Size/Layout Optimization of Truss Structures Using Shuffled Shepherd Optimization Method

Ali Kaveh1*, Ataollah Zaerreza1

1 School of Civil Engineering, Iran University of Science and Technology, Narmak, Tehran, Postal Code 16846-13114, Iran
* Corresponding author, e-mail: alikaveh@iust.ac.ir

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Abstract
The main purpose of this paper is to investigate the ability of the recently developed multi-community meta-heuristic optimization algorithm, shuffled shepherd optimization algorithm (SSOA), in layout optimization of truss structures. The SSOA is inspired by mimicking the behavior of shepherd in nature. In this algorithm, agents are first divided into communities which are called herd and then optimization process, inspired by the shepherd's behavior in nature, is operated on each community. The new position of agents is obtained using elitism technique. Then communities are merged for sharing the information. The results of SSOA in layout optimization show that SSOA is competitive with other considered meta-heuristic algorithms.

Keywords
meta-heuristic algorithms, shuffled shepherd optimization algorithm, size/layout optimization, truss structures

1 Introduction
Structural optimization is one of the most important field in engineers which has attracted a great deal of attention. Structural optimization can be divided into three categories: (1) size optimization that obtains optimal cross-sections for the structural members; (2) size/layout optimization which finds the optimal form for the structure and cross-sections of the structural members; (3) topology optimization that seeks optimal cross-sections and connectivity between structural members. In layout optimization both sizing and configuration optimization variables are involved and these optimize the material usage leading to economical design of truss structures.

Layout optimization has been investigated by different researchers using different methods. For example Wu and Chow [1] used GA for discrete variables for sections and continuous variables for nodal coordinates, Hasançebi and Erbatur [2] proposed an improved GA by combining the GA with annealing perturbation and adaptive design space reduction strategies, Kaveh and Khayatzadeh [3] developed the ray optimization, Kaveh and Laknejadi [4] presented a hybrid evolutionary graph based multi-objective algorithm, Kaveh and Zolghadr [5] suggested the democratic PSO, Kaveh et al. [6] presented hybrid PSO and SSO algorithm, Kaveh and Ildir Ghazaan [7] utilized improved ray optimization, Kaveh and Mahjoubi [8] proposed an improved spiral optimization algorithm for layout optimization of truss structures with frequency constraints, Kazemzadeh Azad et al. [9] utilized big bang-big crunch for layout optimization of truss under dynamic excitation, and Kaveh et al. [10] suggested a modified dolphin monitoring operator for layout optimization of planar braced frames.

Meta-heuristic algorithms can be categorized considering different views [11, 12]. The meta-heuristic algorithms can be categorized based on having one or more communities. As an example, particle swarm optimization (PSO) [13], bat algorithm (BA) [14], cuckoo search algorithm (CS) [15] slap swarm algorithm (SSA) [16], adaptive dimensional search (ADS) [17] and improved ray optimization algorithm (IRO) [18] are single community algorithms, while Shuffled Complex Evolution (SCE) [19], Shuffled Frog-leaping Algorithm (SFLA) [20], improved particle swarm optimization (IPSO) [21], Shuffled artificial bee colony algorithm (Shuffled-ABC) [22] are multi-community optimization algorithms.

As newly developed type of multi-community meta-heuristic algorithm, the shuffled shepherd optimization algorithm (SSOA) is introduced for design of structural
optimization problem by Kaveh and Zareerza [23]. This algorithm can be considered as multi-community and multi-agent method, where each community is called a herd and agent is a sheep. Each sheep when selected is called shepherd and move to new position.

This paper considers: (i) The SSOA is introduced for optimization of layout problems. (ii) A comprehensive study of layout optimization for truss structures is presented. Some examples are chosen from the literature to verify the effectiveness of the algorithm. These examples are as follows: a 15-member planar truss with 23 design variables, an 18-member planar truss with 12 design variables, A 25-member spatial truss with 13 design variables, 47-member planar truss with 44 design variables, and a large-scale 272-member transmission tower with 72 design variables. The results show that the SSOA is very competitive with other methods in finding best solution.

The present paper is organized as follows: In Section 2 the SSOA is briefly described. In Section 3 four layout optimization of truss structures and a large-scale transmission tower are optimized utilizing the SSOA, and finally conclusions are derived in Section 4.

2 Shuffled shepherd optimization algorithm

The main objective of this section is to extend the application of the recently developed meta-heuristic algorithm called SSOA [23]. In SSOA, each solution candidate \( X_i \) containing a number of variables (i.e. \( X_i = \{X_{i,j}\} \)) are considered as sheep. Each sheep is arranged by its objective function value, and then divided into herds. In each herd the sheep are selected in order, selected sheep are called shepherd and sheep with better objective function in a herd are called horses. Therefore, there are some horses and sheep for each shepherd. A shepherd tries to guide the sheep to the horse, the new position of the shepherd is achieved by moving to one of the sheep and horse. This is done for two purposes: (i) moving to worse agent causes exploration; (ii) and moving to a better member results in exploitation. New position of shepherd update when new objective function is not worse than old objective function, this leads to an elitism in the algorithm.

The SSOA procedure can briefly be outlined as follows:

1) The SSOA parameters \( \alpha_0, \beta_0, \beta_{\max}, \text{iter}_{\max}, h, s \) are set. Where \( \text{iter}_{\max} \) is a maximum iteration number, \( h \) is the number of herds; and \( s \) is the number of sheep in each herd.

2) The initial position of the \( i \)th sheep is determined randomly in an \( m \)-dimensional search space by the following equation (Eq. (1)):

\[
X_i^0 = X_{\min} + \text{rand} \odot (X_{\max} - X_{\min}) \quad i = 1, 2, \ldots, n
\]  

where \( X_i^0 \) is the initial solution vector of the \( i \)th sheep, \( X_{\max} \) and \( X_{\min} \) are the bound of design variables, \( \text{rand} \) is a random vector with each component being in the interval \([0,1]\), and the number of components are equal to the number of variables, \( n \) is the number of sheep \((n = h \times s)\) and sign \( \odot \) denotes element-by-element multiplication.

3) The value of the objective function for each sheep is evaluated and sorted by their objective function in an ascending order. To build the herds, spread the sheep to the herd. The first \( h \) sheep are selected and put randomly in each herd (put one sheep in each herd). Then select the second \( h \) sheep and put them in a herd again. This process is continued until all sheep are assigned into herd.

4) Select each sheep on a herd form first to the last one. Selected sheep is shepherd, sheep in herd better than shepherd is called horses. Select randomly one of the horses and the sheep, step size for each shepherd is calculated by

\[
\text{Stepsize}_i = \beta \times \text{rand} \odot (X_j - X_i) + \alpha \times \text{rand} \odot (X_j - X_j),
\]

where \( X_j, X_j, X_i \) are solution vectors of the shepherd, selected horse and selected sheep in an \( m \)-dimensional search space, respectively; \( \text{rand} \) is a random vector which each component is in interval \([0,1]\) and we have the number of components based on the number of components of solution vectors; \( \alpha \) and \( \beta \) calculate by Eq. (3) and Eq. (4), respectively.

\[
\alpha = \alpha_0 - \frac{\alpha_0}{\text{iter}_{\max}} \times \text{iteration}
\]  

\[
\beta = \beta_0 + \frac{\beta_{\max} - \beta_0}{\text{iter}_{\max}} \times \text{iteration}
\]

First sheep selected in herd does not have better than itself so the first term of the step size is zero; and for the last sheep selected in herd which does not have worse than itself, the second term of the step size is zero.

5) The temple solution vector for each sheep calculate by the following equation (Eq. (5)):

\[
X_{\text{temple}}^i = X_{\text{old}}^i + \text{stepsize}_i.
\]

If temple objective function is not worse than old objective function, then the position of the sheep is changed, so we have \( X_{\text{new}}^i = X_{\text{temple}}^i \), otherwise the position of the sheep is not changed and we have \( X_{\text{new}}^i = X_{\text{old}}^i \). After position of the all sheep is updated merged the herds for sharing information.
6) The optimization is repeated from step 3 until a termination criterion, specified as the maximum number of iterations, is satisfied.

The pseudo-code of the SSOA is presented in Algorithm 1.

3 Numerical examples

The ability of the SSOA is tested using five layout optimization problems. Four of these problems include discrete sizing variables and continuous configuration variables, and in the last example sizing and configuration variables are continuous. Parameter settings of the SSOA and the number of iteration limits on numeric examples are listed in Table 1.

3.1 The 15-bar planar truss structure

The first layout optimization problem is the 15-bar planar truss subjected to traversal load of 10 kip as shown in Fig. 1. The optimization problem includes 15 discrete sizing variables for the cross-section areas and 8 continuous layout variables for nodal coordinates. All members are subjected to stress limitation of ±25 ksi. Optimization variables and input data of the truss are given in Table 2.

Table 3 shows that the SSOA finds the optimal solution with the least number of analyses compared to the other algorithm. Average and standard deviation of the SSOA for 30 independent runs are 78.3675 (lb) and 3.0373 (lb), respectively. Best solution for this problem is 72.5152 that has been found by Kazemzadeh Azad and Jayant Kulkarni [24] but average of 50 independent runs is 79.49 that is more than that of the SSOA. Fig. 2 shows the best

Algorithm 1 Pseudo-code of the SSOA algorithm

Procedure SSOA

Initialize algorithm parameters

Initial position by Eq. (1)

The value of objective function of sheep is evaluated

While iteration < maximum iteration

Sort sheep by objective function

Build herds

For each herd

For each sheep

The horse and sheep are chosen

The step size calculated by Eq. (2)

Temple solution vector calculated by Eq. (5)

The value of objective function of temple solution is evaluated

If temple objective function isn’t worse than old objective function

Solution vector is updated

End if

End for

End for

merged the herds

End while

End procedure

Table 1 Parameters setting and maximum iteration number for the SSOA

| Problem                  | $\alpha_0$ | $\beta_s$ | $\beta_m$ | Number of herds | Size of herds | Maximum iteration number |
|--------------------------|------------|-----------|-----------|-----------------|---------------|--------------------------|
| 15-bar planar truss      | 1.5        | 2         | 3         | 4               | 4             | 490                      |
| 18-bar planar truss      | 0.6        | 2.3       | 2.5       | 4               | 4             | 599                      |
| 25-bar spatial truss     | 0.5        | 2.4       | 2.6       | 4               | 4             | 300                      |
| 47-bar planer truss      | 0.5        | 2         | 2.3       | 4               | 5             | 1100                     |
| 272-bar transmission tower | 0.5       | 2.0       | 2.4       | 3               | 10            | 1700                     |

Table 2 Simulation data for the 15-bar planar truss

| Sizing variables | Layout variables |
|------------------|------------------|
| $A_i, i = 1, 2, \ldots, 15$ | $x_1, x_2, \ldots, x_8, y_2, y_3, y_4, y_6, y_7, y_8$ |

Possible sizing variables

- $A_i \in S = \{0.111, 0.141, 0.174, 0.220, 0.270, 0.287, 0.347, 0.440, 0.539, 0.954, 1.081, 1.174, 1.333, 1.488, 1.764, 2.142, 2.697, 2.800, 3.131, 3.565, 3.813, 4.805, 5.952, 6.572, 7.192, 8.525, 9.300, 10.850, 13.330, 14.290, 17.170, 19.180\}(in^2)$

Layout variables bounds

- 100 in. $\leq x_1 \leq 140$ in.;
- 220 in. $\leq x_2 \leq 260$ in.;
- 100 in. $\leq y_1 \leq 140$ in.;
- 100 in. $\leq y_2 \leq 140$ in.;
- 50 in. $\leq y_3 \leq 60$ in.;
- $-20$ in. $\leq y_4 \leq 20$ in.;
- $-20$ in. $\leq y_6 \leq 20$ in.;
- $-20$ in. $\leq y_7 \leq 20$ in.;
- $-20$ in. $\leq y_8 \leq 60$ in.;

Young modulus $E = 10^6$ (ksi)

Material density $\rho = 0.1$ (lb/in$^3$)
shape of the 15-bar planar truss find by the present work. Fig. 3 shows the convergence histories of the best result and the mean performance of 30 independent runs for the 15-bar planar truss.

### 3.2 The 18-bar planar truss structure

For the 18-bar planar truss structure shown in Fig. 4, material density is 0.1 lb/in\(^3\) and the modulus of elasticity is 10,000 ksi. The members are subjected to the stress limit of ±25 ksi and Euler buckling stresses for compression member (the buckling strength of the ith element is set to \(4EA/L^2\)). Members are classified into four groups as follows: \(A_1 = A_4 = A_5 = A_{12} = A_{16}\); \(A_2 = A_6 = A_{10} = A_{14} = A_{18}\); \(A_3 = A_7 = A_{11} = A_{15}\); \(A_8 = A_9 = A_{13} = A_{17}\). Hence there are four sizing variables for cross section areas which are chosen from following discrete set:

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**Table 3 Optimum result for the 15-bar planar truss**

| Design variables | Tang et al. [25] | Rahami et al. [26] | Kazemzadeh Azad et al. [24] | Miguel et al. [27] | Ho-Huu et al. [28] | Present work |
|------------------|------------------|-------------------|---------------------------|------------------|-------------------|-------------|
| \(A_1\)          | 1.081            | 1.081             | 0.954                     | 0.954            | 1.081             | 1.081       |
| \(A_2\)          | 0.539            | 0.539             | 0.539                     | 0.539            | 0.539             | 0.539       |
| \(A_3\)          | 0.287            | 0.287             | 0.111                     | 0.220            | 0.270             | 0.141       |
| \(A_4\)          | 0.954            | 0.954             | 0.954                     | 0.954            | 0.954             | 0.954       |
| \(A_5\)          | 0.954            | 0.539             | 0.539                     | 0.539            | 0.539             | 0.539       |
| \(A_6\)          | 0.220            | 0.141             | 0.347                     | 0.22             | 0.22              | 0.287       |
| \(A_7\)          | 0.111            | 0.111             | 0.111                     | 0.111            | 0.111             | 0.111       |
| \(A_8\)          | 0.111            | 0.111             | 0.111                     | 0.111            | 0.111             | 0.111       |
| \(A_9\)          | 0.287            | 0.539             | 0.111                     | 0.287            | 0.287             | 0.141       |
| \(A_{10}\)       | 0.220            | 0.440             | 0.44                      | 0.22             | 0.347             | 0.44        |
| \(A_{11}\)       | 0.440            | 0.270             | 0.174                     | 0.22             | 0.27              | 0.174       |
| \(A_{12}\)       | 0.111            | 0.220             | 0.174                     | 0.22             | 0.27              | 0.174       |
| \(A_{13}\)       | 0.220            | 0.141             | 0.347                     | 0.27             | 0.27              | 0.347       |
| \(A_{14}\)       | 0.347            | 0.287             | 0.111                     | 0.22             | 0.174             | 0.111       |
| \(x_2\)          | 133.612          | 101.575           | 105.785                   | 114.967          | 117.4983          | 111.2513    |
| \(x_3\)          | 234.752          | 227.9112          | 258.5965                  | 247.040          | 242.9729          | 238.7010    |
| \(y_2\)          | 100.449          | 134.7986          | 133.6284                  | 125.919          | 112.3731          | 132.8471    |
| \(y_3\)          | 104.738          | 128.2206          | 105.0023                  | 111.067          | 101.2684          | 125.3669    |
| \(y_4\)          | 73.762           | 54.8630           | 54.4546                   | 58.298           | 54.6397           | 60.3072     |
| \(y_5\)          | -10.067          | -16.4484          | -19.929                   | -17.564          | -12.3953          | -10.6651    |
| \(y_6\)          | -1.339           | -13.3007          | 3.6223                    | -5.821           | -14.3909          | -12.2457    |
| \(y_7\)          | 50.402           | 54.8572           | 54.4474                   | 31.465           | 54.6396           | 59.9931     |
| Weight (lb)       | 79.820           | 76.6854           | 72.5152                   | 75.55            | 80.5688           | 74.6818     |
| No. of analyses   | 8,000            | 8,000             | 10,000                    | 8,000            | 7,980             | 7,980       |

**Fig. 2** Comparison of optimized layout for the 15-bar planar truss

**Fig. 3** Convergence histories of the optimization for the 15-bar planar truss
and eight layout variables with the following bounds:

- \(775 \text{ in.} \leq x_3 \leq 1225 \text{ in.}\)
- \(525 \text{ in.} \leq x_5 \leq 975 \text{ in.}\)
- \(275 \text{ in.} \leq x_7 \leq 725 \text{ in.}\)
- \(25 \text{ in.} \leq x_9 \leq 475 \text{ in.}\)
- \(-225 \text{ in.} \leq y_3, y_5, y_7, y_9 \leq 245 \text{ in.}\)

Table 4 presents the optimum designs obtained by the other methods and SSOA. It can be seen that SSOA has found a smaller weight compared to those of Hasançebi and Erbatur [29], Kaveh and Kalatjari [30], Rahami et al. [26] and Ho-Huu et al. [28] but with higher number of analyses than them and found higher weight than Kazemzadeh Azad et al. [24] but with smaller number of analyses, and the average and standard deviation of SSOA for 40 independent runs are 4768.5 (lb) and 474.10 (lb), respectively. Optimum layout found by SSOA is shown in Fig. 5. The convergence curves for the best result and the mean performance of 40 independent runs for the 18-bar planar truss are shown in Fig. 6.

### 3.3 The 25-bar spatial truss

The third layout optimization problem is the 25-bar spatial truss as shown in Fig. 7. The optimization problem includes 13 design variables containing 8 discrete sizing variables for the cross-section areas and 5 continuous layout variables for nodal coordinate. All members are subjected to stress limitation of ± 40 ksi and all nodal displacement in all directions is limited to ±0.3 in. Optimization variables and input data of this truss are provided in Table 5.
Table 5 Simulation data for the 25-bar spatial truss

**Sizing variables**

A1; A2=A3=A4=A5; A6=A7=A8=A9; A10=A11; A12=A13; A14=A15=A16=A17; A18=A19=A20=A21; A22=A23=A24=A25

**Layout variables**

\[x_4 = x_5 = -x_3, \quad x_8 = x_9 = -x_7 = -x_6;\]

\[y_3 = y_4 = -y_5 = -y_6; \quad y_7 = y_8 = -y_9 = -y_{10};\]

\[z_3 = z_4 = z_5 = z_6\]

Possible sizing variables

\[A_i \in S = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.8, 3.0, 3.2, 3.4\} (in^2)\]

**Layout variables bounds**

20 in. \(\leq x_4 \leq 60\) in.;
40 in. \(\leq x_8 \leq 80\) in.;
40 in. \(\leq y_4 \leq 80\) in.;
100 in. \(\leq y_8 \leq 140\) in.;
90 in. \(\leq z_4 \leq 130\) in.;

**Loads**

| nodes | \(F_x\) (kips) | \(F_y\) (kips) | \(F_z\) (kips) |
|-------|----------------|----------------|----------------|
| 1     | 1.0            | -10            | -10            |
| 2     | 0.0            | -10            | -10            |
| 3     | 0.5            | 0.0            | 0.0            |
| 6     | 0.6            | 0.0            | 0.0            |

Young modulus \(E = 10^6\) (ksi)

Material density \(\rho = 0.1\) (lb/in^3)

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Table 6 Optimum result for the 25-bar spatial truss

| Design variables | Wu and Chow [1] | Kaveh and Kalatjari [30] | Tang et al. [25] | Rahami et al. [26] | Ho-Huu et al. [28] | Present work |
|------------------|-----------------|--------------------------|------------------|--------------------|--------------------|--------------|
|                  | R-ICDE | D-ICDE | SSOA | R-ICDE | D-ICDE | SSOA | R-ICDE | D-ICDE | SSOA | R-ICDE | D-ICDE | SSOA |
| A1               | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 |
| A2               | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 |
| A6               | 1.1 | 1.1 | 1.1 | 1.1 | 0.9 | 0.9 | 1.0 |
| A10              | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 |
| A12              | 0.3 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 |
| A14              | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 | 0.1 |
| A18              | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| A22              | 0.9 | 1.0 | 0.7 | 0.8 | 1.0 | 1.0 | 0.9 |
| x4               | 41.07 | 36.23 | 35.47 | 33.0487 | 36.380 | 36.83 | 37.6762 |
| y4               | 53.47 | 58.56 | 60.37 | 53.5663 | 57.080 | 58.53 | 54.4273 |
| z4               | 124.6 | 115.59 | 129.07 | 129.9092 | 126.62 | 122.67 | 129.9991 |
| x8               | 50.80 | 46.46 | 45.06 | 43.7826 | 48.200 | 49.21 | 51.9006 |
| y8               | 131.48 | 127.95 | 137.06 | 136.8381 | 139.90 | 136.74 | 139.5535 |
| Weight (lb)      | 136.20 | 124.0 | 124.943 | 120.115 | 145.275 | 118.76 | 117.2591 |
| No. of analyses  | N/A   | N/A   | 6,000 | 10,000 | 6,000 | 6,000 | 4,816 |

Table 6 shows that SSOA has found the best solution with the least number of analyses among the other algorithms. Average weight and standard deviation for 30 independent runs are 122.4073 lb and 6.3443 lb, respectively. Optimum layout found by SSOA is shown in Fig. 8.
Convergence curves for the best result and the mean performance of 30 independent runs for the 25-bar spatial truss are shown in Fig. 9.

### 3.4 47-bar planar truss

The 47-bar planar truss shown in Fig. 10 is optimized by different researchers for three load cases as shown in Table 7. The optimization problem includes 44 design variables containing 27 discrete sizing variables for the cross-section areas and 17 continuous layout variables for nodal coordinate. All members are subjected to stress limitation in tension and compression of 20 ksi and 15 ksi, respectively. Euler buckling stresses for compression members (the buckling strength of the $i$th element) is set to $3.96 \frac{EA}{L^2}$, and there is no limitation for nodes displacement. Optimization variables and input data of truss are given in Table 7.

Comparison of the optimal design by this work with optimum designs obtained by Salajegheh and Vanderplaats [31], Hasançebi and Erbatur [2, 29] and Panagant and Bureerat [32] is provided in Table 8. It can be seen that SSOA found the lightest weight (1869.876 lb) in less number of analyses (20,020), with average and standard deviation being 1929.91 lb and 29.55 lb, respectively. Optimum layout found by SSOA is shown in Fig 11. Fig. 12 shows the convergence curves for the best result and the mean performance of 30 independent runs for the 47-bar planar truss.

### 3.5 The 272-bar transmission tower

Last layout optimization problem is the optimization of 272-bar transmission tower shown in Fig. 13. The 272-bar transmission tower first time presented by Kaveh and

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**Fig. 9** Convergence histories of the optimization for the 25-bar spatial truss

**Fig. 10** Schematic of the 47-bar planar truss

**Table 7 Simulation data for the 47-bar planar truss**

| Sizing variables |
|------------------|
| $A_1 = A_2 = A_3$; $A_4 = A_5 = A_6$; $A_7 = A_8 = A_9$; $A_{10} = A_{11}$; $A_{12} = A_{13}$; $A_{14} = A_{15}$; $A_{16} = A_{17}$; $A_{18} = A_{19}$; $A_{20} = A_{21}$; $A_{22} = A_{23}$; $A_{24} = A_{25}$; $A_{26} = A_{27}$; $A_{28}$; $A_{29} = A_{30}$; $A_{31} = A_{32}$; $A_{33} = A_{34}$; $A_{35} = A_{36}$; $A_{37} = A_{38}$; $A_{39} = A_{40}$; $A_{41} = A_{42}$; $A_{43}$; $A_{44} = A_{45}$; $A_{46} = A_{47}$ |

| Layout variables |
|------------------|
| $x_2 = -x_1; x_4 = -x_3; y_4 = y_3; x_6 = -x_5; y_6 = y_5$; $x_9 = -x_8; y_9 = y_8$; $x_{10} = -x_9; y_{10} = y_9; x_{12} = -x_11; y_{12} = y_11; x_{14} = -x_{13}; y_{14} = y_{13}$; $x_{20} = -x_{19}; y_{20} = y_{19}; x_{21} = -x_{20}; y_{21} = y_{20}$ |

| Possible sizing variables |
|---------------------------|
| $A \in \mathbb{S} = \{0.1, 0.2, 0.3, 0.4, \ldots, 4.8, 4.9, 5.0 \}$ (in²) |

**Table 8 Design parameters**

| Loads | case | Nodes | $F_1$ (kips) | $F_2$ (kips) |
|-------|------|-------|-------------|-------------|
| 1     | 17   | 6.0   | -14.0       |
| 2     | 22   | 6.0   | -14.0       |
| 3     | 17   | 6.0   | -14.0       |

Young modulus $E = 3 \times 10^4$ (ksi)

Material density $\rho = 0.3$ (lb/in³)
Table 8 Optimum result for the 47-bar planar truss

| Design variables | Salajegheh and Vanderplaats [29] | Hasançebi and Erbatur [2] | Hasançebi and Erbatur [25] | Panagant and Bureerat [30] | Present work |
|------------------|----------------------------------|---------------------------|---------------------------|----------------------------|--------------|
|                  | SSOA                             |                           |                           | SSOA                       | SSOA         |
| $A_1$            | 2.61                             | 2.5                       | 2.5                       | 2.7                        | 2.8          |
| $A_2$            | 2.56                             | 2.2                       | 2.5                       | 2.6                        | 2.5          |
| $A_3$            | 0.69                             | 0.7                       | 0.8                       | 0.7                        | 0.7          |
| $A_4$            | 0.47                             | 0.1                       | 0.1                       | 0.1                        | 0.1          |
| $A_5$            | 0.80                             | 1.3                       | 0.7                       | 0.8                        | 1.0          |
| $A_{13}$         | 1.13                             | 1.3                       | 1.3                       | 1.2                        | 1.1          |
| $A_{12}$         | 1.71                             | 1.8                       | 1.8                       | 1.7                        | 1.8          |
| $A_{14}$         | 0.77                             | 0.5                       | 0.7                       | 0.8                        | 0.7          |
| $A_{15}$         | 1.09                             | 0.8                       | 0.9                       | 0.9                        | 0.8          |
| $A_{16}$         | 1.34                             | 1.2                       | 1.2                       | 1.3                        | 1.5          |
| $A_{17}$         | 0.36                             | 0.4                       | 0.4                       | 0.3                        | 0.4          |
| $A_{18}$         | 0.97                             | 1.2                       | 1.3                       | 1.0                        | 1.0          |
| $A_{19}$         | 1.00                             | 0.9                       | 0.9                       | 1.0                        | 1.1          |
| $A_{20}$         | 1.03                             | 1.0                       | 0.9                       | 1.0                        | 1.0          |
| $A_{27}$         | 0.88                             | 3.6                       | 0.7                       | 0.9                        | 5.0          |
| $A_{28}$         | 0.55                             | 0.1                       | 0.1                       | 0.1                        | 0.1          |
| $A_{29}$         | 2.59                             | 2.4                       | 2.5                       | 2.6                        | 2.7          |
| $A_{30}$         | 0.84                             | 1.1                       | 1.0                       | 0.9                        | 0.9          |
| $A_{31}$        | 0.25                             | 0.1                       | 0.1                       | 0.1                        | 0.1          |
| $A_{32}$         | 2.86                             | 2.7                       | 2.9                       | 2.8                        | 3.0          |
| $A_{33}$         | 0.92                             | 0.8                       | 0.8                       | 1.1                        | 0.8          |
| $A_{34}$         | 0.67                             | 0.1                       | 0.1                       | 0.1                        | 0.1          |
| $A_{35}$         | 3.06                             | 2.8                       | 3.0                       | 3.0                        | 3.2          |
| $A_{36}$         | 1.04                             | 1.3                       | 1.2                       | 1.1                        | 1.1          |
| $A_{37}$         | 0.10                             | 0.2                       | 0.1                       | 0.1                        | 0.1          |
| $A_{38}$         | 3.13                             | 3.0                       | 3.2                       | 3.1                        | 3.3          |
| $A_{39}$         | 1.12                             | 1.2                       | 1.1                       | 1.1                        | 1.1          |
| $x_2$            | 107.76                           | 114                       | 104                       | 109.61                      | 100.5396     |
| $x_3$            | 89.15                            | 97                        | 87                        | 93.078                      | 81.0279      |
| $y_4$            | 137.98                           | 125                       | 128                       | 126.65                      | 137.2003     |
| $x_4$            | 66.75                            | 76                        | 70                        | 70.752                      | 63.8334      |
| $y_5$            | 254.47                           | 261                       | 259                       | 246.32                      | 254.1838     |
| $x_5$            | 57.38                            | 69                        | 62                        | 56.172                      | 56.1445      |
| $y_6$            | 342.16                           | 316                       | 326                       | 356.26                      | 327.9040     |
| $x_{10}$         | 49.85                            | 56                        | 53                        | 48.498                      | 48.2708      |
| $y_{10}$         | 417.17                           | 414                       | 412                       | 436.37                      | 407.5132     |
| $x_{12}$         | 44.66                            | 50                        | 47                        | 42.37                      | 42.4458      |
| $y_{12}$         | 475.35                           | 463                       | 486                       | 490.66                      | 468.8267     |
| $x_{14}$         | 41.09                            | 54                        | 45                        | 41.61                      | 45.8692      |
| $y_{14}$         | 513.15                           | 524                       | 504                       | 521.04                      | 515.2907     |
| $x_{16}$         | 17.90                            | 1.0                       | 2.0                       | 1.4026                      | 0.0010       |
| $y_{16}$         | 597.92                           | 587                       | 584                       | 597.36                      | 586.9443     |
| $x_{18}$         | 93.54                            | 99                        | 89                        | 95.312                      | 80.7351      |
| $y_{18}$         | 623.94                           | 631                       | 637                       | 625.99                      | 621.5769     |
| Weight (lb)      | 1900                             | 1925.79                   | 1871.7                    | 1871.7                      | 1869.876     |
| No. of analyses  | 100,000                           | N/A                       | 187,488                   | 22,020                      |              |
In this paper layout variables are added to this problem and all nodes are considered to be free to move in all directions. Nodes 1, 2, 11, 20, 29 are fixed and 62, 63, 64, 65 are fixed in the z-direction. Nodal coordinate, grouping members and end nodes of the members are available in [33]. The optimization problem includes 72 design variables containing 28 continuous sizing variables for the cross-section areas and 44 continuous layout variables for nodal coordinate. The modulus of elasticity is $2 \times 10^8$ kN/m$^2$ and all members are subjected to stress limitation of $\pm 275000$ kN/m$^2$, Euler buckling stresses for compression members (the buckling strength of the $i$th element is set to $4EA/L^2$) and displacement of nodes 1, 2, 11, 20, 29 are limited to 20 mm in Z-direction and to 100 mm in X- direction and Y- direction. Optimization variables of truss are given in Table 10.

Optimum volume found by SSOA is presented in Table 11. Optimum volume obtained by Kaveh and Zaerreza [23] without configuration variables has been 1168200.624, that is 36.93 percent more that value obtained by the present work. This indicates that optimization processes of this structure need configuration variables. Maximum stresses ratio is 0.89 which has happened in load Case 1 in element 263, and average volume and standard deviation for 30 independent runs are 764061.589 cm$^3$ and 15485.12 cm$^3$, respectively. Displacements for nodes 1, 2, 11, 20, 29 are shown in Fig. 14. Optimum layout found by SSOA is shown in Fig. 15. The convergence curves for the best result and the mean performance of 30 independent runs for the 272-bar transmission tower are illustrated in Fig. 16.

4 Conclusions

In this paper, the capability of the new meta-heuristic algorithm so-called Shuffled Shepherd Optimization algorithm in layout optimization of structure is investigated. SSOA is a multi-community algorithm that mimics the shepherd behavior in nature.
Table 9 Loading condition for the 272-bar transmission tower

| Case | Force direction | Nodes | Other free nodes |
|------|-----------------|-------|-----------------|
| | $F_x$ (kN) | $F_y$ (kN) | $F_z$ (kN) | 1 | 2 | 11 | 20 | 29 | |
| 1 | 20 | 20 | 20 | 20 | 20 | 20 | 5 |
| 2 | 0 | 20 | 20 | 20 | 20 | 20 | 5 |
| 3 | 20 | 0 | 20 | 20 | 20 | 20 | 5 |
| 4 | 20 | 20 | 20 | 0 | 20 | 5 |
| 5 | 20 | 0 | 20 | 20 | 20 | 5 |
| 6 | 20 | 0 | 20 | 20 | 20 | 5 |
| 7 | 20 | 0 | 20 | 20 | 20 | 5 |
| 8 | 20 | 0 | 20 | 20 | 20 | 5 |
| 9 | 20 | 0 | 20 | 20 | 20 | 5 |
| 10 | 20 | 0 | 20 | 20 | 20 | 5 |
| 11 | 20 | 0 | 20 | 20 | 20 | 5 |
| 12 | 20 | 0 | 20 | 20 | 20 | 5 |

In order to demonstrate the ability of the SSOA in layout optimization problems, four classic layout optimization problems (consisting of the optimization of 15-bar planar truss, 18-bar planar truss, 25-bar spatial truss and 47-bar planar truss) and one large scale problem (optimization of 272-bar transmission tower) are performed by the SSOA. For the 15-bar planer truss, the solution found by SSOA is only 0.3463 lb more than the best solution found by other method but with smaller number of analyses among the others. In the 18-bar planar truss best solution is found by SSOA which is only 0.1 percent more than other method. In the 25-bar spatial truss and in 47-bar planar truss SSOA has found best solution with less number of analyses among the others and the result of 272-bar spatial truss shows that this problem needs configuration variables for improving the optimal solution. In SSOA both worst and
better agents have role in optimization process and results of the present study show that considering the worst agents in the optimization process can improve the performance of the algorithm and leads to better design.

Compliance with ethical standards
Conflict of interest: No potential conflict of interest was reported by the authors.
Fig. 14 Compression of allowable and existing displacements for the 272-bar transmission tower

Fig. 15 Comparison of optimized layout for the 272-bar transmission tower

Fig. 16 Convergence histories of the optimization for the 272-bar transmission tower
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