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Hybrid optimization proposal for the design of collective on-rotation operating irrigation networks

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Abstract

Hybrid models have been used in many engineering applications in order to find better solutions and to reduce project costs. In this paper a methodology for the optimal design of collective working shift irrigation systems is proposed. The proposal is based on a hybrid model of optimization, which includes Linear Programming (LP) and Genetic Algorithms (GA). The method is applied to an irrigation network to check its effectiveness to minimize the total investment costs for pipelines. The results are compared to another hybrid model for optimization, which is based on Nonlinear Programming (NLP) and GA. The advantage of the developed method is a more cost effective design using discrete pipeline diameters.

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Keywords: Collective irrigation networks, irrigation on-rotation, optimal network design, optimization, genetic algorithms

1. Introduction

Irrigation systems are instrumental solutions for the growing food demand worldwide. Design, management and operation of these systems are fundamental for a rational use of water, for economic development in agriculture and for environmental sustainability [1]. Advanced technical irrigation systems facilitate the operation and make the service more efficient. However, one important decision parameters for these systems is the economic aspects. The

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design of Pressurized Collective Irrigation Networks (PCINs) is of special interest in the agricultural sector, because they are suitable for high crop production concurrently with reductions in investment and operating costs, as well as to mitigate environmental and social impacts [2]. The implementation of working shift on-rotation irrigation systems in PCINs has been strengthened due to its simplicity in operation and economy, especially in small farms with high dispersion of hydrants, irregular plots and topography [3]. However, this practice includes an additional variable compared to irrigation demand system, which must be considered in the design of the network, namely the allocation of working shifts for each hydrant. The model input data are the costs of the pipelines (locally available), the network topology and the hydraulic requirements. The output data are the lengths of the pipes at each branch of the network, the operating pressure at the head of the network, the total investment costs and the working shifts assigned to each hydrant. For a feasible model run the speed range of the flow inside the pipes has to be established to prevent sedimentation and scour, as well as the pressure range set for each hydrant. The objective of the proposed methodology is to reduce the total investment costs for pipelines of working shift on-rotation irrigation systems.

The paper is structured as follows: In section 2 a brief introduction of hybrid models implemented in hydraulic engineering and their importance is given. Section 3 presents general applications of hybrid models in working shift on-rotation irrigation systems. Section 4 describes the components of the proposed hybrid model and its architecture. In section 5 the implementation of the hybrid model is explained and in section 6 the model is applied to a case study. The paper ends with general conclusions.

Nomenclature

C_T	total investment costs of the network [$]
i	pipe number
C_i	pipe unit price [$/m]
$L_{i,j}$	length of the path sections and diameter corresponding to section j [m]
j	section number
$S_{0,n,k}$	set of lines belonging to the path between nodes 0 and n (in the turn k)
$hf_{i,k}$	head losses in the set of lines belonging to the path (in the turn k)
$\Delta H_{0,n,k}$	maximum allowable head loss between node 0 and node n [m]
ND	number of sections in line i

2. Hybrid models

Applying hybrid models have solved many problems in hydraulic engineering and water management. One type of hybrid model combines artificial neural networks with the continuity equation. Thus, the prediction of the discharge downstream a river system is possible [4]. Other hybrid models are used to predict the outflow of pressurized hydrocarbon pipes by coupling numerical solution techniques with hydraulic flow models [5]. In the area of irrigation networks hybrid models are implemented to minimize power consumption of the working shift hydrants by combining Dynamic Programming (DP) and Genetic Algorithms (GA) [6]. Another application in this area is the allocation of the working shifts to different hydrants, looking for the most cost effective option by means of GA [7]. Finally, hybrid models are used to minimize the total investment costs of working shift PCINs using Nonlinear Programming (NLP) and GA [8].

3. Working shift on-rotation irrigation system

The development of algorithms for working shift on-rotation irrigation networks is important, due to the improvement of the flow circulation in the pipelines. It offers a reduction of total investment costs for irrigation networks [9], because all designed flow at each section are taken into account for the total downstream discharge. The flow in each section is equal to the total consumption of all hydrant downstream, considering the assigned irrigation time.

The number of working shifts for irrigation depends on the EOT (Effective Operation Time) [10]. The EOT for reservoir networks is longer compared to pump networks, because no time restrictions for operation must be considered, due to their independency from electric power. However, the duration of EOT has to be sufficient to irrigate with all working shift hydrants below the required water pressure and quantity [11].

4. Components and architecture of the proposed system

Two major components are part of this hybrid model: "Linear Programming" (LP) and "Genetic Algorithms". The optimization algorithm, developed through LP, calculates the minimum investment costs for pipe diameters. The implementation of GA generates the ideal number of working shift hours for each hydrant. The process is detailed in the next subsections.

4.1 Linear Programming (LP)

Before implementing the LP algorithm, preliminary work has to be done. Therefore, the following basic data is needed:

- Definition of agronomic variables
- Determination of working shifts, location of hydrants and network layout
- Calculation of discharge per section
- Development of the network topology
- Calculation of the hydraulic gradients for each pipe diameter, section and hydrant
- Determination of minimum and maximum speed range during the working shift at each section
- Calculation of hydraulic losses per section

Then, the LP can be implemented, considering that each pipeline section is divided in two sectors. The advantage of using LP consists in the determination of optimal discrete pipe diameters for the whole network [12], which are locally available. The performance of the algorithm is tested for water pressure and quantity at each hydrant.

The main input data of LP are:

- Speed restrictions: Minimum flow is determined by the maximum pipe diameter and maximum flow by the minimum pipe diameter.
- Pressure restrictions: Maximum pressure depends on the altitudinal level of the reservoir above the irrigation network.

4.2 Genetic Algorithm (GA)

This optimization method analyzes all feasible solutions respective to cost reduction in pipelines [13]. First, the algorithm calculates the optimal working shift for each hydrant. Then, by means of this allocation, GA includes all available pipeline diameters to optimize the investment cost for each section of the network. This process is repeated continuously until the most cost effective design is obtained (see Fig. 1) considering water pressure and quantity at each hydrant [14].

The main input data of GA are:

- Total number of hydrants
- Covered area of each hydrant

- Water pressure and quantity at each hydrant

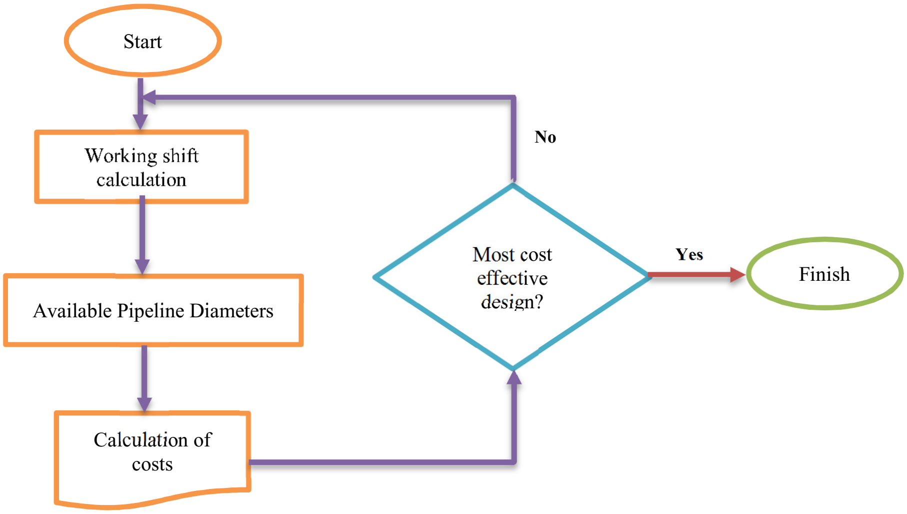

Fig. 1. Flowchart of the hybrid optimization model.

The results are compared to a hybrid model using Nonlinear Programming and Genetic Algorithms, where the decision variable (pipeline diameters) is continuous, which may not be locally available, in contrast to the developed model using LP and GA (discrete diameters). The sequence of the developed model is described in more detail in [8].

5. Optimization Model

The optimization model for of working shift on-rotation irrigation systems using LP and GA estimates the most effective total investment costs for the whole network and the optimal number of working shifts for each hydrant. The estimation is based on the following equation:

$$C_T = \sum_{i=1}^{L} \sum_{j=1}^{ND} C_j . L_{i,j} \,. \tag{1}$$

For an optimal design three additional parameters have to be defined, considering multiple working shifts and an irrigation network recharged by reservoirs, which are installed at a known altitude (system pressure).

a) Minimal loss of hydraulic load

$$\sum_{i \in S_{0,n,k}} hf_{i,k} \underset{T}{=} \sum_{i \in S_{0,n,k}} \sum_{j=1}^{ND} j_{i,j,k} . L_{i,j} \le \Delta H_{0,n,k} \ \forall \text{ turn } k \text{ and node } n \,. \tag{2}$$

b) Geometric condition

$$\sum_{j=1}^{ND} L_{i,j} = L_i \; \forall \text{ line } i \,. \tag{3}$$

6. Case Study

To test the cost effectiveness of the developed optimization method, an irrigation network installed in the Tuncarta community (150 users) was selected. The irrigation system covers an area of 114 ha, which is watered by 84 hydrants. The EOT is 18 hours, divided in three working shifts; Fig. 2. shows the topology of the network.

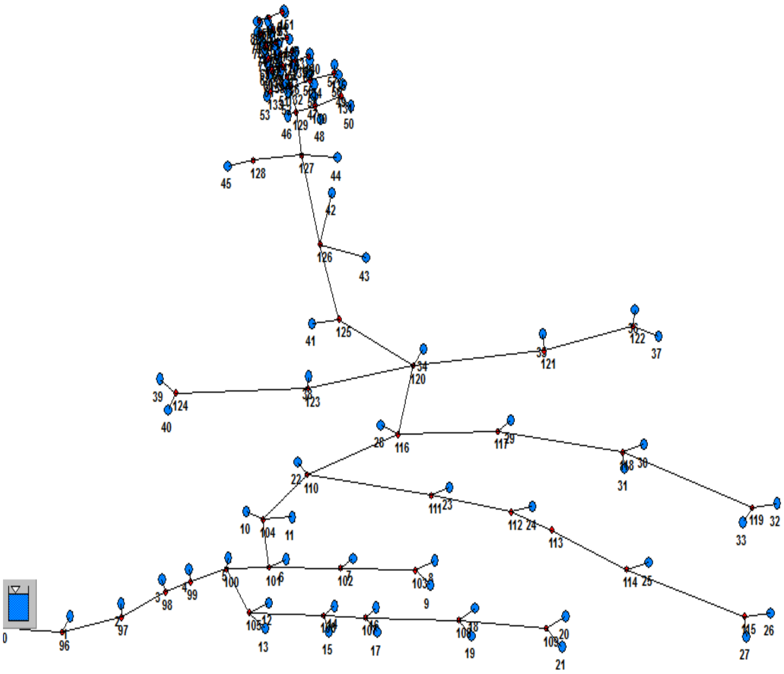

Fig. 2. Irrigation system topology in the Tuncarta community.

After running the model (LP and GA) the optimal pipeline diameters are obtained. In Fig. 3. the calculated percentages of each pipe diameter for the irrigation system are shown (blue line, LPGA) and compared to a nonlinear model (NLP and GA, green line, NLPGA).

It can be seen that the LPGA solution presents a lower percentage of pipe diameters corresponding to 50mm, 63mm, 110mm, 125mm and 160mm; higher percentages are obtained for pipe diameters of 25mm, 32mm, 40mm, 75mm and 140mm. This results in different total investment costs for the irrigation system, which are displayed in Fig. 4.

It is obvious that the LPGA model provide a more cost effective design compared to the NLPGA model. The total investment costs of the irrigation system can be reduced by about 12%, because of the higher percentage of small pipe diameters. Beside this, the LPGA model calculates discrete pipe diameters, whereas the NLPGA model continuous pipe diameters, which must be adjusted to the closest local available pipe diameter.

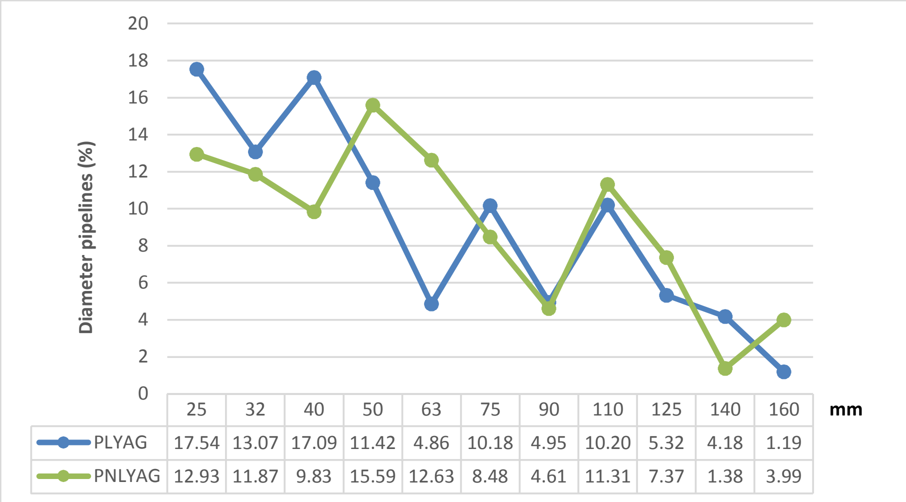

Fig. 3. Percentages pipe diameters suggested from LPGA (blue) and NLPGA (green).

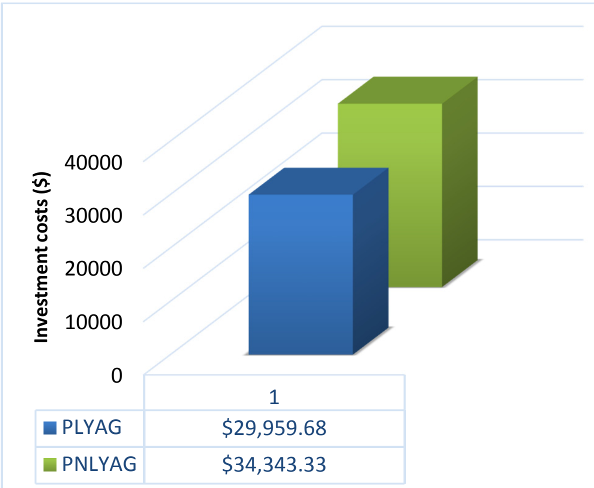

Fig. 4. Total investment cost for the irrigation system based on the LPGA model (blue) and the NLPGA model (green).

7. Conclusions

The developed hybrid model, LPGA, offers lower total investment cost for PCINs compared to the NLPGA model. Furthermore, the LPGA uses discrete pipe diameters, which comply with the initially imposed speed ranges of the model and allows a proper functioning of the network. In summary, this application optimizes the design of PCINs and reduces the economic and environmental impacts.

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