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SaDE algorithm for reliability-based design of water distribution networks

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Abstract: Design of Water Distribution Networks (WDNs) is an NP hard problem, which is typically an optimization problem consisting of a large search space even for a small sized WDN. Design of a robust WDN requires consideration of aspects such as reliability, resiliency etc., which further increases the complexity of the problem. This paper presents an efficient way of reliability-based design of WDNs using Self-adaptive Differential Evolution (SaDE) algorithm, which is an evolutionary optimization technique and an improvised version of the DE algorithm. The reliability of the WDNs is estimated as the level of demand satisfaction considering the mechanical failure of pipes. Simulations are performed using EPANET for generating the pressure and flow values using demand driven analysis, for various failure and working conditions. The efficacy of the proposed approach is tested by applying it to two WDN problems. A thorough comparison is made between the performance of SaDE and DE algorithms. It is found that the SaDE converges much faster than DE, with high success rate, thus making it a more preferable option for solving WDN design problems and for reliability-based design of WDNs.

Key words: Self-adaptive differential evolution; water distribution networks; reliability-based design; mechanical failure

1. INTRODUCTION

WDNs form an integral part of our day-to-day life and are vital infrastructures for human survival. The design of WDNs is essentially an optimization problem consisting of minimization of the cost of pipes subject to the constraints on satisfying the conservation of mass and energy equations, and minimum head requirements at various demands nodes. The WDN design is an NP hard problem, consisting of a large search space even for a small sized problem and the search space increases exponentially with the increase in the size of the WDN. Also, the design process requires discretizing the decision variables, since the practically available pipe diameters are discrete values. The simplest way of solving such problem is to consider all possible combinations of decision variables and determine the most suitable alternative considering the objectives and constraints. However, for large problems, this process becomes impracticable as the number of possible combinations increases exponentially with the increase in the number of decision variables. For robust design of WDNs, other aspects such as reliability subject to mechanical and hydraulic failures, resiliency etc., need to be incorporated in the design process. This makes the problem even more complex and computationally expensive. From past studies, it was noticed that different types of Evolutionary Algorithms (EAs) quite effectively solved the WDN design problems. These EAs include Genetic Algorithms (GA; Savic and Walters 1997; Vairavamoorthy and Ali 2000; Tolson *et al*. 2004; Prasad and Park 2004; Kadu *et al*. 2008), Ant Colony Optimization (ACO; Maier *et al*. 2003; Zecchin *et al*. 2007; Ostfeld and Tubaltzev 2008), Particle Swarm Optimization (PSO; Suribabu and Neelkantan 2006), Shuffled Frog Leaping Algorithm (Eusuff and Lansey 2003), Simulated Annealing (Cunha and Sousa 1999), and Differential Evolution (DE; Suribabu 2010) etc. In recent times, DE was emerging as a more efficient and preferable tool for solving WDN problems as it converges quickly and easy to implement (Suribabu 2010).

In the past, many studies were conducted to compare the performance of DE and other optimization techniques and it was found that DE performed better than GA (Ali and Torn 2004), PSO (Vesterstrom and Thomsen 2004), etc. Suribabu (2010) employed DE for the problem of least cost design of WDNs and found that DE performed distinctly better than GA and other heuristic algorithms and noted that DE can be a good alternative for solving WDN design problems. Vasan and Simonovic (2010) developed DENET for optimal design of WDNs and noted that the DE algorithm performed well by providing good solutions at a faster convergence rate. The performance of DE was also found satisfactory for the problem of resilience maximization. Dong *et al* (2012) compared the performance of DE with GA for the problem of least cost design of WDNs, and it was found that the success rate of DE is much higher than GA and is thus more reliable than GA. Thus, many studies have suggested that DE is a simple yet robust tool for solving WDN design problems. However, like many EAs, the key drawback of DE is that, the performance of the algorithm is dependent on the parameter values such as mutation and crossover factors. The most suitable values of these factors are problem dependent and require proper sensitivity analysis, which is a very time consuming process. In order to overcome this difficulty, recently few studies have proposed self-adaptive DE algorithms such as fuzzy adaptive DE (FADE; Liu and Lampinen 2005), Self-Adaptive DE (SaDE; Qin and Suganthan 2005), DE with Self-Adaptive Population (DESAP; Teo 2006), jDE (Brest *et al.* 2006) and Adaptive DE with optional external archive (JADE; Zhang and Sanderson 2009) etc. Among these algorithms, SaDE was found to be more effective in terms of obtained optimal solutions and convergence speed (Zhang and Sanderson, 2009), etc.

SADE is an improvised version of DE, in which the mutation and crossover factors are not fixed but are assigned to each individual of the population and are self-adapted by the algorithm itself based on values of the parameters that lead to successful trial vectors. This paper thus aims at employing the SaDE algorithm for the problem of reliability based design of WDNs and evaluating its performance by comparing with that of the DE algorithm.

In the present study, reliability is estimated considering the mechanical failure of pipes. Reliability is basically defined as the level of demand satisfaction in case of working and failure conditions, which are classified into two types: mechanical and hydraulic failures (Bao and Mays 1990). Mechanical failure of the pipes can occur due to various factors such as excessive internal pressure, corrosion, sudden failure of pump, external loadings etc. Various factors can be attributed to the rate of failure of pipes such as pipe diameter, age, length, material and previous breakage data. Pipe length, age and diameter are found to be the most influential parameters affecting future failure rates of pipes (Kettler and Goulter 1985). Various models have been developed for assessing the future failure rates of the components, such as neural networks (Achim *et al.* 2007), Bayesian Belief Network (Kabir *et al.* 2015). However, the relationships developed will vary with the study area and hence requires a detailed analysis based on previous breakage records (Asnaashari *et al.* 2013). The developed relationship will be useful in assessing the mechanical reliability of the network.

Mechanical failure of components leads to changed pressure and flow conditions inside the network, whereas hydraulic failure occurs due to the uncertainty in input parameters such as nodal demands and pipe roughness coefficients etc. The level of demand satisfaction in such situations is termed as the reliability of the WDNs. Reliability can be assessed in different ways. Shamir and Howard (1981), Su *et al.* (1987) and Fujiwara and Silva (1990) measured reliability as the shortfall due to failure of links. Bao and Mays (1990) considered the uncertainties in demand and roughness coefficients for estimating the reliability of the system. Shibu and Reddy (2014) considered fuzzy random demands for assessment of the reliability of the WDNs. Sirsant and Reddy (2017) adopted minimum cut set method for assessing the mechanical reliability of WDNs. From the various studies conducted, reliability was found to be an important consideration for the design of WDNs. From the previous studies on design of WDNs, it was also be noticed that, in many studies more focus was given to hydraulic failures and very little attention was given to the mechanical failures. The present study focuses on reliability based design of WDNs considering mechanical failure of pipes.

The objective of this study is to present SaDE algorithm for reliability-based design of WDNs considering mechanical failure of pipes and evaluate its performance by applying on few case studies and comparing with that of the DE algorithm.

2. METHODS AND TOOLS

The methodology comprises of three main components: optimization model, reliability assessment model and simulation model. Optimization is carried out using SaDE algorithm, reliability is assessed considering the mechanical failure of pipes and simulations are performed using EPANET 2 tool kit. The details each of these components are presented below.

2.1 Optimal design of WDNs

The problem of optimal design of WDNs is formulated as a single objective optimization problem for determining the pipe sizes such that the cost of pipes is minimum for a certain minimum level of reliability subject to constraints on minimum head requirements and conservation of mass and energy. Mathematical representation of the problem is as follows:

$$\text{Minimize Cost} = \sum_{i=1}^{n_p} f(D_i)L_i \tag{1}$$

subject to:

$$H \geq H_{min} \quad \text{(for all nodes)} \tag{2}$$

$$\sum HL_i - \sum E_p = 0 \quad \text{(for all loops)} \tag{3}$$

$$\sum Q_{in} - \sum Q_{out} = 0 \quad \text{(for all nodes)} \tag{4}$$

$$R \geq R_{\min} \quad \text{(for both system and individual demand nodes)} \tag{5}$$

$$HL_i = \frac{10.68\ Q^{1.85}\ L_i}{C_{HW}^{1.85}\ D_i^{4.87}}$$

$$\text{and } Q = \frac{\pi}{4} D^2 V$$

where D_i and L_i are diameter and length of pipe I; H is the head; H_{min} is the minimum required head at any node; HL is the head loss for a pipe; E_p is the energy added by the pump; R is the reliability, and R_{min} is the minimum required reliability value; Q_{in} and Q_{out} are the discharges flowing towards and away from a node respectively; C_{HW} is the Hazen William's roughness coefficient; and V is the velocity of flow for any particular pipe.

2.2 Reliability assessment of WDNs considering mechanical failure of pipes

The mechanical failure of pipes leads to changed pressure and flow conditions inside the network. This can lead to insufficient supply at one or more nodes. To assess the performance of the WDN in such cases, the mechanical reliability is assessed as the level of demand satisfaction considering the possible failure conditions. The stepwise procedure followed for estimating the mechanical reliability of WDNs is as follows:

1. Determine the probability of failure of each pipe $p_1, p_2, p_3, \ldots, p_n$, which is usually expressed in terms of diameter and/or length of the pipe, where n is the number of pipes in the WDN.

In the present study, probabilities of failure of pipes are calculated as equal to the ratio of the length of that link to the summation of lengths of all the links.

$$p_i = \frac{L_i}{\sum_{i=1}^{n} L_i} \tag{6}$$

where L_i is the length of i^{th} pipe and n is the number of pipes.

2. Consider the failure of a single pipe and solve the network hydraulics for the situation to determine the supply at each node. Repeat the step for failure of each pipe at a time. Calculate the failure probability for the system as the weighted sum of the ratios of deficit in supply to required demand.

$$F = \sum_{i=1}^{n} p_i \frac{D - S_i}{D} \tag{7}$$

where F is the failure probability of the system, p_i is the failure probability of i^{th} pipe, D is the required demand for the entire WDN and S_i is the actual supply to the WDN in case of failure of i^{th} pipe.

3. The process can be carried out by considering failure of combinations of two or more pipes also. But since the probability of failure of a single pipe itself is very less, the probability of failure of combinations would be still lesser and thus ignored.
4. The overall system reliability is then calculated as one minus the failure probability of the system.

$$R_s = 1 - F \tag{8}$$

where R_s is the system reliability.

2.3 Simulation of WDN hydraulics

The simulations of the WDN hydraulics are performed using EPANET 2 tool kit. EPANET is a hydraulic simulation tool useful for design of water piping system and it was developed in 1993 by the United States Environmental Protection Agency (EPA) Water Supply and Water Resources Division (Rossman 2000). EPANET simulates the WDN hydraulics using Gradient algorithm proposed by Todini and Pilati (1987) which involves solving a set of equations mainly conservation of mass for each junction and loop headloss equation. For simulating the failure of a pipe, the status of the pipe is set to close. In the present study, the simulations are performed through MATLAB coding linking with EPANET DLL files.

2.4 SaDE algorithm

SaDE algorithm proposed by Qin and Suganthan (2005) is employed in the present study with some modifications for solving the optimization problem. The step wise procedure for the algorithm (as depicted in Figure 1) is as follows:

1. Initialise the population with some random values.
2. Set initial values of the means of mutation and crossover factors as 0.5 each and standard deviation as 0.3 and 0.1 respectively.
3. Generate initial random values of mutation and crossover factors for each individual from a normal distribution with the specified mean and standard deviation values.

4. Now calculate the cost and reliability values for each individual.
5. Perform mutation for each individual using the relation

$$V_{i,G} = X_{r_1,G} + F_i(X_{r_2,G} - X_{r_3,G}) \tag{9}$$

where $V_{i,G}$ = mutant vector associated with population i and generation G $X_{r1,G}$, $X_{r2,G}$ and $X_{r3,G}$ are three randomly chosen population vectors from the present generation and F_i is the mutation factor for population vector i.

6. The next step is to perform cross over, which is nothing but to select certain features from the original vector and rest from the mutant vector, to generate a trial vector. Crossover can be performed using the equation

$$u_{j,i,G} = \begin{cases} v_{j,i,G}, & \text{if } (rand_j[0,1] \leq CR \text{ or } (j = j_{rand}) \\ x_{j,i,G}, & \text{otherwise} \end{cases} \tag{10}$$

where $u_{j,i,G}$ is the trial vector, $rand_j$ is a random value between 0 to 1 for each dimension of the vector and j_{rand} is a random number from 1 to D, the dimension of each vector.

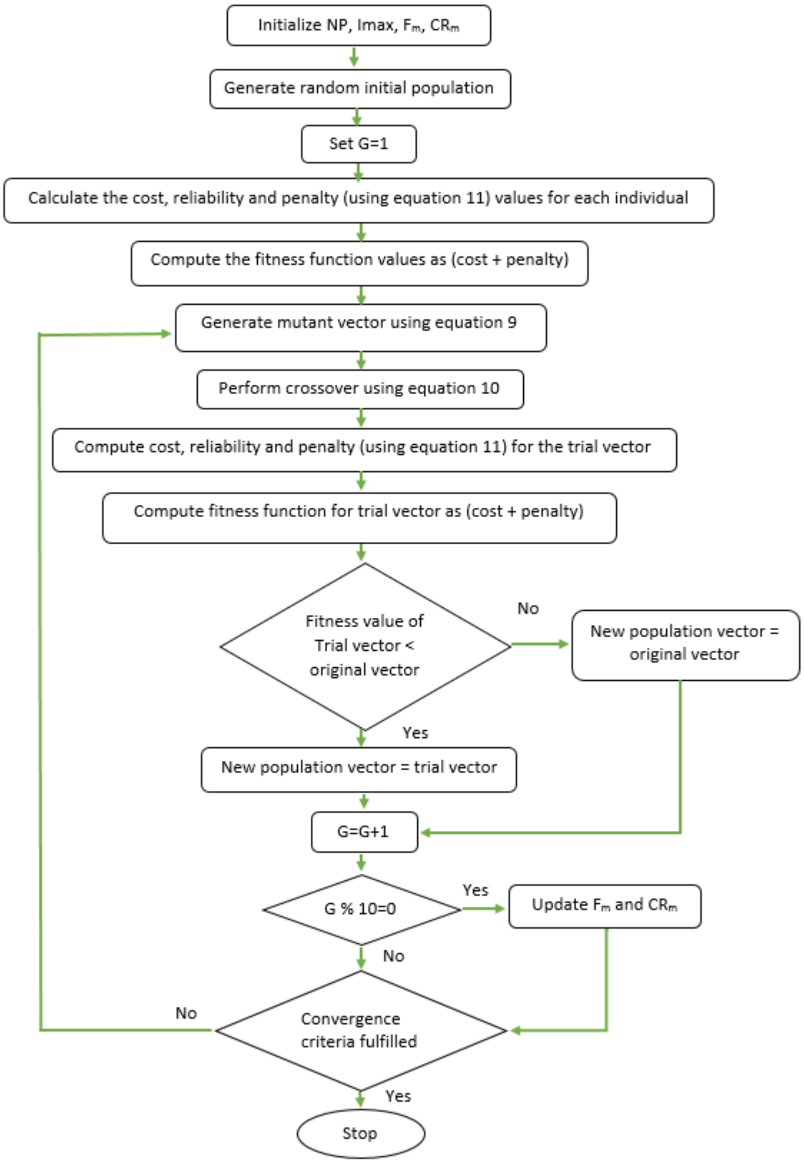

Figure 1. SaDE algorithm for reliability based design of WDNs

7. Now, for the trial vector generated, compute the cost and reliability values. The fitness function can be calculated as cost plus penalty, where penalty is computed using the rule

$$Penalty = \begin{cases} (R_{\min} - R) \text{ x } 10^{n} & \text{if } R < R_{\min} \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

   where the value of *n* depends on the size of the network and the cost values of the pipe diameters.
8. Generate the new population by applying the selection process. Here, the selection is kept simple by comparing the fitness function of the trial vector with the corresponding original population vector. The one with better fitness function is forwarded to the next generation.
9. The process is continued till the convergence criteria are fulfilled. Here, the convergence criteria are that either a maximum number of iterations is achieved or there is no improvement in the fitness function value for a certain number of iterations (say 20).

In order to update the values of mutation and crossover factors, the values of these factors leading to successful trial vectors are noted for a certain number of iterations, say 10. After the required number of iterations are over, the mean of mutation and crossover factors are updated as equal to the mean of the successful values of these factors respectively. New set of mutation and crossover factors are then generated from normal distributions with the updated mean values.

3. APPLICATION AND RESULTS

The proposed approach is applied to two case studies, namely Apulian WDN and Fossolo WDN. Apulian WDN is a small sized WDN consisting of 34 pipes in Apulian town in Southern Italy (Giustolisi *et al.* 2009), whereas Fossolo WDN is an intermediate sized WDN comprising of 58 pipes (Bragalli *et al.* 2008). The WDN problem is first solved for deterministic design case to perform sensitivity analysis for determining the most suitable population size for that particular network. The results obtained are compared with those obtained from the previous studies. The population size found using sensitivity analysis is used to perform reliability-based design of the WDN. The problem is formulated as a single objective problem taking minimization of cost and satisfying a minimum level of reliability, which is taken as 0.8 for both the case studies. The steps are carried out by writing MATLAB codes and simulating the network hydraulics using EPANET DLL files.

3.1 Case study 1: Apulian WDN

This case study was earlier studied by Giustolisi *et al.* (2009), so the layout and other data details are taken from the same study. The layout of the Apulian WDN is shown in Figure 2. The network consists of a single source at a fixed head of 36.4 m and supplies water by gravity. There are 34 pipes and 24 nodes (one supply node and 23 demand nodes). The details about the network layout, such as pipe length, start and end node, as well as node data such as nodal demands and elevation, can be found in Giustolisi *et al.* (2009). The minimum head requirement at all the nodes is taken as 10 m. The available pipe sizes and their unit costs are listed in Table 1. Pipes are considered as cast iron (new pipes) and Hazen-William’s roughness coefficient (C_{HW}) is taken as 130 for all pipes.

Table 2 shows the results of the sensitivity analysis for population size for Apulian WDN. For performing sensitivity analysis, the SaDE algorithm is run for each population size for 10 trial runs for deterministic design problem. Table 2 represents the statistics of the results obtained for different population sizes in terms of average value of the minimum cost obtained for 10 trial runs, its Standard Deviation (S.D.), number of trail runs leading to the best value of the minimum cost obtained, and the average number of function evaluations needed to obtain the best cost for the successful trial runs (N_{avg}). From the table, it can be seen that population size of 350 performs the best in terms of the average minimum cost, S.D., success rate and the number of function evaluations needed to obtain the optimal solution.

Table 1. Available pipe diameters and their unit costs for Apulian WDN

S.No.	Available pipe size (mm)	Unit Cost (€/m)
1	100	240.1
2	150	387.78
3	180	435.66
4	200	483.84
5	225	542.34
6	250	610.90
7	300	690.24
8	325	780.19
9	350	881.55

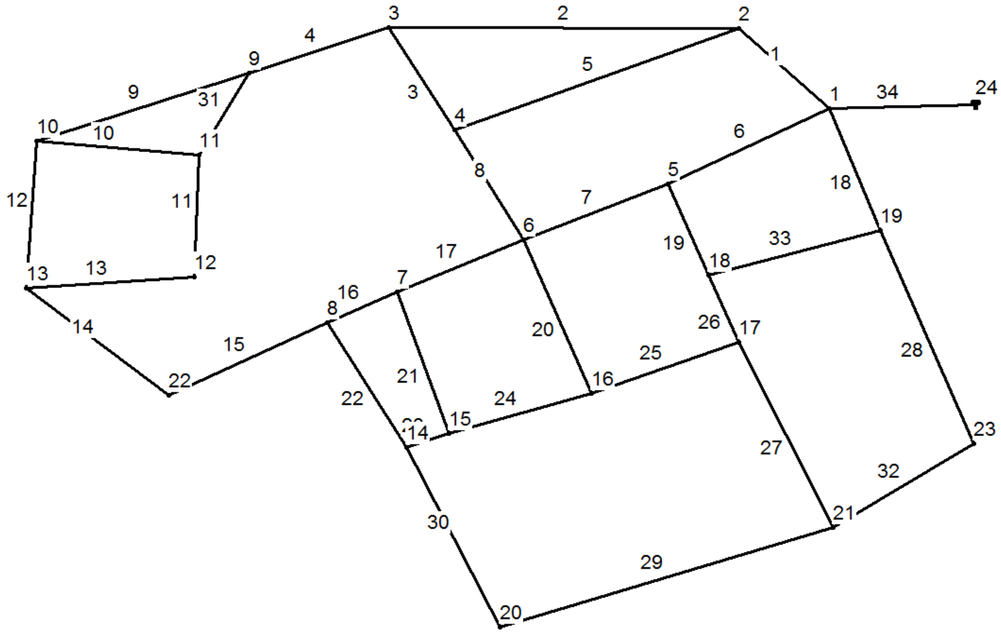

Figure 2. Layout of Apulian WDN.

Table 2. Sensitivity Analysis for population size for Apulian WDN

Population size	Avg. min. cost (10^6 €)	S.D. (10^6 €)	Successful trial runs (out of 10)	N_{avg}
200	7.195	0.733	0	-
250	6.679	0.481	2	82500
300	6.464	0.420	5	153000
350	***6.247***	***0.032***	***8***	***105000***
400	6.331	0.279	3	218000
450	6.268	0.645	1	245250

Table 3 shows the comparison of the performance of SaDE and DE algorithms for deterministic design of Apulian WDN. It can be seen that both the algorithms lead to the same value of best cost obtained, but the average cost, number of function evaluations and success rate of SaDE are better than those of DE. This shows, that SaDE converges faster than DE and is more reliable since it has a higher success rate.

Table 3. Comparison of the performance of SADE with DE algorithm for deterministic design of Apulian WDN

Evaluation criteria	**SaDE**	**DE**
Best solution	6224800	6224800
Avg. min cost	6247000	6454250
N_{min}	53000	72680
N_{max}	182490	225720
N_{avg}	105000	184480
Success rate	80%	70%

Note: N_{min}, N_{max}, and N_{avg} are the minimum, maximum and average number of function evaluations needed to obtain the optimal solution.

Table 4. Comparison of optimal solutions obtained for deterministic design using SaDE (present study) and GA (previous study) for Apulian WDN. Also, it gives comparison of the solution obtained for reliability-based design using SaDE.

Pipe No.	**Optimal diameter obtained (in mm) for**		
	Deterministic design		Reliability based design
	SaDE algorithm (Present Study)	GA algorithm (Giustolisi *et. al.* 2009)	SaDE algorithm (Present Study)
1	300	325	300
2	250	300	250
3	100	100	100
4	225	300	225
5	100	100	100
6	350	350	325
7	300	325	300
8	100	100	100
9	100	100	100
10	150	180	180
11	100	100	100
12	100	180	180
13	100	100	100
14	100	100	100
15	150	150	100
16	225	300	300
17	225	300	300
18	100	150	200
19	250	225	100
20	100	100	100
21	100	100	100
22	100	250	200
23	100	100	100
24	100	100	100
25	100	100	100
26	225	200	100
27	180	150	100
28	100	100	150
29	150	100	100
30	100	180	150
31	225	250	225
32	100	100	100
33	100	100	100
34	350	350	350
Total Cost (€)	62,24,800	69,51,600	62,83,116
Corresponding reliability	0.7896	0.8884	0.8023
N_{min}	53000	35000	96950

The population size of 350 is used to perform reliability-based design of Apulian WDN. The optimal diameter values obtained for both deterministic and reliability based design of Apulian WDN is presented and compared with the previous study in Table 4. From the table it can be seen that the present study yields a better solution for deterministic design of Apulian WDN. This shows that SaDE does not get trapped in local optima. On comparing the deterministic solution with that of the reliability-based solution, it can be seen that the reliability based solution leads to a higher cost. Also, the deterministic solution leads to a lower value of reliability, which means that neglecting mechanical reliability during the design process can lead to poor performance of the WDN in case of failure of one or more components. On comparing the minimum number of function evaluations needed to obtain the optimal solution, it can be seen that SaDE leads to a slightly more number of function evaluations than GA, but since the solution obtained by GA is not the global optima, so it cannot be considered as a true representation of the number of function evaluations needed. Also, the number of function evaluations needed for performing reliability based design increases slightly than that required for the deterministic design case, probably due to the additional constraint on satisfying the minimum reliability level of 0.8.

3.2 Case study 2: Fossolo WDN

Fossolo WDN consists of 58 pipes, 36 demand nodes and one reservoir with a fixed head of 121.0 m. This WDN was previously studied by Bragalli *et al.* (2008) and the network details are taken from the same study. The layout of the Fossolo WDN is shown in Figure 3. The minimum pressure head for each demand node is 40 m. The material for all the pipes being polyethylene, a high roughness coefficient of 150 is assigned to each pipe. There are 22 available pipe sizes ranging from 16 mm to 409.2 mm. More details about the available pipe diameters and the corresponding unit costs is given in Table 5.

Table 5. Available pipe sizes and corresponding unit costs for Fossolo WDN

S.No.	Available pipe diameter (mm)	Unit Cost (€/m)	S.No.	Available pipe diameter (mm)	Unit Cost (€/m)
1	16.0	0.38	12	130.8	19.61
2	20.4	0.56	13	147.2	24.78
3	26.0	0.88	14	163.6	30.55
4	32.6	1.35	15	184.0	38.71
5	40.8	2.02	16	204.6	47.63
6	51.4	3.21	17	229.2	59.70
7	61.4	4.44	18	257.8	75.61
8	73.6	6.45	19	290.6	99.58
9	90.0	9.59	20	327.4	126.48
10	102.2	11.98	21	368.2	160.29
11	114.6	14.93	22	409.2	197.71

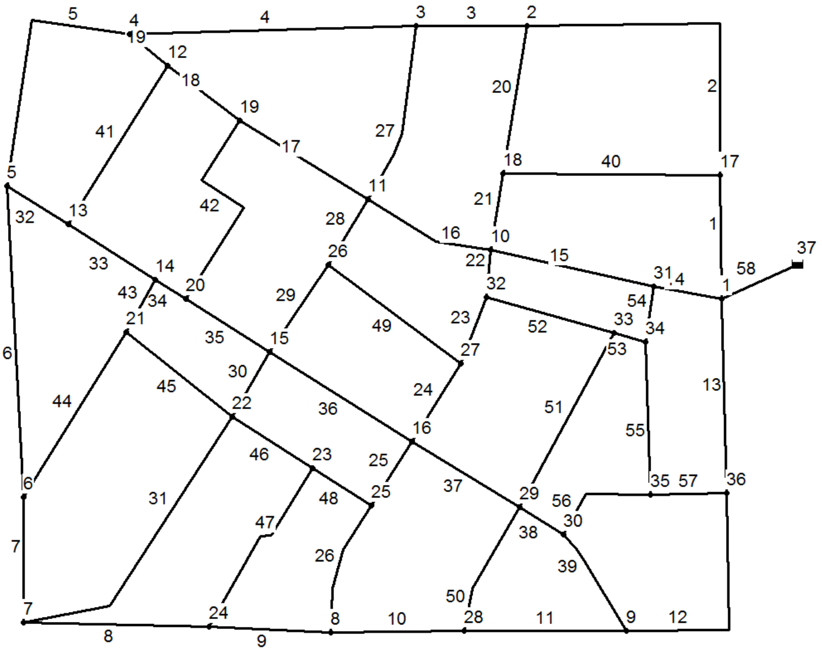

Figure 3. Layout of Fossolo WDN

On performing sensitivity analysis on population size for Fossolo WDN, the statistics obtained are presented in Table 6. It can be seen that population size of 300 performs the best (based on the different criteria). Thus, reliability based design of the Fossolo WDN is performed using population size of 300. It can also be seen that the success rate of SaDE is 80%, which means SaDE is performing satisfactorily for the problem of WDN design even for larger networks like Fossolo WDN.

Table 6. Sensitivity Analysis for population size for Fossolo WDN

Population size	**Avg. min. cost (10^4 €)**	**S.D. (10^4 €)**	**Successful trial runs (out of 10)**	**N_{avg}**
100	2.1042	0.306	0	-
200	2.0915	0.338	5	346000
300	***2.0845***	***0.194***	***8***	***705000***
400	2.1041	0.246	3	874000
500	2.0918	0.259	3	845000
600	2.0908	0.148	5	1275560

Table 7. Comparison of the performance of SADE with DE algorithm for deterministic design of Fossolo WDN

Evaluation criteria	**SaDE**	**DE**
Best solution	20478.5	20478.5
Avg. min cost	20761.8	22450.4
N_{min}	123000	245400
N_{max}	967600	1153200
N_{avg}	351200	700230
Success rate	80%	60%

Note: Nmin, Nmax, and Navg are the minimum, maximum and average number of function evaluations needed to obtain the optimal solution.

Table 8. Optimal solutions obtained for deterministic and reliability based design for Fossolo WDN using SaDE algorithm

Pipe No	**Optimal Diameter (in mm) for**	
	Deterministic design	Reliability based design
1	40.8	40.8
2	16	16
3	16	40.8
4	16	16
5	16	26
6	16	16
7	16	32.6
8	20.4	20.4
9	40.8	32.6
10	16	51.4
11	20.4	26
12	32.6	20.4
13	40.8	16
14	147.2	147.2
15	130.8	130.8
16	114.6	114.6
17	61.4	61.4
18	40.8	51.4
19	32.6	32.6
20	32.6	40.8
21	51.4	51.4
22	90	73.6
23	73.6	61.4
24	73.6	51.4
25	61.4	51.4
26	51.4	20.4
27	32.6	20.4
28	102.2	90
29	90	90
30	73.6	73.6
31	32.6	20.4
32	32.6	32.6
33	40.8	32.6
34	51.4	40.8
35	61.4	51.4
36	16	16
37	16	16
38	20.4	16
39	16	16
40	16	20.4
41	16	32.6
42	16	16
43	16	16
44	40.8	61.4
45	51.4	61.4
46	16	16
47	16	26
48	32.6	40.8
49	16	16
50	16	51.4
51	32.6	61.4
52	16	20.4
53	40.8	73.6
54	51.4	73.6
55	32.6	51.4
56	16	16
57	16	26
58	147.2	163.6

Table 7 shows the comparison between the performance of SaDE and DE algorithms for deterministic design of Fossolo WDN. From the table, it can be noticed that the SaDE performs better than DE in terms of the convergence speed and average minimum cost obtained. It is also found that the success rate of SaDE is much higher than DE in the case of Fossolo WDN. This shows that SaDE converges much faster and has a considerably higher success rate than DE especially for larger WDNs.

The optimal diameters obtained by performing deterministic and reliability based design of Fossolo WDN are presented in Table 8. The cost for deterministic design is found to be 20478.5 € with a reliability value of 0.765, whereas for the reliability based solution the cost is obtained as 22006.98 € with a reliability value of 0.806. Thus, the results of the study infer that neglecting reliability during the design process may lead to unsatisfactory performance of the WDN in certain failure situations. Also, the consistency in results obtained as well as fast convergence rate of SaDE makes it attractive alternative for solving deterministic as well as reliability-based design of the large scale WDN problems.

4. SUMMARY AND CONCLUSIONS

In the present study, the SaDE algorithm is presented for reliability-based design of WDNs considering mechanical failures. The algorithm is first tested for deterministic design case by applying to two WDN problems (Apulian WDN and Fossolo WDN) and then applied for the problem of reliability-based design for both the WDNs. The results obtained illustrate that SaDE is efficient, since it converges fast and does not get trapped in local optima. On comparing the performance of SaDE with that of the DE algorithm, it is seen that the performance of SaDE is much better than DE in terms of convergence speed and success rate, especially in case of larger WDN problems. Also, the reliability-based solutions are achieved in reasonable number of function evaluations, even for larger network like Fossolo WDN. On comparing the solutions obtained for both deterministic and reliability based solutions, it is found that neglecting mechanical reliability consideration during the design process leads to unsatisfactory performance of the WDN due to failure of components, making it less robust to handle such failure situations. Since the failure of pipes is one of the most common types of failures for real world WDNs, it is important that such considerations must be incorporated during the design process itself. The efficient and consistent results obtained using SaDE algorithm makes it one of the preferable options for the problem of WDN design. The present study thus recommends the use of SaDE algorithm for the problem of reliability-based design of WDNs incorporating the effect of mechanical failure of pipes.

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