Optimization of Tree Pipe Networks Layout and Size, Using Particle Swarm Optimization

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Abstract: A commonly used design method for irrigation pipe network (IPN) layout and size often involves trial and error approach. This makes it difficult to minimize capital investment and energy cost. Objective of this study was to optimize simultaneously size and layout of the irrigation pipe networks using particle swarm optimization (PSO) technique. This technique was linked to the MATLAB software to reduce the pipeline investment cost in irrigation projects. The Pipe layout and size optimization model for a tree irrigation pipe network are therefore, presented in this paper. The performance of PSO technique was tested and results were compared with non-optimized (Step-by-step) and genetic algorithm optimization methods. The proposed PSO technique with an increase in the search space showed a quick response in the size of the swarm and the initial swarm compared to the non-optimized (Step-by-step) design method and genetic algorithm.

Key words: Irrigation; Tree pipe network; Particle swarm optimization (PSO); Investment cost; non-optimized (Step-by-step)

1 Introduction

Optimal design of the irrigation pipe network (IPN) is defined as a selection of combination of discrete pipe size at minimum possible cost without violating the specified constraints. The primary objective of the IPN design is to optimize size of the pipes and their associated costs [25]. However, small-scale irrigation has been popularly adopted by farmers and considered as a supplementary production strategy to overcome the low agricultural production. One of the difficulties is the high cost of water pumping due to lack of appropriate irrigation scheduling system [36].In addition; it is possible to optimize an on-demand network layout by selecting the layout and the economic pipe sizing simultaneously [3]. IPN optimization is a big multidisciplinary work taking into account reliability, hydraulic, and availability requirements. The reliability requirement is mainly addressed by taking into account looped (tree), fixed, and network layout to be designed [28], [35]. The layout optimization problem for tree networks has obtained less consideration because of its complication [2], [25]. The purpose of a pipe network's layout is highly dependent on considerations of reliability [2]. Among the IPN distribution systems, the pressurized systems have been built up and widely used over the last decades with noticeable advantages [17]. However, the simulation of the hydraulic behavior of water pipe network in which pressurized water is supplied is not a simple work. Additionally, the optimal network design is quite intricate and this is due to the nonlinear relationship between head loss and flow and the presence of discrete variables, like market sizes of pipes [14],[22].

1.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) algorithm is a stochastic optimization approach used to discover the search space of a given problem. Kennedy and Eberhart first published this technique in (1995) [13][15],[16],[34]. The technique was invented from the inspiration of swarm intelligence based off the scrutiny of swarming habits (birds flock and fish) trying to reach an unknown destination and the field of evolutionary computation. The first authentic concept of Kennedy and Eberhart's was to simulate the social behavior of a flock of birds in their endeavor to reach, when flying through the field (search space), their unknown destination (fitness function). However, in PSO, each problem result is a bird of the flock and is referred to as a particle [12], flies in the problem search space looking for the best possible position to land. Non-linearity and non-convexity of the problem domain are easier to be handled by using PSO, the search does not depend on initial population, and it may overcome the problem of trapping to local best that are common in some conventional non-linear optimization technique [9],[30].

The application of the PSO algorithm for IPN is relatively new. PSO algorithm is becoming more powerful due to its simplicity and easiness in implementation and its ability to converge quickly to a reasonably good solution [32]. PSO algorithm was used for optimal design problems with discrete variables for water supply system benchmark examples [4], [23]. Whereas the PSO algorithm shows a good results when applied to optimizing pump operations in water distribution systems [11], [20]. The complexity involved in the problem of IPN optimization is mainly due to the strong coupling between the pipe size and layout determination.

In this paper, the PSO algorithm with several changes was used to simulate the results for various optimization problems in IPN. PSO was used for simultaneous layout and pipe-size optimization of the IPN with a given level of reliability. The problem of least-cost layout and size design was developed. The application of PSO algorithm to the problem was also described. The necessity of a combined solution of the layout and pipe-sizing problem is explained. A model of the irrigation pipe collection network was used to demonstrate the algorithm performance and the achieved results was compared with those given by using a genetic algorithm (GA) and non-optimized (Step-by-step) design method to solve the same problem under the same conditions. Lastly, the applicability of the model for the optimization of the IPN layout with predefined reliability was illustrated by testing of the technique against a benchmark example in the literature. However, the most common benchmark problems in water distribution system design, are not typical real systems [29].

2 Optimization Model

In general, the pipes network problems are complex and trial solutions are required. Therein basic circuits are balanced in turn until all conditions for the flow are satisfied. Irrigation pipe network (IPN) structure includes valves, a hydrant, pumps, pipes, and water sources connected in series or parallel to each one to transfer water from the sources to the farmers. The IPN is developed as a least-cost optimization problem in which the pipe sizes are used as the decision variables, as well as the pipe layout and its nodal demand, connectivity, and minimum head requirement. The pipe layout including all the links within the networks is shown in Fig.1.

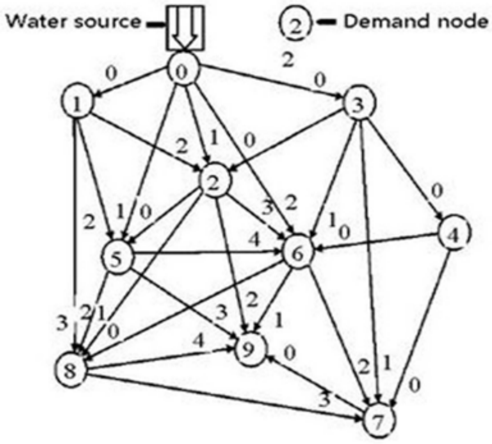


Fig.1 The pipe layout included all the links within the networks [7]

Simultaneous optimization of the network layout and the economic pipe size are included to outline the optimum branched irrigation network and its pipe size using the particle swarm optimization (PSO) technique. The network is obtained by considering the possible alternatives of branched irrigation networks, while taking into consideration the restrictions imposed by plot boundaries and gravel roads [3]. Therefore, non-outflow nodes of the networks were formed using Fig.1 that shows the maximum layout of the network. The correct lengths of the pipelines and the topography level of the nodes were carefully taken into considerations. The irrigation networks used have been traditionally utilized in the literature and provide a classified and elucidated environment to accomplish a large area of test and analyses. Hence, in order to expedite the comparison with results obtained by previous authors and to establish the objective function of the pipe network with minimal investment, we make use of the following objective function to calculate roughly the entire cost of the tube network.

$$\text{Min Z} = \sum_{i=1}^{N}(a + bD_i^c)L_i + \text{P} \qquad (1)$$

where: *Z* is the total investment cost of the pipe network (*CNY*= Chinese Yuan Renminbi); *N* is the number of existing pipes; *Li* and *Di* =Length (*m*) and Diameter (*mm*) of ith pipe; *a*, *b*, *c*, represent the pipeline cost coefficient and an index, respectively. The penalty *P* only applies when the pressure in any node is less than a predetermined minimal value [23].

For nodes with pressures larger than this minimal value, the associated individual penalties vanish, and one uses the usual Heaviside step function *H* in the explicit expression for *P*: [23].

$$P = \sum_{i=1}^{N} H\left(P_{\min} - P_i\right).P.\left(P_{\min} - P_i\right). \qquad (2)$$

In this model, the individual penalties grow linearly with Δpi. The factor *P* multiplies with the pressure difference $\Delta pi = p_{\min} - p_{\text{i}}$ represents a fixed value which becomes effective whenever the minimal pressure requirement is not met [24]

2.1. Pressure Constraints:

To guarantee the supply of minimum pressure to each node in the network, the pressure elevation (*gi*) was set to be higher than the pressure level of service nodes as shown in (3).

$$g_i = E - \sum_{j=1}^{I_i} \alpha f \frac{Q_{ij}^m}{D_{ij}^n} L_{ij} - E_i - H_i^{\min} \geq 0 \qquad (3)$$

where *E* is the water surface elevation (*m*), *α* is the head loss coefficient, *f* is the coefficient related to frictional resistance, *m* is the index of discharge, *n* is an index of pipe diameter. *I* is the number of pipelines from the premises by the water flow to the earth water demands nodes. Q_{ij} is the designed flow where the water flows from the source to a node *i* through *jth* (*m/s*). *Dij* the diameter of pipe *i*, which the material is selected from number *j* (*mm). Lij* the pipe's length where the water flows from source to a node *i* (*m*), *Ei* is the elevation of node *i* (*m*), *Hi* the required minimum hydraulic head of node *i* (*m*).

2.2. Velocity Constraints:

$$V_{\min} \leq V_i \leq V_{\max}, \qquad i=1\ldots,N \qquad (4)$$

where $V_{\min}$, $V_{\max}$ is the allowable minimum and maximum pipe velocity (*m/s*);

2.3. Diameter Constraints:

The diameter of each pipe was chosen from the commercially available pipe sizes:

$$D_i \in \left[d_1, d_2, \ldots, d_M\right] \forall i\theta \qquad (5)$$

where D_i is the diameter of pipe *i*; *M* is the number of available pipe sizes; d_1, $d_2 \ldots$ d_M. Is the commercially available pipe diameter (*mm*)

3 The Particle Swarm Optimization Modelling

Swarm particles are initialized with particles at random positions and the optimum solution of the problem through the generation can be found by exploring the search space to find better solutions. In both iterations, each particle adjusts its velocity to follow solutions. The first part is cognitive; at this time particle follows its own best solution found so far. The solution produces the lowest cost (highest fitness), the value is called pBest (particle best). The additional best value is the current best solution of the swarm, which is the best solution by any particle in the swarm; this value is called gBest (global best).

The PSO algorithm merges local search method with global search methods, attempting to balance exploration and exploitation. A particle status of the search space is portrayed by its position and velocity [26]. In addition, PSO algorithm Pseudo code is presented in Fig 2.

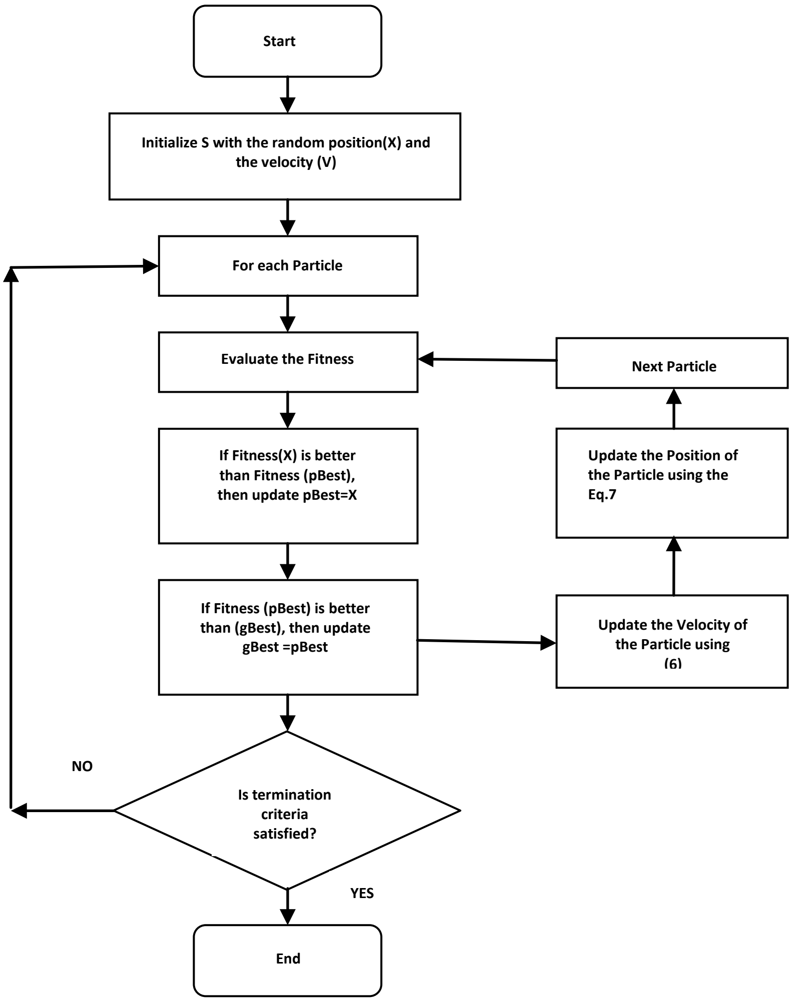


Fig. 2 showing the principle of the Particle swarm optimization process

Therefore, every particle adjusts its velocity and position using the following two equations [33], [37].

$$V_i^{iter+1} = x(wV_i^{iter} + c_1 r_1^{iter}(P_i^{iter} - X_i^{iter}) + c_2 r_2^{iter}(P_g^{iter} - X_i^{iter})) \tag{6}$$

$$X_i^{iter+1} = X_i^{iter} + V_i^{iter+1} \tag{7}$$

where i =1, 2, 3… N is the size of the swarm; c_1 and c_2 are positive constants termed as acceleration constant. If a better global exploration is required, high values of c_1 and c_2 provides new points in relatively distant regions of the search space. r_1 and r_2 are evenly distributed random numbers in the interval of (0,1) [2], w is the inertia weight and X is a constricting factor which is used alternatively to limit velocity. V_i^{iter} , X_i^{iter} and V_i^{iter+1}, X_i^{iter+1} stand for the velocity and position vectors of particle i, in iteration $iter$ and $iter + 1$ respectively; pBest is the best position vector that particle i is found. Whereas gBest shows the corresponding best position found by the whole swarm.

The new velocity of the particle is computed by using (6). It is due to the previous velocity and the distance of its current position from its own best position and the group's best position. A PSO algorithm for velocity change is presented in Fig 3.

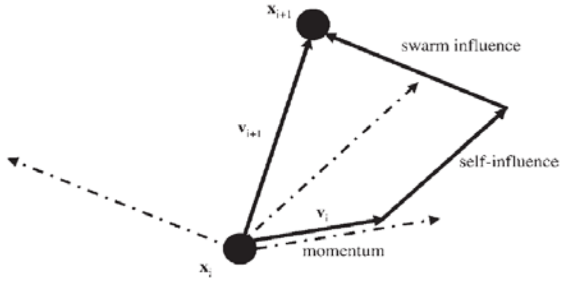


Fig. 3 A graphical representation of PSO algorithm for velocity and position change

The function of inertial weight w in (8) is to control the impact of the current velocities on the previous velocity. In order to facilitate global exploration of the search space, inertia weight is supposed to be set to an initial large value, that gradually decrease it to get solutions that are more advanced, because the small weight tends to promote local exploration. There are some important developments made on the PSO performance through a linearly varying inertia over the iterations, which linearly vary from w_{max} at the start of the search to w_{min} at the end of the search [19], [37]. In a mathematical framework, inertial weight w is presented as in (8) below:

$$w = \frac{\max iter - iter}{\max iter} \tag{8}$$

where *maxiter* is the maximum number of allowable iterations and *iter* is the current iteration number [31].

3.1 Integer Coding

This multivariable constrained optimization problem uses the PSO and genetic algorithm to carry out optimization. Simultaneously considering the pipe layout and diameter, in Fig.4 the integer method is used to code with the water demand node as its basis.

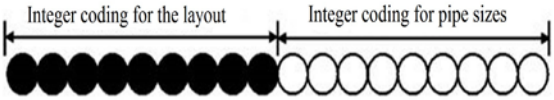


Fig. 4 A typical code networks with the water demand node

The front and end parts of the code respectively specify for codes and the pipe diameter for the water supply pipelines of every water demand node, where the length of two ends of the code is the number of water demand nodes. The number of pipes that are initially directed at the node within the connection layout to supply water determines the range of values of the segment of the code for pipe layout. Taking Fig. 1 as an example, the second position gene of the pipe layout segment can be represented by the integers (0, 1, 2), if integer 2 is chosen then this means that the pipe segment that is coded as 2 supplies water to node number 2.

Table 2.The 11 commercial pipe data for the IPN that includes

Pipe	Tube Length(*m*)	Diameter (*mm*)	Cost (*CNY*/*m*)
1	154	50	381.92
2	92	75	334.88
3	88	90	382.80
4	76	110	456.96
5	144	125	1036.80
6	166	140	1425.65
7	84	160	895.42
8	140	180	1817.77
9	60	200	933.54
10	86	225	1644.87
11	90	245	2003.17

Based on standardization, the way in which there is monotonous decrease or increase in the pipe diameter, an integer code can be used to represent the pipe diameter. However, the pipe diameters are considered the design parameters that have been chosen from a set of commercially available diameters shown in Table 2 above. Hence, the pipe diameter code can take any integer between the ranges of 0 to 10. The code(0,2,0,0,2,3,2,3,1,7,6,3,1,2,4,2,0,1) represents the pipe layout as shown in Fig.5.

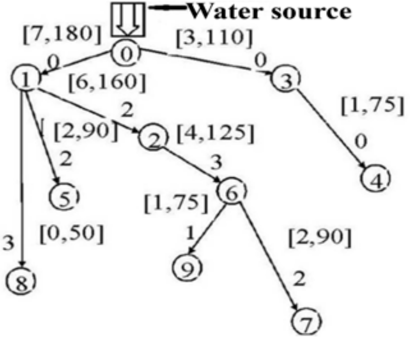


Fig. 5 Pipe network layout showing [Integer codes, Diameter/mm]

Therefore, with water demand nodes as the basis, integer codes are used to show that pipe layout and the diameter can cause the pipe to satisfy connectivity, single node water supple restriction, as well as guaranteeing that the chosen pipeline has a standardized diameter. It also overcomes the coding redundancy and easily produced non-feasible solutions of binary coding and deals with low efficiency and other faults

3.2 Decoding of Water Flow Rates

We use Equation 1 to calculate *Li*, *Di*. However *Ei* and *Hi* from Equation 3 are already known, while *Qij*, *Dij*, *Lij* are the water flow, pipe diameter and pipe length respectively of the j^{th} pipe that provide water to the i^{th} water-demand node from the water source. Due to the continuous change of the flow rate going to each water-demand node, determination is somewhat difficult, in the process of heredity optimization. Therefore, it is necessary to employ the computer that automatically distinguishes corresponding water paths based on the pipe network's arrangement and pipe diameter code of the genetic algorithm. Fig. 6 explains how the flow in the water supply pipe using different pipe networks is derived.

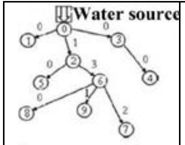
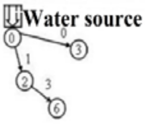
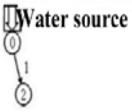
 **1-a**	 **1-b**	 **1-c**	 **1-d**
Water demand node =[1,2,3,4,5,6] Water supply node =[0,0,0,3,2,2,6,6,6] Q=[25,25,30,30,30, 25,25,25,25] Logging matrix =[-1,2,3,-1,-1,6,-1,-1,-1] **2-a**	**Water demand node =[2,3,6] Water supply node =[0,0,2] Q=[25,55,60,30,30,100,25,25,25] Logging matrix=[2,-1,-1]** **2-b**	**Water demand node =[2] Water supply node =[0] Q=[25,150,60,30,30,100,25,25,25] Logging matrix=[-1]** **2-c**	**Water demand node =[] Water supply node =[] Q=[25,150,60,30,30,100,25,25,25] End .** **2-d**
$\begin{bmatrix} 1&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 2&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 3&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 4&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 5&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 6&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 7&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 8&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 9&-1&-1&-1&-1&-1&-1&-1&-1&-1 \end{bmatrix}$ **3-a**	$\begin{bmatrix} 1&0&-1&-1&-1&-1&-1&-1&-1&-1\\ 2&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 3&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 4&3&-1&-1&-1&-1&-1&-1&-1&-1\\ 5&2&-1&-1&-1&-1&-1&-1&-1&-1\\ 6&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 7&6&-1&-1&-1&-1&-1&-1&-1&-1\\ 8&6&-1&-1&-1&-1&-1&-1&-1&-1\\ 9&6&-1&-1&-1&-1&-1&-1&-1&-1 \end{bmatrix}$ **3-b**	$\begin{bmatrix} 1&0&-1&-1&-1&-1&-1&-1&-1&-1\\ 2&-1&-1&-1&-1&-1&-1&-1&-1&-1\\ 3&0&-1&-1&-1&-1&-1&-1&-1&-1\\ 4&3&0&-1&-1&-1&-1&-1&-1&-1\\ 5&2&-1&-1&-1&-1&-1&-1&-1&-1\\ 6&2&-1&-1&-1&-1&-1&-1&-1&-1\\ 7&6&2&-1&-1&-1&-1&-1&-1&-1\\ 8&6&2&-1&-1&-1&-1&-1&-1&-1\\ 9&6&2&-1&-1&-1&-1&-1&-1&-1 \end{bmatrix}$ **3-c**	$\begin{bmatrix} 1&0&-1&-1&-1&-1&-1&-1&-1&-1\\ 2&0&-1&-1&-1&-1&-1&-1&-1&-1\\ 3&0&-1&-1&-1&-1&-1&-1&-1&-1\\ 4&3&0&-1&-1&-1&-1&-1&-1&-1\\ 5&2&0&-1&-1&-1&-1&-1&-1&-1\\ 6&2&0&-1&-1&-1&-1&-1&-1&-1\\ 7&6&2&0&-1&-1&-1&-1&-1&-1\\ 8&6&2&0&-1&-1&-1&-1&-1&-1\\ 9&6&2&0&-1&-1&-1&-1&-1&-1 \end{bmatrix}$ **3-d**

Fig.6 Finding the flow rate (discharge) using different pipe networks

The pipe network arrangement and initial water-demand node matrix of the structure is (1,2,3,4,5,6,7,8,9) and the corresponding water-supply node matrix is (0,0,0,3,2,2,6,6,6). Based on each node's required amount of water, the initial water flow rate of each water-supply pipe is (25, 25, 30, 30, 30, 25, 25, 25, 25) as shown in Fig. 6-2-a. The nodes that have not appeared in the water-supply node's are found in the water-demand node's matrix, this would be (1,4,5,7,8,9) and is the final-stage water-demand node (end nodes). -1 is used to replace the end node in the water-demand node matrix to obtain the logging matrix (-1, 2,3,-1,-1,6,-1,-1,-1) as shown in Fig. 6-2-a. Depending on the previous logging matrix's value of -1, the corresponding water-supply node matrix is found (0, 3, 2, 6, 6, 6). In Fig. 6-2-b any non-zero value of this matrix means that, node is not a water source as such the water flow of this final-stage water-demand node is transferred to the upper level pipe to obtain a new flow matrix. The -1 number is found in the logging matrix, the corresponding numbered nodes of the end node matrices are deleted Fig 6-2-b to obtain new water-demand and water-supply node matrices. The water supply path after simplification is shown in Fig 6-1-b. Thereafter, based on the water-demand and water-supply node matrices that have undergone simplification, the above process is repeated until the water demand and supply node matrices become empty matrices, then the flow matrix of the pipe that supplies water to each node can be obtained, as shown in Fig. 6-2-d. Thus, the water flow rate matrix of each pipe when irrigation pipe network are arranged is derived. Based on water demand and supply node matrices that have been simplified, the above process is repeated and therefore, the water flow path matrices of each stage in the process of simplification are obtained, as shown in Fig. 6-3-b, c, and d. The final water-supply point is the water source node 0.Thus, the flow path of water supplied to each water-demand node is derived as shown in Fig.7.

$$\begin{bmatrix} 1 \leftarrow & 0 & & \\ 2 \leftarrow & 0 & & \\ 3 \leftarrow & 0 & & \\ 4 \leftarrow & 3 \leftarrow & 0 & \\ 5 \leftarrow & 2 \leftarrow & 0 & \\ 6 \leftarrow & 2 \leftarrow & 0 & \\ 7 \leftarrow & 6 \leftarrow & 2 \leftarrow & 0 \\ 8 \leftarrow & 6 \leftarrow & 2 \leftarrow & 0 \\ 9 \leftarrow & 6 \leftarrow & 2 \leftarrow & 0 \end{bmatrix}$$

Fig.7 The flow rate supplied to each water-demand node

Finally, the genetic code of the pipe network arrangement and pipe diameter is combined to determine the other parameters *Ii, Qij, Dij, Lij, Vi* of Equations (1), (3), (4), (5). However, in certain cases, it may turn out that the calculated discharge of a section serving five or six hydrants is below that of the downstream part serving four hydrants whose flows have been summed. Hence, the discharge in the upstream section will be the same as the discharge in the downstream section. Even though a farmer supplied by an on-demand system is free to use his hydrant at all time, a physical constraint is nevertheless inevitable regarding the maximum flow that can be drawn. This is accomplished by fitting the hydrant with a flow regulator (flow limiter)[18]

4 PSO Model Application and Results

The outcome of the PSO model for optimization of IPN is illustrated through the previous methods used for optimization of the irrigation networks in Danfeng County, which is in the Southeast of Shaanxi Province, China. In this design of IPN, an optimum network layout was used in order to minimize the entire cost of the network and calculate the optimum pipe size diameters to minimize the investments and energy cost. This will help to make comparisons with other methods. The cost of the pipes is determined simultaneously for both the network layout and pipe size. The pipe sizes are used as the decision variables, diameters are treated as discrete, due to the fact that is needed to be adjusted to the available commercial pipes. The cost of a completed pipeline unit price and pipe diameter fitting function is adopted using Equation 9. However, Table 3 shows the commercial pipe data for the IPN that includes the diameters, tube length of the pipes and the corresponding cost in *CNY*.

Table 3. The commercial pipe data for the IPN that includes the diameters, Tube length of the pipes and the corresponding cost in *CNY*

Pipe	Tube Length(*m*)	Diameter (*mm*)	Cost (*CNY/m*)
1	140	180	1817.20
2	84	160	895.44
3	76	110	456.96
4	92	75	334.88
5	88	90	382.80
6	144	125	1036.80
7	126	90	548.10
8	154	50	381.92
9	225	75	819.00

Furthermore, Table 3 displays the cost of the pipes obtained by means of the pipe cost fitting function a. The assumed Hazen William's roughness coefficient used is 130 [25] and that is used for all pipes.

$$S = 1.5 + 0.000537D^{1.92} \tag{9}$$

where; *S* is the pipeline unit price (*CNY* / *m*); and *D* pipe diameter (mm).

At the final stage, the total lowest cost is determined using the PSO algorithm done in MATLAB 7.11（R2010b）software. The technique used in this part of discrete variables involves the use of the integer part of the different components of velocities starting with a main network that have all the nodes included in the network shown in Fig.1. The branched irrigation pipe networks were given consideration to obtain the network. The improved PSO algorithm was used to enforce explicit constraints [5]. The improved version of the algorithm was used to avoid ramification that might have arise while considering complicated PSO algorithms. The algorithm was defined by using Equations (4), (6), (7) and (8). For descriptive purposes, the PSO model parameters given in Table 4 were considered all over the remainder of this article and *w* was calculated using Equation 8.

Table 4. The PSO model parameters

Parameter	Value
x	1
c_1	0.5
c_2	2.0
Violation tolerance	10^{-5}
Swarm size	3000
Particle Size	18

The adopted maximum velocity was 50% of the variable range and minimum velocity to minus maximum velocity [23][27]. The maximum number of iterations used was 60; nine demand nodes were included in IPN, nine pipes, and one source node. The algorithm took five (5) central processing unit (CPU) minutes on a Dell Inspiron computer. The

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