Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Member Sizing Optimization of Large Scale Steel Space Trusses Using a Symbiotic Organisms Search Algorithm

To cite this article: F T Wong *et al* 2020 *J. Phys.: Conf. Ser.* **1625** 012019

Member Sizing Optimization of Large Scale Steel Space Trusses Using a Symbiotic Organisms Search Algorithm

F T Wong, D Prayogo, R E Putra and J Joseph

Department of Civil Engineering, Petra Christian University, Surabaya - Indonesia
Corresponding author: wftjong@petra.ac.id

Abstract. A systematic approach of optimization is needed to achieve an optimal design of large and complex truss structures. In the last three decades, several researchers have developed and applied various metaheuristic optimization methods to the design of truss structures. This paper investigates a new metaheuristic algorithm called symbiotic organisms search (SOS) for member sizing optimization of relatively large steel trusses. The case studies include a 120-bar dome truss and a 942-bar tower truss. The structural analyses are carried out using the standard finite element method. The profiles of the truss members are circular hollow structural sections selected from a set of the American Institute of Steel Construction standard profiles. The design results using the SOS are then compared to those obtained using other metaheuristic methods, namely the particle swarm optimization, differential evolution, and teaching-learning-based optimization. The comparison shows the superior performance of the SOS in terms of the optimal solution, consistency, and convergence. Thus, the SOS is a good alternative for optimizing the design of steel truss structures in real engineering practice.
Keywords: steel truss, metaheuristic, symbiotic organisms search

1. Introduction

Structural design optimization is a process of minimizing the weight and cost of a structure without exceeding limitations stated in building codes and standards [1]. The minimization of the weight reduces the amount of material needed. This is necessary as most structures require non-renewable material resources. Optimization does not only promote the idea of eco-friendly, but it also reduces economic expenses.

With the increased complexity in modern structures, researchers have been developing various 'metaheuristic' optimization methods (that is, a class of stochastic methods that simulates different natural phenomena to obtain a nearly optimal solution) during the past four decades. Early algorithms include genetic algorithm (GA) [2], particle swarm optimization (PSO) [3], and differential evolution (DE) [4]. More recently developed algorithms are, for examples, teaching–learning-based optimization (TLBO) [5] and symbiotic organisms search (SOS) [6].

Among many newly developed metaheuristic algorithms, the SOS has drawn our attention because of its excellent performance and parameter-less nature. The SOS algorithm has been successfully applied to solve different optimization problems in engineering [7], including truss design optimization problems [8]. However, the truss problems considered in the previous studies are relatively small. In other words, the performance of the SOS in member size design optimization of large scale trusses has not known yet. Thus, it is the purpose of this paper to examine the performance of the SOS in optimizing member sizes of relatively large trusses.

Journal of Physics: Conference Series **1625** (2020) 012019 doi:10.1088/1742-6596/1625/1/012019

The truss structures considered in this study are two steel space trusses taken from literature, namely: (1) a 120-bar dome shaped truss [9-10] and (2) a 942-bar truss tower [11-12]. The structural analyses are carried out using the standard finite element method (the direct stiffness method). The profiles of the members are circular hollow structural sections selected from a set of the American Institute of Steel Construction standard profiles [13]. The design results are then compared to those obtained using other metaheuristic methods, namely the PSO, DE, and TLBO.

2. Formulation of the Truss Design Optimization Problem

The objective of member size design optimization is to obtain a truss with a minimum weight that satisfies a set of given design requirements. The size optimization is carried out by selecting a collection of member profiles from a list of readily available standard sections. Here we consider a steel truss composed of N_m members, which are grouped into N_d different profiles.

2.1. Objective Function

The objective of the optimization is to obtain a vector,

$$\mathbf{x} = [x_1, x_2, \dots, x_{N_\mathrm{d}}]^\mathrm{T} \tag{1}$$

that represents the sections used for N_d design variables and corresponds to a vector of cross sectional areas,

$$\mathbf{A} = [A_1, A_2, \dots, A_{N_\mathrm{m}}]^\mathrm{T} \tag{2}$$

such that the structural weight (objective function),

$$W(\mathbf{A}) = \sum_{m=1}^{N\mathrm{m}} \rho_m g L_m A_m \tag{3}$$

attains its minimal value. Here, ρ_m, L_m and A_m are the mass density, length and cross sectional area of the *m*-th truss member, respectively, and g is the gravitational acceleration.

2.2. Constraint Functions

Generally, the design constraints consist of the following limitations imposed on the structure as well as individual members:

$$g_m = \frac{\sigma_m}{(\sigma_m)_\mathrm{all}} - 1 \le 0,\ m = 1, \dots, N_\mathrm{m} \tag{4}$$

$$s_m = \frac{\lambda_m}{(\lambda_m)_\mathrm{all}} - 1 \le 0;,\ m = 1, \dots, N_\mathrm{m} \tag{5}$$

$$\delta_{j,k} = \frac{d_{j,k}}{(d_{j,k})_\mathrm{all}} - 1 \le 0;,\ j = 1, \dots, N_\mathrm{j} \tag{6}$$

In equations (4) − (6), g_m, s_m and $\delta_{j,k}$ are the optimization constraints on stresses, slenderness ratio, and joint displacements, respectively. Symbols σ_m and $(\sigma_m)_\mathrm{all}$ are the computed and allowable axial stress for the *m*-th member, respectively. Symbols $\lambda_m$and $(\lambda_m)_\mathrm{all}$ are the slenderness ratio and its upper limit for the *m*-th member, respectively. Symbols $d_{j,k}$ and $\left(d_{j,k}\right)_\mathrm{all}$ are computed displacements in the *k*-th direction of the *j*-th joint and its allowable value, respectively. N_j is the total number of joints in the structure.

3. Symbiotic Organisms Search Optimization Method

Symbiosis is a relationship between different organisms living in an ecosystem. The purpose of their relationship is to increase survivability inside the ecosystem. Three major types of symbiotic relationships are mutualism, commensalism, and parasitism. Mutualism means both sides are benefited. Commensalism is when one party is benefited, but the other is neither benefited nor harmed. Parasitism results in one party benefited and the other is harmed. Examples of these three types of symbiosis are illustrated in figures 1–3.

Figure 1. Rhinos and oxpeckers living in symbiotic mutualism.

Figure 2. Clown fishes and sea anemones living in symbiotic commensalism.

Figure 3. A leech and human living in symbiotic parasitism.

Simulating the symbiosis process in nature, the SOS algorithm first initializes an ecosystem with a number population of organisms. Each organism then interacts with a randomly chosen organism and undergoes the three phases of symbiosis. The purpose of these symbiosis phases is to improve the fitness values of the organisms. This process is repeated until a termination criterion is met. In the following, each phase of symbiosis is briefly addressed. A detailed SOS algorithm can be found in the original article [6].

3.1. Mutualism Phase

An example of a mutualistic relationship is between oxpeckers and rhinos (figure 1). The oxpecker, a bird species, eats bugs and parasites on the rhino. The rhino benefits in better hygiene and the oxpecker benefits from obtaining food.

In the SOS algorithm, at the *i*-th iteration, an organism (solution candidate) $\mathbf{x}_i$ is chosen and paired randomly with another organism called $\mathbf{x}_j$. The process of creating a better solution through the mutual relationship between $\mathbf{x}_i$ and $\mathbf{x}_j$ can be expressed as

$$\mathbf{x}_{i\text{new}} = \mathbf{x}_i + \text{rand}(0,1) \times (\mathbf{x}_{\text{best}} - \textit{Mutual\_Vector} \times BF_1) \tag{7}$$

$$\mathbf{x}_{j\text{new}} = \mathbf{x}_j + \text{rand}(0,1) \times (\mathbf{x}_{\text{best}} - \textit{Mutual\_Vector} \times BF_2) \tag{8}$$

$$\text{Mutual\_Vector} = \frac{1}{2}(\mathbf{x}_i + \mathbf{x}_j) \tag{9}$$

In equations 7 and 8, *BF* is a beneficial factor that determines how much an organism would benefit from a mutual relationship. *BF* is set to a randomly chosen number, either 1 or 2. Each new organism, $\mathbf{x}_{i\text{new}}$ and $\mathbf{x}_{j\text{new}}$, will replace $\mathbf{x}_i$ and $\mathbf{x}_j$ only if its fitness value (objective function value) is better than the fitness value of $\mathbf{x}_i$ and $\mathbf{x}_j$.

3.2. Commensalism Phase

Symbiotic commensalism is seen through the relationship between clown fishes and sea anemone, an aquatic plant (figure 2). The sea anemone produces nematocysts, stinging capsules, which fend off predators. The clown fish can protect itself from predators by swimming near the sea anemones. The clown fish benefits from the sea anemone's protection, but the sea anemone itself does not benefit.

In the SOS algorithm, an organism $\mathbf{x}_j$ is chosen to interact with organism $\mathbf{x}_i$ (from the mutualism phase). In this interaction, only organism $\mathbf{x}_i$ will benefit and organism $\mathbf{x}_j$ will remain the same. The commensalism phase can be expressed as

$$\mathbf{x}_{i\text{new}} = \mathbf{x}_i + \text{rand}(-1,1) \times (\mathbf{x}_{\text{best}} - \mathbf{x}_j) \tag{10}$$

Organism $\mathbf{x}_{i\text{new}}$ will replace $\mathbf{x}_i$ only if its fitness value is better than that of $\mathbf{x}_i$.

3.3. Parasitism Phase

Parasitism can be seen in the everyday life of smaller organisms, which attach themselves to bigger organisms in order to benefit from its host. An example of parasitism is between leeches and humans (figure 3). A leech lives by feeding on blood. When in contact with human skin, the leech bites and sucks the blood out. The leech is benefited with food while the human is harmed in the process.

The SOS algorithm provides a parasite by altering some components of organism $\mathbf{x}_i$. The altered organism is given the name "Parasite_Vector" and is compared with a randomly selected organism $\mathbf{x}_j$. The fitness of both Parasite_Vector and organism $\mathbf{x}_j$ are then evaluated. If Parasite_Vector is better than organism $\mathbf{x}_j$ then it kills organism $\mathbf{x}_j$ and replaces it. Conversely, if organism $\mathbf{x}_j$ is better, then the Parasite_Vector dies.

4. Tests of the Symbiotic Organisms Search Algorithm - Results and Discussion

The optimization problems below are used to evaluate the capability of the SOS algorithm in finding a minimum weight in steel truss structures. The results are compared to those available from literature and to other metaheuristic algorithms, namely the PSO, DE, and TLBO. The algorithms are coded in Matlab.

The common algorithm parameters used for all algorithms are: the number of organisms is 20, and the number of function evaluations is 50,000 (the looping termination criterion). Since the algorithms considered are stochastic, each algorithm run will most likely give a different result. Therefore, each algorithm is run 30 times as independent runs to investigate the consistency of the results.

4.1. 120 - Bar Dome - Shaped Truss

The first structure is a 120-bar dome truss. It was originally used by Soh and Yang [9] as a shape optimization problem to evaluate the performance of a fuzzy-controlled genetic algorithm search. Subsequently, this structure was employed by Kaveh and Mahdavi [10] as a case study in the member sizing optimization using the so-called colliding bodies optimization (CBO). The truss is composed of 120 elements and 49 nodes, which is divided into 7 groups of member size as shown in figure 4. The members made from steel pipes with the material properties: mass density = 7971.81 kg/m^3, modulus of elasticity = 210,000 MPa and yield stress = 400 MPa. The member cross sectional areas are ranging from 500 mm^2 to 12,903 mm^2. All joints in the structure, except restrained joints, are subjected to a gravitational point load: at node 1 = 60 kN, at nodes 2–13 = 30 kN, and at nodes 1437 = 10 kN.

A displacement constraint of 5 mm for all nodes in the *x*, *y*, and *z* directions and stress constraints according to AISC ASD 1989 [13] are applied [10]. The stress limitation for each truss member number *m* is given as

$$\sigma_m = \begin{cases} 0.6F_y & \text{if } \sigma_m \geq 0 \\ \sigma_m^{\mathrm{b}} & \text{if } \sigma_m < 0 \end{cases} \tag{11}$$

where σ_m^{b} is the buckling stress of member *m*, which is a function of the slenderness ratio, given as

$$\sigma_m^{\mathrm{b}} = \begin{cases} \dfrac{\left(1-\frac{\lambda_m{}^2}{2C_{\mathrm{c}}{}^2}\right)F_{\mathrm{y}}}{\frac{5}{3}+\frac{3\lambda_m}{8C_{\mathrm{c}}}-\frac{\lambda_m{}^3}{8C_{\mathrm{c}}{}^3}} & \text{if } \lambda_m < C_{\mathrm{c}} \\ \dfrac{12\pi^2 E}{13\lambda_m{}^2} & \text{if } \lambda_m \geq C_{\mathrm{c}} \end{cases} \tag{12a}$$

$$\lambda_m = \frac{KL_m}{r_m}, \quad C_{\mathrm{c}} = \sqrt{\frac{2\pi^2 E}{F_{\mathrm{y}}}} \tag{12b}$$

where *E* is the modulus of elasticity, F_{y} is the yield stress of steel, λ_m is the slenderness ratio of member number *m*, C_{c} is the slenderness ratio dividing the elastic and inelastic buckling regions, *K* is the effective length factor (*K* = 1), L_m is the length of member *m* and r_m is the radius of gyration of member *m*. The radius of gyration is calculated in terms of cross-sectional areas as:

$$r_m = aA_m{}^b \tag{13}$$

where *a* = 0.4993 and *b* = 0.6777 for pipe sections and *A* must be in cm^2.

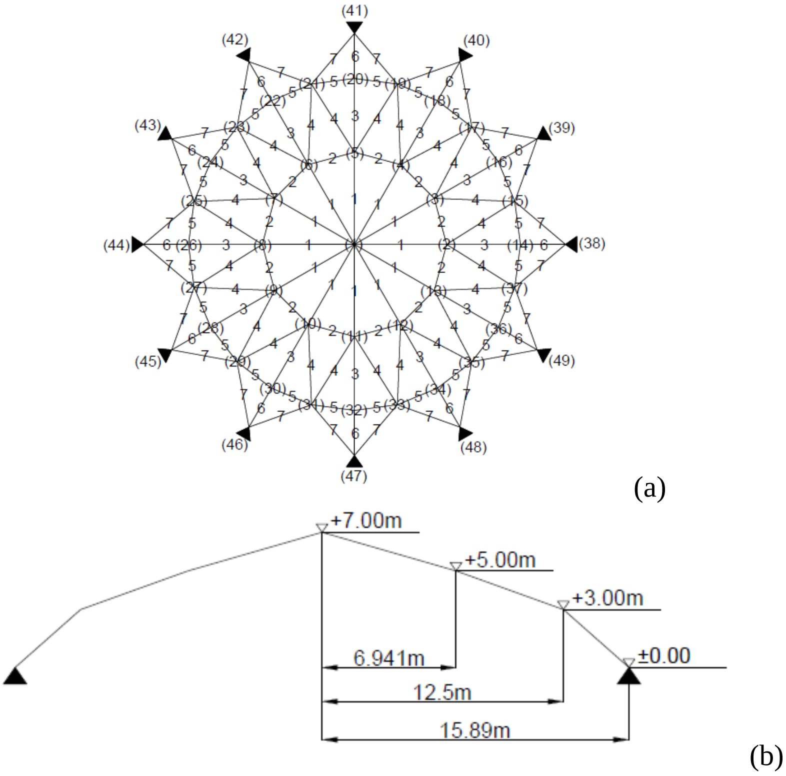


Figure 4. Schematic of 120-bar dome truss: (a) top view and (b) side view.

The best optimization results (the least structural weight) from 30 or less independent runs using the SOS and other comparative methods are presented in table 1. The number of independent runs could be less than 30 because the results obtained from some algorithm runs violate the given design constraints. The statistics of the running process and the weight results are shown in table 2. The table shows that the least weight is attained by the TLBO and SOS, that is, 14,479 kgf. It verifies that the SOS to be more reliable as it is successful in all 30 independent runs and all obtained results are similar to the best result.

Table 1. The best member cross sectional areas (mm^2) of the 120-bar dome truss obtained using different optimization algorithms[a].

Area (mm^2)	CBO [10]	PSO	DE	TLBO	SOS
A1	1953	1550	1725	1476	1476
A2	9789	12903	10955	10070	10076
A3	3377	12903	3338	3547	3554
A4	2012	1509	1694	1617	1617
A5	5228	3487	5763	5758	5757
A6	2204	12903	1898	2313	2294
A7	1608	1218	1440	1273	1276

[a] From 30 or less independent runs (see table 2).

Table 2. Statistics of optimization runs using different algorithms for the 120-bar dome truss.

	CBO [10]	PSO	DE	TLBO	SOS
Best weight (kgf)	15098	23767	14940	14479	14479
Average weight (kgf)	-	42407	22043	14559	14481
Standard deviation (kgf)	-	8776	13778	214	2
CoV (%)	-	20.69	62.51	1.47	0.01
Successful independent runs	-	30	15	21	30
No. FE	14960	50000	50000	50000	50000
Average running time (sec)	-	6929	6694	6781	6894

Figure 5 shows the convergence history of the PSO, DE, TLBO and SOS algorithms in terms of the weight vs. number of function evaluations. The figure demonstrates that the SOS algorithm has better search efficiency than the PSO and DE and is comparable to the TLBO. It should be mentioned here that we use the number of function evaluations, instead of the number of iterations, to assess the convergence because the number of function of evaluations employed by each algorithm for each iteration is different, that is, 20 for the PSO and DE, 40 for the TLBO, and 80 for the SOS.

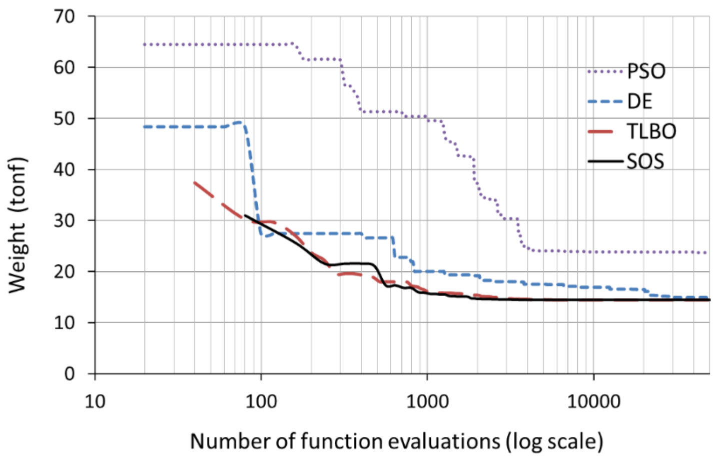


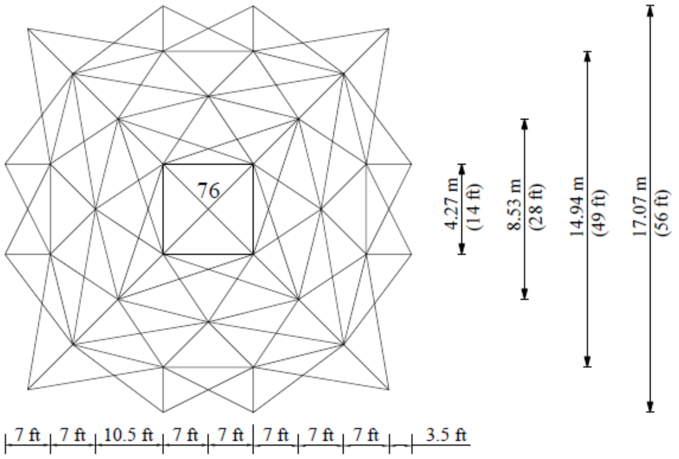
Figure 5. Convergence to a minimum weight for the 120-bar dome truss.

4.2. 942 - Bar Tower Truss

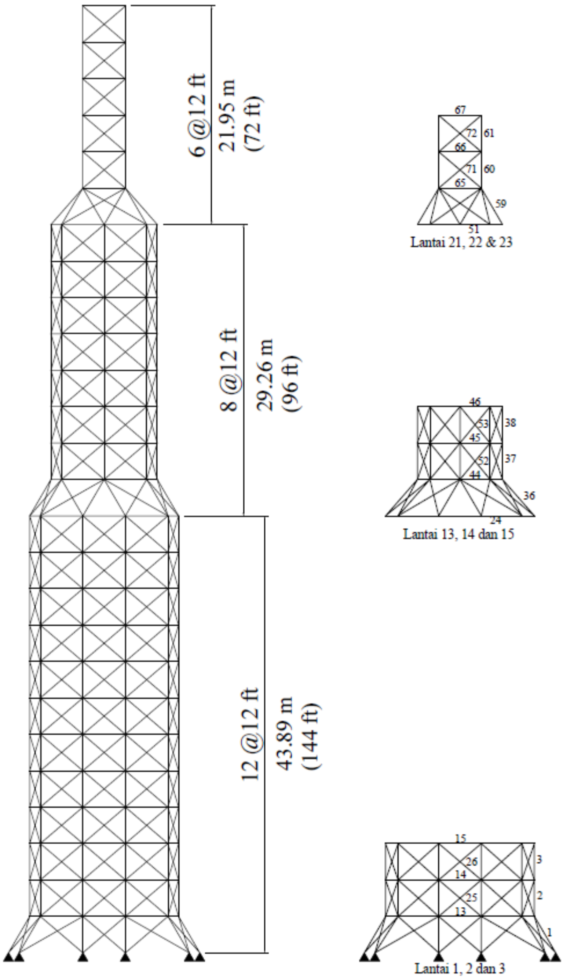
This 942-bar tower consists of 26 floors and has been optimized with 59 groups of member sizes by Hasancebi using adaptive evolution strategies [11]. The structure is then optimized with 76 groups of member sizes by Kaveh and Ghazaan [12] using the so-called vibrating system (VPS) algorithm. The schematic of this structure can be seen in figure 6. This structure is subjected to concentrated forces on all of the unrestrained nodes with the magnitudes of 5 kN in the x direction, 5 kN in the y direction and −30 kN in the z direction. The material used has the following properties: mass density = 7972 kg/m^3, modulus of elasticity = 200,000 MPa and yield stress = 248 MPa. The member profiles are selected from the AISC-ASD standard list [14] of 259 WF profiles.

The structural deformation is limited to a maximum displacement of 80 mm for all nodes in all directions. The stress constraint is calculated according to AISC-ASD [13] as given in equations (11) and (12). An additional constraint applied to this structure is the slenderness ratio. If the element is in tension, the maximum slenderness ratio is 300. If the element is in compression, the maximum slenderness ratio is 200.

Journal of Physics: Conference Series **1625** (2020) 012019 doi:10.1088/1742-6596/1625/1/012019



(a)



(b)

Figure 6. Schematic of 942-bar tower truss: (a) top view and (b) side view (redrawn from [12]).

Statistics of 30 independent runs of the SOS and the other comparative methods are reported in Table 3. It is seen that the DE gives the least weight of 422,988 kgf, followed by the SOS with 428,086 kgf. The performance of the DE is the best both in terms of the minimum weight and consistency (the lowest coefficient of variation), while the SOS is the second best.

Table 3. Statistics of optimization runs using different algorithms for the 942-bar tower truss.

	VPS [12]	PSO	DE	TLBO	SOS
Best weight (kg)	430,598	1,224,881	422,988	461,414	428,086
Average weight (kg)	-	1,508,806	423,837	546,844	451,437
Standard deviation (kg)	-	175,886	2,012	60,319	15,924
CoV (%)	-	11.66	0.47	11.03	3.53
Successful independent runs	-	30	30	30	30
No. FE	26180	50000	50000	50000	50000
Average running time (sec)	-	106200	93713	92685	93723

Figure 7 shows the convergence of the best result for each algorithm. It is seen that all of the metaheuristic algorithms, except the PSO, convert to nearly the same value of the weight. The convergence rate of the SOS is comparable to that of the DE.

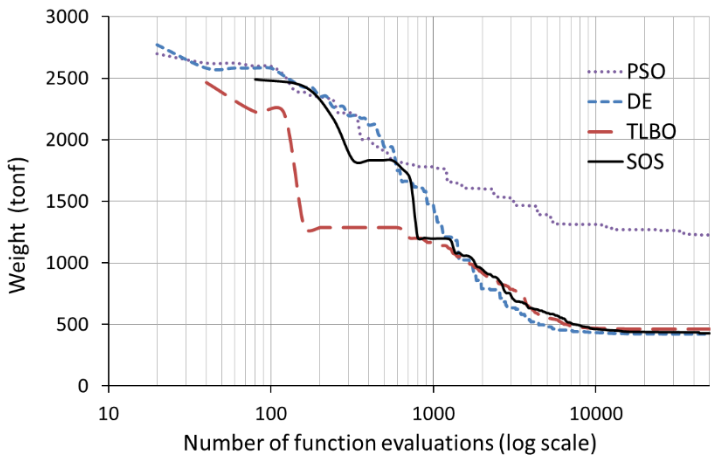


Figure 7. Convergence to a minimum weight for the 942-bar tower truss.

5. Conclusions

The SOS algorithm has been tested for member sizing optimization of two relatively large steel trusses, namely a 120-bar dome and a 942-bar tower truss structures. The results were compared to other meta-heuristic algorithms, that is, the particle swarm optimization (PSO), differential evolution (DE), teaching-learning-based optimization (TLBO), and those given in the references. The SOS gave the least weight for the 120-bar dome structure in comparison to the other metaheuristic methods. For the 942-bar tower structure, however, the SOS yielded the second best optimum result. The SOS competed closely with a heavier weight difference of only 1.21% relative to the least weight obtained using the DE. In both study cases, the SOS was very consistent in all 30 independent runs and had excellent convergence behavior in both cases. The SOS generally performs well in optimizing large scale steel truss structures. Therefore, the SOS is a reliable method that may be used for member sizing optimization of large scale truss structures in practical engineering design.

6. References

[1] Cheng M Y, Prayogo D, Wu Y W and Lukito M M 2016 *Autom. Constr.* **69** 21–33
[2] Holland J H 1975 *Adaptation in Natural and Artificial Systems* (Ann Arbor: University of Michigan Press)
[3] Eberhart R and Kennedy J 1995 *Proc. 6th Int. Symp. on Micro Machine and Human Science* (IEEE) pp. 39–43

Journal of Physics: Conference Series **1625** (2020) 012019 doi:10.1088/1742-6596/1625/1/012019

[4] Storn R and Price K 1997 *J. Glob. Optim.* **11** 341–59
[5] Rao R V, Savsani V J and Vakharia D P 2011 *CAD Comput. Aided Des.* **43** 303–15
[6] Cheng M Y and Prayogo D 2014 *Comput. Struct.* **139** 98–112
[7] Ezugwu A E and Prayogo D 2019 *Expert Systems with Applications* **119** 184–209
[8] Prayogo D, Wong F T, Gunawan R, Ali S K and Sugianto S 2018 *J. Tek. Sipil ITB* **25** 41–52
[9] Soh C K and Yang J 1996 *J. Comput. Civ. Eng.* **10** 143–50
[10] Kaveh A and Mahdavi V R 2014 *Comput. Struct.* **139** 18–27
[11] Hasançebi O 2008 *Comput. Struct.* **86** 119–32
[12] Kaveh A and Ghazaan M I 2017 *Int. J. Optim. Civ. Eng.* **7** 355–66
[13] AISC 1989 *Manual of Steel Construction-Allowable Stress Design* (USA)

Acknowledgment
We gratefully acknowledge that the present research is financially supported by the Ministry of Research, Technology and Higher Education of the Republic of Indonesia under “Penelitian Dasar Unggulan Perguruan Tinggi (PDUPT)” 2019 Research Grant Scheme.