72, 2004.
[21] T. D. Prasad and N. S. Park, "Multi-objective genetic algorithms for design of water distribution networks," *J. Water Resour. Plann. Manage.* vol. 130, no. 1, pp. 73-82, 2004.
[22] R. Farmani, D. A. Savic, and G. A. Walters, "Evolutionary multi-objective optimization in water distribution network design", *Eng. Optim*, vol. 37, no. 2, pp. 167-185, 2005.
[23] R. Farmani, G. A. Walters, and D. A. Savic, "Trade-off between total cost and reliability for Anytown water distribution network," *J. Water Resour. Plann. Manage.* vol. 131, no. 3, pp. 161-171, 2005.
[24] G. C. Dandy and M. O. Engelhardt, "Multi-objective trade-offs between cost and reliability in the replacement of water mains," *J. Water Resour. Plann. Manage.* vol. 132, no. 2, pp. 79-88, 2006.
[25] E. Keedwell and S. T. Khu, "A novel evolutionary meta-heuristic for the multi-objective optimization of real-world water distribution networks," *Eng. Optim*, vol. 38, no. 3, pp. 319-333, 2006.
[26] S. Sun, S. T. Khu, Z. Kapelan, and S. Djordjevic, "A fast approach for multi-objective design of water distribution networks under demand uncertainty," *J. Hydroinf*, vol. 12, no. 2, pp. 143-152, 2011.
[27] P. Montesinos, E. Camacho, and S. Alvarez, "Application of genetic algorithms for optimal seasonal furrow irrigation," *J. Hydroinf.* vol. 4, no. 3, pp. 145-156, 2002.
[28] J. Reca and J. Martinez, "Genetic algorithms for the design of looped irrigation water distribution networks", *Water Resour. Res*, vol. 42, W05416, 2006.
[29] Y. P. Mathur, G. Sharma, and A. W. Pawde, "Optimal operation scheduling of irrigation canals using genetic algorithm," *Int. J. Recent Trends in Eng*, vol. 1, no. 6, pp. 11-15, 2009.
[30] L. A. Rossman, *EPANET 2 Users Manual*, Cincinnati, OH: USEPA, 2000.
[31] M. Greco and D. Del Giudice, "New approach to water distribution network calibration," *J. Hydraul. Eng.*, vol. 125, no. 8, pp. 849-855, 1999.
[32] J. P. Vìtkovsky, A. R. Simpson, and M. F. Lambert, "Leak detection and calibration using transients and genetic algorithms", *J. Water Resour. Plann. Manage.* vol. 126, no. 4, pp. 262-265, 2000.
[33] R. W. Meier, and B. D. Barkdoll, "Sampling design for network model calibration using genetic algorithms," *J. Water Resour. Plann. Manage.* vol. 126, no. 4, pp. 245-250, 2000.
[34] A. Bascià and T. Tucciarelli, "Simultaneous zonation and calibration of pipe network parameters," *J. Hydraul. Eng*, vol. 129, no. 5, pp. 394-403, 2003.
[35] Z. Kapelan, D. A. Savic, and G. A. Walters, "Optimal sampling design methodologies for water distribution model calibration," *J. Hydraul. Eng.* vol. 131, no. 3, pp. 190-200, 2005.
[36] M. Nicolini, C. Giacomello, and K. Deb, "Calibration and optimal leakage management for a real water distribution network", *J. Water Resour. Plann. Manage.* vol. 137, no. 1, pp. 134-142.
[37] M. Wall, *GAlib: a C++ library of genetic algorithm components,* Mechanical Engineering Department, Massachussets Institute of Technology, 2000.
[38] M. Nicolini, "A two-level evolutionary approach to multi-criterion optimization of water supply systems," in *Evolutionary Multi-Criterion Optimization*, C. A. Coello Coello et al, Eds., LNCS 3410, Berlin: Springer-Verlag, 2005, pp. 736-751.
[39] M. Nicolini, and L. Zovatto, "Optimal location and control of pressure reducing valves in water networks," *J. Water Resour. Plann. Manage.* vol. 135, no. 3, pp. 178-187, 2009.
[40] M. J. H. Sterling and A. Bargiela, "Leakage reduction by optimized control of valves in water networks," *Trans. Inst. Meas. Control (London)*, vol. 6, no. 6, pp. 293-298, 1984.
[41] G. Germanopoulos and P. W. Jowitt, "Leakage reduction by excess pressure minimization in a water supply network," in *Proc. Inst. Civ. Eng. Part 2 Res. Theory*, vol. 87, pp. 195-214, 1989.
[42] P. W. Jowitt and C. Xu, "Optimal valve control in water distribution networks," *J. Water Resour. Plann. Manage.* vol. 116, no. 4, pp. 455-472, 1990.
[43] K. S. Hindi and Y. M. Hamam, "Locating pressure control elements for leakage minimization in water supply networks: an optimization model", *Eng. Optim*, vol. 17, pp. 281-291, 1991.
[44] K. Vairavamoorthy and J. Lumbers, "Leakage reduction in water distribution systems: optimal valve control," *J. Hydraul. Eng.* vol. 124, no. 11, pp. 1146-1154.
[45] J. M. Alonso et al, "Parallel computing in water network analysis and leakage minimization," *J. Water Resour. Plann. Manage.* vol. 126, no. 4, pp. 251-260, 2000.
[46] D. A. Savic and G. A. Walters, "An evolution program for optimal pressure regulation in water distribution networks," *Eng. Optim.* vol. 24, pp. 197-219, 1995.
[47] L. F. R. Reis, R. M. Porto, and F. H. Chaudry, "Optimal location of control valves in pipe networks by genetic algorithms," *J. Water Resour. Plann. Manage.* vol., 123, no. 6, pp. 317-326, 1997.
[48] K. Deb, A. Pratap, and S. Agarwal, "A fast and elitist multi-objective genetic algorithm: NSGA-II," *IEEE Trans. on Evolutionary Computation*, vol. 6, no. 2, pp. 182-197, 2002.

M. Nicolini is Assistant professor of Hydraulic Engineering at University of Udine (Italy), Faculty of Engineering. He graduated in Civil Engineering at University of Padova and obtained a PhD at University of Udine. His main research field is focused on the modeling and optimization of water distribution and collection systems, through a coupling between simulation models and evolutionary optimization algorithms. He has ongoing collaborations with Prof. Zoran Kapelan from University of Exeter – Centre of Water Systems and Prof. Kalyanmoy Deb from Indian Istitute of Technology – Kanpur (India). He is an independent referee for the Royal Society of London (Leverhulme Royal Sociaty Africa Awards) and is reviewer of a number of scientific Journals (Journal of Hydroinformatics, Water Resources Management, European Journal of Operations Research, Acta Mechanica, Journal of the Taiwan Institute of Chemical Engineeers) and member of the scientific committee of several international conferences. He worked at Italian Consorzio Pisa Ricerche as a numerical modeler and is also active as a consultant for many private and public water utilities.