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Optimal Design of Plane Truss Structures Using Differential Evolution Algorithm

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ABSTRACT

Economical attention in the field of steel structures is gaining importance over the years and has motivated researchers for the development of many algorithms, such as : Genetic, Particle Swarm, Artificial Bee Colony,… etc. These algorithms aim at achieving optimal design of truss structures. In this paper, Differential Evolution Algorithm with discrete design variables is applied to optimize the design of plane truss structures. Optimization of trusses aims at reducing their weight; i.e., in search of a most economic section. The optimum values for cross-sectional areas of truss members are to be such that they minimize the structural weight of truss, without violating the constraints. The constraints are a specified range of area, as well as deflection and stress values with upper and lower limits which have to be satisfied by each and every individual member of the truss. Fitness values are calculated for the population from the objective function derived and penalized if the constraints are violated. The process of differential evolution starts with an initial population and continues until the termination condition is satisfied. C++ programming language is employed for efficient operation. To study the efficiency of Differential Evolution Algorithm applied to truss optimization, five plane trusses are designed. When compared with manually designed truss structures, the result of DEA is found to give robust and superior truss structures. Final results show that the optimized weight of trusses obtained is 30% less than that of the same truss designed manually. Ultimately, a common DEA applied program to optimize any plane truss is developed and optimal F and CR values are found.

KEYWORDS: Optimization, Plane truss, Differential evolution, Deflection, Stress.

INTRODUCTION

Demand for economical construction is a common challenge faced by most of designers and engineers. After various research and practical experiments, researchers have found that the weight of the structure seriously affects the cost of construction. Hence, preferring light weight structures is the wise idea to carry out economical construction. Preference of light weight structures is greatly realized in the design of steel structures. Presently, steel structures are much preferred over RCC structures for industrial purposes. Hence, a light weight steel structure which replaces a primitive structure should be rigid and strong enough to carry the same amount of loading and sustain greater deflection and stress. These conditions can be satisfied only through optimization. This research paper aims at optimizing industrial truss structures. Each and every member of the truss structure is optimized, so that the gross weight of the whole structure is reduced, which ultimately results in most economical construction of the structure.

Economical consideration in the field of steel

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structures has gained importance in recent years and pushed for the development of various population-based evolutionary algorithms. Genetic algorithm (GA) (Shallan et al., 2014) is the foremost approach for truss optimization, which is based on natural evolutionary process. Particle swarm optimization (Luh and Lin, 2011) clearly explained the superiority of two-stage ant algorithm over one-stage genetic algorithms. Modified teaching-learning-based optimization (Camp and Farshchin, 2014) is an interesting method applying the behavior of a teacher and students in a classroom. One of the theories of evolution of universe, Big Bang-Big Crunch, was effectively used for truss optimization (Kaveh and Talatahari, 2009). The effectiveness of artificial bee colony algorithm was clearly demonstrated by Sonmez (2010). One-dimensional collision between two bodies was modeled into an algorithm for truss optimization by Kaveh and Mahdavi (2014). The robust algorithm for minimization problems, differential evolution algorithm, was applied for simultaneous optimization of truss by Yin Wu et al. (2010). The above mentioned approaches and attempts incorporate various algorithms and perform various optimization types, such as: size, shape or topology optimization. Truss optimization using continuous variables may lead to unfeasible or non-practical solutions. This paper presents a differential evolution algorithm that can handle discrete variables to optimize the area of industrial plane trusses. Each and every member of a truss is optimized; that is, in search of the most economic section, thereby reducing the structural weight of the truss. Meanwhile, the constraints to be satisfied are not violated. If violated, based on the extent of violation, corresponding penalty is levied to exclude such a bad result from further generations.

Truss Design

Truss optimization refers to optimal design of truss structures so as to minimize the structural weight of the truss without violating the area, stress and displacement constraints. Hence, for a given truss the geometry of which is fixed, the objective is to find a steel section with minimum cross-sectional area while satisfying the constraints. The truss optimization problem can be formulated as:

$$Minimize W = \sum_{m=1}^{N} \gamma_m L_m A_m \qquad (1)$$

Subject to:

$$\sigma^L \leq \sigma_m \leq \sigma^U \qquad (2)$$

$$\delta^L \leq \delta_m \leq \delta^U \qquad (3)$$

$$A^L \leq A_m \leq A^U \qquad (4)$$

where W is the structural weight of the assumed truss with N members and for each member m, γ_m is the unit weight of the material. L_m and A_m are the length and cross-sectional area of the corresponding member, respectively. The optimized result must be such that the member stress σ_m and nodal deflection δ_m should be within the specified upper U and lower L limits. If violated, a penalty is levied based on the extent of violation.

Differential Evolution Algorithm

Differential evolution algorithm (DEA) is a population- and evolution-based algorithm. The initial population for the algorithm is randomly generated within the specified upper and lower limits. The initial population is generated using the following equation:

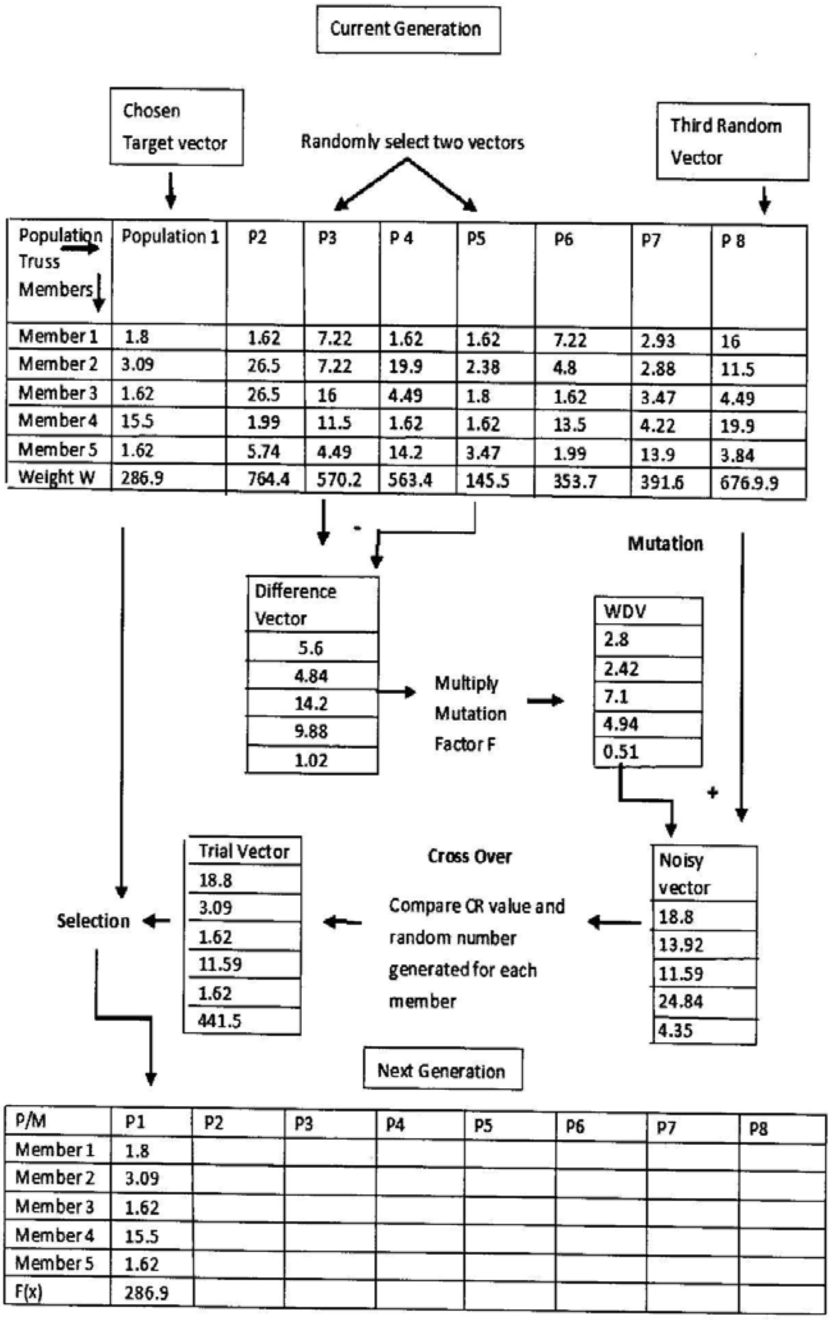
$$A_{ij} = A_{min} + rand\ (A_{max} - A_{min}) \qquad (5)$$

where

A_{ij} = area of j^{th} member on i^{th} population.

rand = random number generated in the range (0.1-0.9).

A_{max} and A_{min} = upper and lower bounds of area.



Population → Truss Members ↓	Population 1	P2	P3	P 4	P5	P6	P7	P 8
Member 1	1.8	1.62	7.22	1.62	1.62	7.22	2.93	16
Member 2	3.09	26.5	7.22	19.9	2.38	4.8	2.88	11.5
Member 3	1.62	26.5	16	4.49	1.8	1.62	3.47	4.49
Member 4	15.5	1.99	11.5	1.62	1.62	13.5	4.22	19.9
Member 5	1.62	5.74	4.49	14.2	3.47	1.99	13.9	3.84
Weight W	286.9	764.4	570.2	563.4	145.5	353.7	391.6	676.9.9

Difference Vector
5.6
4.84
14.2
9.88
1.02

WDV
2.8
2.42
7.1
4.94
0.51

Noisy vector
18.8
13.92
11.59
24.84
4.35

Trial Vector
18.8
3.09
1.62
11.59
1.62
441.5

P/M	P1	P2	P3	P4	P5	P6	P7	P8
Member 1	1.8							
Member 2	3.09							
Member 3	1.62							
Member 4	15.5							
Member 5	1.62							
F(x)	286.9							

Figure (1): Mechanism of DEA (Suribabu, 2010), explained considering a 5-bar truss

DEA includes three operations: 1) mutation, 2) cross-over and 3) selection. It also comprises three controlling factors: 1) mutation factor F, 2) cross-over factor CR and 3) population size NP.At the start of DEA, two vectors are randomly selected from the population. Difference is found out between the vectors and then multiplied by the mutation factor. It becomes the weighted difference vector (WDV). A third vector is randomly selected and added to WDV to get the noisy vector. Now a random number is generated for each individual in a vector and then compared with the cross-over factor (initial input). The process of selection takes place. The individuals of the target vector (fixed at the start) are compared with that of the noisy vector.

If the random number > CR, then the target vector value is selected.

If the random number < CR, then the noisy vector value is selected.

The selection process results in the trial vector. The objective function for the trial vector is calculated. At this juncture, the area of the member is converted into the nearest available value. The objective function of the trial vector is compared with that of the target vector. The vector with the lowest objective function becomes the population for the next generation. This process continues until the entire population array is filled up. The number of generations created depends on the termination criteria. Fig. 1 illustrates the various processes involved in the optimization of a 5- bar truss structure.

Implementation of Differential Evolution Algorithm

To implement differential evolution algorithm, C++ programming language has been used. Dev C++ 5.6.2 is the toolbox used to execute this optimization process. STAAD pro software is used to collect the structural details of the design examples used. The sequence of the execution process of the program is listed below.

1. Input parameters F, CR and NP are entered.
2. Population initialization.
3. Calculation of objective function.
4. Mutation, cross-over, selection.
5. Checking with the constraints.
6. Application of penalty, if required.
7. Population array for next generation is filled up.

The user-specified or input parameters are F, CR and NP. The termination criteria are; i.e., number of iterations that the algorithm has to run. For each generation, a text file containing the current populations and their objective functions is created. The minimum value from each generation is compiled and stored in a separate text file, so that the user can identify the optimal result and the point of convergence.

Design Examples

To examine the efficiency and accuracy of the algorithm and the coding, the following five industrial plane trusses (Figs. 2-6) are chosen as design examples.

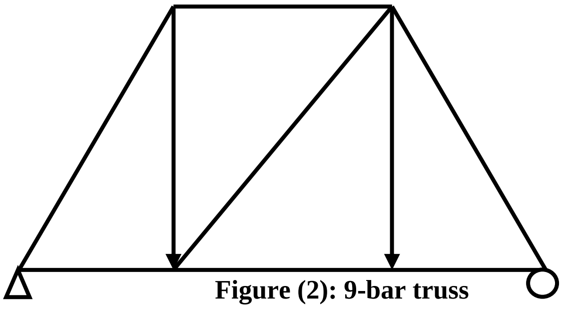


Figure (2): 9-bar truss

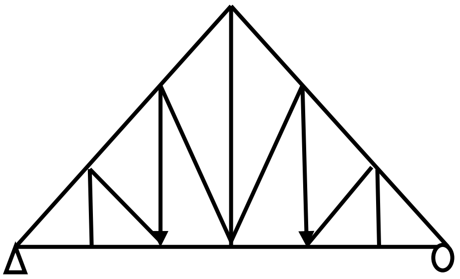


Figure (3): 21-bar howe roof

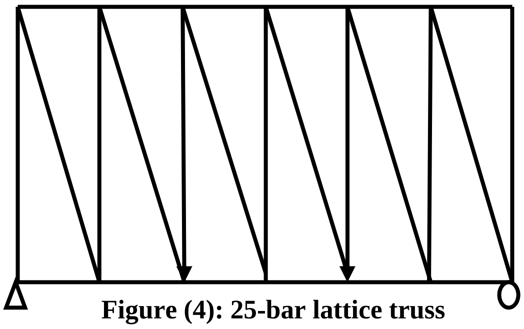


Figure (4): 25-bar lattice truss

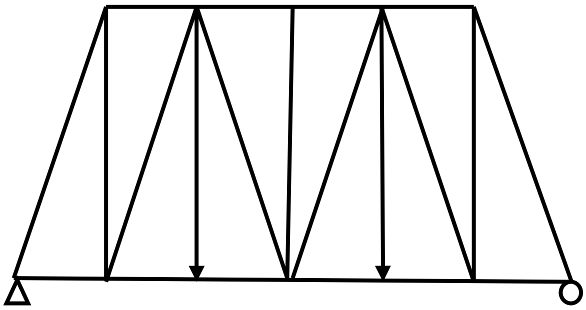


Figure (5): 21-bar howe bridge

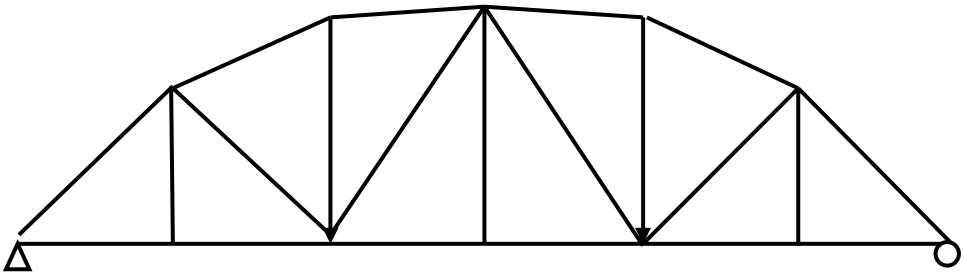


Figure (6): Bowspring truss

In each design example, two vertical loads of P= 445 kN (100 kips) (Camp and Farshchin, 2014) are symmetrically applied. The points of load application are indicated with the arrow marks in the figures of design examples. The length of each member in the design examples is decided such that no member is longer than 5 meters. The supporting condition of the trusses is maintained as simply supported. The material is assumed to be industrial steel with a density of $\rho = 0.1$ Lb/in^{3}and a modulus of elasticity of $E = 1 \times 10^4$ ksi (Yin Wu et al., 2010). The axial forces on the truss members under loading condition are found out. Vertical displacement at the loading nodes is found out using the principle of virtual forces. Hence, for the coded program to execute the algorithm, an input file for member lengths, member axial forces under actual loading and member virtual forces under two unit loadings is required.

Constraints to Be Checked

Once the input parameters are fed and the initial population is generated, the program executes the differential evolution algorithm. At the end of first generation, the population members for the next generation are created. But, these values have to be checked with the constraints before filling the population array for the next generation. The foremost constraint to be checked is area. The generated values must be within the range of user-specified A_{max} and A_{min}. As continuous design variables may lead to an unfeasible solution and considering their non-availability in the market, only discrete design variables (cross-sectional area of members in inch^2) are used in this approach. The discrete design area values taken are (1.62, 1.80, 1.99, 2.13, 2.38, 2.62, 2.88, 2.93, 3.09, 3.13, 3.38, 3.47, 3.55, 3.63, 3.84, 3.87, 3.88, 4.18, 4.22, 4.49, 4.59, 4.80, 4.97, 5.12, 5.74, 7.22, 7.97, 11.5, 13.5, 13.9, 14.2, 15.5, 16.0, 16.9, 18.8, 19.9, 22.0, 22.9, 26.5, 30.0 and 33.5 inch^2) (Camp and Farshchin, 2014). The second constraint to be checked is member stress. The member stress is found out by the ratio of axial force in the member to the area for the corresponding member obtained from the current generation. The maximum allowable stress in any truss member is limited to ± 25 ksi (Yin Wu et al., 2010) (1Lb = 4.45 N and 1 inch^2 = 6.452 cm^2). The third constraint to be checked is displacement. The vertical displacement at any loading node (consider a node C) is found out by the principle of virtual forces using the relation:

$$(\Delta_c)_v = \sum \frac{kFL}{AE} \tag{6}$$

where k= truss member forces due to unit vertical load.

F= truss member forces due to live load.

L= member length.

A= area of the member.

E= Modulus of elasticity of steel.

The maximum nodal deflection in the vertical direction in all the design examples is limited to ± 2.0 inches (Camp and Farshchin, 2014). Each time the obtained design variable violates these constraints, a penalty of 1000 is added or levied to the objective function of the particular population. For instance, if a particular population violates these constraints 10 times, then a penalty of 10000 is added to the objective function, so that such a bad population can be neglected from further generations. There stands the advantage of differential evolution algorithm, which justifies greater use of DEA in minimization problems.

Table 1. Manual and optimal design of 9-bar truss

Truss Members	Axial forces in members in kN	Length of members in m	Angle sections designed based on IS 800	Area provided in inch^2	Volume of each member in inch^3	Optimized area of members in inch^2
1	445	3	ISA 60x 60 x 6	3.0349	358.45203	5.74
2	629.32(C)	4.24	ISA 200x 200 x 12	7.2245	1205.9854	1.62
3	445	3	ISA 60x 60 x 6	3.0349	358.45203	4.18
4	445	3	ISA 60x 60 x 6	3.0349	358.45203	1.62
5	445	4	ISA 45x 45 x 6	3.0349	477.93605	2.38
6	445	3	ISA 60x 60 x6	3.0349	358.45204	5.74
7	445(C)	4	ISA 150 x 150 x 15	6.6309	1044.2341	1.99
8	0	5	ISA 20 x 20 x 3	0.868	170.8658	2.62
9	629.32(C)	4.24	ISA 200 x 200 x 12	7.2245	1205.9855	1.62
			Total volume of members =5538.8151 inch^3(0.090765 m^3) Structural weight of truss = 553.8 lb (250 kg) Optimized volume of members= 3785.72 inch^3 (0.06204m^3) Optimized structural weight of truss = 378.5 lb (171 kg)			

Table 2. Manual and optimized design of howe roof

Truss Members	Axial forces in members in kN	Length of members in m	Angle sections designed based on IS 800	Area provided in inch^2	Volume of each member in inch^3	Optimized area of members in inch^2
1	1112.5	3.333	ISA 80 x 80 x 10	7.58725	995.6005	1.99
2	1112.5	3.333	ISA 80 x 80 x 10	7.58725	995.6005	4.8
3	1112.5	3.333	ISA 80 x 80 x 10	7.58725	995.6005	3.63
4	1112.5	3.333	ISA 80 x 80 x 10	7.58725	995.6005	7.97
5	1112.5	3.333	ISA 80 x 80 x 10	7.58725	995.6005	4.8
6	1112.5	3.333	ISA 80 x 80 x 10	7.58725	995.6005	3.09
7	1198.2(C)	3.59	ISA 200 x 200 x 25	14.539	2054.917	2.38
8	1198.2(C)	3.59	ISA 200 x 200 x 25	14.539	2054.918	1.8
9	798.8(C)	3.59	ISA 200 x 200 x 15	14.539	2054.918	2.88
10	798.8(C)	3.59	ISA 200 x 200 x 15	14.539	2054.918	22.9
11	1198.2(C)	3.59	ISA 200 x 200 x 25	14.539	2054.918	3.55
12	1198.2(C)	3.59	ISA 200 x 200 x 25	14.539	2054.918	7.97
13	0	1.33	ISA 20 x 20 x 3	0.2309	12.08978	3.13
14	445	2.67	ISA 65 x 65 x 6	3.0349	319.0223	1.8
15	593.33	4	ISA 60 x 60 x 6	3.3490	527.4017	1.62
16	445	2.67	ISA 65 x 65 x 6	3.0349	319.0223	3.55
17	0	1.33	ISA 20 x 20 x 3	0.2309	12.08978	4.18
18	0.0026(C)	3.59	ISA 20 x 20 x 3	0.6232	88.08542	4.49
19	474.89(C)	4.27	ISA 150 x 150 x 15	6.6309	1114.719	4.49
20	474.89(C)	4.27	ISA 150 x 150 x 15	6.6309	1114.719	3.47
21	0.0136	3.59	ISA 20 x 20 x 3	0.6232	88.08542	13.5
			Total volume of members =21898.34 inch^3 (0.35885 m^3) Structural weight of truss = 2189.8 lb (992 kg) Optimized volume of members = 14392.3 inch^3(0.23585 m^3) Optimized structural weight of truss =1439.2 lb (651 kg)			

Table 3. Manual and optimized design of lattice truss

Truss Members	**Axial forces in members in kN**	**Length of members in m**	**Angle sections designed based on IS 800**	**Area provided in inch^2**	**Volume of each member in inch^3**	**Optimized area of members in inch^2**
1	0	3.33	ISA 20 x 20 x 3	0.578088	75.78855	7.22
2	370.833	3.33	ISA 45 x 45 x 6	2.529042	331.5627	4.59
3	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	5.74
4	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	1.62
5	741.668	3.33	ISA 55 x 55 x 10	5.058162	663.1356	1.62
6	370.829	3.33	ISA 45 x 45 x 6	2.529042	331.5627	1.62
7	370.833(C)	3.33	ISA 150 x 150 x 12	5.36145	702.8974	3.38
8	741.668(C)	3.33	ISA 200 x 200 x 12	7.22455	947.1537	1.62
9	741.668(C)	3.33	ISA 200 x 200 x 12	7.22455	947.1537	1.62
10	741.668(C)	4	ISA 200 x 200 x 15	8.959	1410.863	1.62
11	370.829(C)	4	ISA 130 x 130 x 15	5.70555	898.5100	1.62
12	0	4	ISA 20 x 20 x 3	0.6944	109.3541	2.93
13	445(C)	4	ISA 150 x 150 x 15	6.6309	1044.234	1.62
14	445(C)	4	ISA 150 x 150 x 15	6.6309	1044.234	5.74
15	0.00070(C)	4	ISA 20 x 20 x 3	0.6944	109.3541	1.62
16	0.00071(C)	4	ISA 20 x 20 x 3	0.6944	109.3541	5.74
17	445	4	ISA 45 x 45 x 6	3.0349	477.9361	1.62
18	445	4	ISA 45 x 45 x 6	3.0349	477.9361	4.18
19	0	4	ISA 20 x 20 x 3	0.6944	109.3541	1.62
20	579.26	5.21	ISA 45 x 45 x 6	3.950547	810.3271	1.62
21	579.26	5.21	ISA 45 x 45 x 6	3.950547	810.3271	1.62
22	0.00092	5.21	ISA 20 x 20 x 3	0.904456	185.5199	3.13
23	0.00092	5.21	ISA 20 x 20 x 3	0.904456	185.5199	1.62
24	579.264(C)	5.21	ISA 200 x 200 x 12	7.22455	1481.883	2.93
25	579.264(C)	5.21	ISA 200 x 200 x 12	7.22455	1481.883	1.62
			Total volume of members =16072.11 inch^3(0.26337 m^3) Structural weight of truss = 1607.2 lb (728 kg) Optimized volume of members = 10836.3 inch^3 (0.17757 m^3) Optimized structural weight of truss =1083.6 lb (490 kg)			

Table 4. Manual and optimized design of howe bridge

Truss Members	Axial forces in members in kN	Length of members in m	Angle sections designed based on IS 800	Area provided in inch^2	Volume of each member in inch^3	Optimized area of members in inch^2
1	370.833	3.33	ISA 45 x 45 x 6	2.529073	331.5668	3.88
2	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	3.38
3	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	4.18
4	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	1.62
5	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	1.62
6	370.829	3.33	ISA 45 x 45 x 6	2.529042	331.5627	3.84
7	370.829	3.33	ISA 45 x 45 x 6	2.529042	331.5627	4.8
8	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	3.38
9	741.668	3.33	ISA 55 x 55 x 10	5.058161	663.1356	2.93
10	370.829	3.33	ISA 45 x 45 x 6	2.529042	331.5627	2.13
11	445	4	ISA 45 x 45 x 6	3.0349	477.9361	2.62
12	445	4	ISA 45 x 45 x 6	3.0349	477.9361	4.8
13	0	4	ISA 20 x 20 x 3	0.6944	109.3541	2.13
14	445	4	ISA 45 x 45 x 6	3.0349	477.9361	3.09
15	445	4	ISA 45 x 45 x 6	3.0349	477.9361	1.62
16	579.26(C)	5.21	ISA 200 x 200 x 12	7.22455	1481.883	5.74
17	579.26(C)	5.21	ISA 200 x 200 x 12	7.22455	1481.883	3.84
18	579.26(C)	5.21	ISA 200 x 200 x 12	7.22455	1481.883	1.62
19	0.00092	5.21	ISA 20 x 20 x 3	0.904456	185.5199	4.18
20	0.00092(C)	5.21	ISA 20 x 20 x 3	0.904456	185.5199	1.62
21	579.26(C)	5.21	ISA 200 x 200 x 12	7.22455	1481.883	1.62
			Total volume of members =13624.73 inch^3 (0.22327 m^3) Structural weight of truss = 1362.4 lb (617 kg) Optimized volume of members =10228.8 inch^3 (0.16762 m^3) Optimized structural weight of truss =1022.8 lb (463kg)			

Table 5. Manual and optimized design of boewspring truss

Truss Members	Axial forces in members in kN	Length of members in m	Angle sections designed based on IS 800	Area provided in inch^2	Volume of each member in inch^3	Optimized area of members in inch^2
1	534	3	ISA 70 x 70 x 6	3.64188	522.1757	4.18
2	534	3	ISA 70 x 70 x 6	3.64188	522.1757	4.22
3	667.5	3	ISA 70 x 70 x 8	4.55235	815.8996	1.62
4	667.5	3	ISA 70 x 70 x 8	4.55235	815.8996	7.22
5	534	3	ISA 70 x 70 x 6	3.64188	522.1757	5.12
6	534	3	ISA 70 x 70 x 6	3.64188	522.1757	3.87
7	695.1(C)	3.91	ISA 200 x 200 x 12	7.22455	2054.883	4.49
8	771.3(C)	3.25	ISA 150 x 150 x 18	7.87245	2439.974	3.13
9	714.4(C)	3.01	ISA 150 x 150 x 18	7.87245	2439.974	7.97
10	714.4(C)	3.01	ISA 150 x 150 x 18	7.87245	2439.974	7.97
11	771.3(C)	3.25	ISA 150 x 150 x 18	7.87245	2439.974	2.38
12	695.1(C)	3.91	ISA 200 x 200 x 12	7.22455	2054.883	1.62
13	0	4	ISA 20 x 20 x 3	0.6944	18.98387	1.62
14	237.3	3.75	ISA 35 x 35 x 5	1.618386	103.1169	3.13
15	237.3	3.75	ISA 35 x 35 x 5	1.618386	103.1169	4.49
16	0	2.5	ISA 20 x 20 x 3	0.434	7.415576	1.62
17	0	2.5	ISA 20 x 20 x 3	0.434	7.415576	3.84
18	231.7	3.91	ISA 35 x 35 x 5	1.580194	98.30740	3.84
19	74.1	5	ISA 20 x 20 x 3	0.505362	10.05473	2.38
20	74.1	5	ISA 20 x 20 x 3	0.505362	10.05473	2.93
21	231.7	3.91	ISA 35 x 35 x 5	1.580194	98.30740	4.18
			Total volume of members =18046.93inch^3 (0.29574 m^3) Structural weight of truss = 1804.6 lb (818 kg) Optimized volume of members = 10829.9 inch^3(0.1775 m^3) Optimized structural weight of truss =1082.9 lb (490 kg)			

RESULTS AND DISCUSSION

For each design example, manual and optimal design specifications are tabled (Tables 1-5) above. The design examples are manually designed using IS 800: 2007.The truss members are assigned angle sections. But, according to the objective of the approach, any steel sections of specified area can be used for the efficient construction of industrial trusses.

The total weight of a truss from the optimal solution is much less than the one designed manually. From the overall comparison of optimal and manual designs of all trusses, it is observed that the reduction in the gross weight of the truss is mainly due to the reduction of cross-sectional area for compressive members. The reduction of gross weight of the same truss structures, when designed optimally using the differential evolution algorithm, is very evident from the results tabulated above.

Table 6. Extraction of optimal results of DEA

F	CR	NP*	Gross Volume (inch^3) - Best of 5 Trials				
			9-bar Truss	**Howe Roof**	**Lattice Truss**	**Howe Bridge**	**Bowspring**
0.5	0.1	A	4530.83	17895.6	15561.2	12895.56	16569.8
		B	4908.81	14441.3	14253.65	11356.25	14452.65
	0.2	A	4743.01	16543.21	14158.51	13021.41	13692.51
		B	4595.61	16021.3	12185.62	10365.2	11321.2
	0.3	A	5118.75	15247.5	11269.5	11201.8	12302.7
		B	**3785.72**	**14392.3**	**10836.3**	**10228.8**	**10829.9**
	0.4	A	5075.7	15854.2	13259.28	12456.64	12984.6
		B	4013.6	14695.1	12148.65	10853.47	11095.14
0.6	0.1	A	4758.95	18427.8	13399.6	13002.89	17452.69
		B	4862.97	16489.1	11489.2	12674.6	14021.14
	0.2	A	4059.54	15039.4	14697.67	12560.7	16890.37
		B	4649.2	15121.1	13459.46	11201.45	13328.56
	0.3	A	4085.42	15598.95	12549.26	10112.3	12453.8
		B	4604.42	14753.25	11183.4	10931.08	10856.2
	0.4	A	4078.6	16359.5	14598.8	12765.36	13562.91
		B	4689.22	14409.56	12147.1	11345.28	12126.39
0.7	0.1	A	5025.99	19789.2	15369.21	13161.89	15782.12
		B	4149.5	16210.6	11258.54	12598.65	14365.35
	0.2	A	5294.82	18128.9	12789.3	11156.47	13129.4
		B	4240.7	16459.26	10459.6	10458.9	12031.6
	0.3	A	4678.98	16126.58	11123.37.	11526.8	11650.45
		B	3968.5	15485.6	10603.25	1130225	10980.78
	0.4	A	5388.6	15540.5	13896.65	12021.1	12648.5
		B	4862.97	16369.2	12204.59	10960.8	10845.1
0.8	0.1	A	5324.4	20128.4	13560.05	13089.48	15190.6
		B	5102.3	18485.8	12458.45	11124.43	14267.1
	0.2	A	4862.7	16124.5	14369.96	12367.20	13357.87
		B	4085.42	16805.2	12128.14	11299.4	11169.4
	0.3	A	4609.42	18452.1	11479.36	10698.24	12298.1
		B	4078.6	15087.6	10654.47	10758.96	10959.89
	0.4	A	5314.62	16259.45	12012.58	12636.5	11054.5
		B	4149.5	15128.9	11650.25	10896.12	10936.26

*NP-A = 10 (for 9-bar truss) or 20 (for other 21-bar trusses).
NP-B = 20 (for 9-bar truss) or 30 (for other 21-bar trusses).

Each design example is optimized using differential evolution algorithm module. The optimal values of F, CR and NP differ, depending on the nature of each problem. Hence, to derive optimal results, various combinations of F, CR and NP are tried. Based on the point of convergence and compared with the other results, the optimal solution is extracted (Table 6). Five optimization trial runs are executed for each design example under each combination and the best one (local optimal value) is tabulated above. Then, by comparing all the local optimal values, the best of all (global optimal value) is found. After several trial runs with different combinations of mutation factor F (range: 0.5 - 0.8) and cross-over factor CR (range: 0.1 - 0.4), it is found that "F= 0.5 and CR= 0.3" gives the best optimized result consistently in most of the trials. This best mutation and cross-over factors can be used for efficient exploration of the search space of truss design. Further, by experimenting with different population sizes, it is evaluated that the population size of 20 or 30 for plane truss holds good for quick convergence to the optimal results.

Table 7. Results confirming the need for optimization

Design Example	Manually Designed	Optimized by DEA	Reduction of Structural Weight
9-bar Truss	250 kg	171 kg	28 %
Howe Bridge	617 kg	463 kg	25%
Lattice Truss	728 kg	490 kg	33%
Howe Roof	992 kg	651 kg	35%
Bowspring	817 kg	563 kg	40%

Need for Optimization

The tension members and compression members of the truss are designed using IS 800: 2007 and steel sections are assigned from steel table. Angle sections (ISA) are assigned for every member of the trusses. The gross area of the section is found and then multiplied by the length of the member in order to find the gross volume of steel to be used in the truss structures. The volume of steel obtained is then multiplied by the unit weight of the material (unit weight of steel= 0.1 lb/inch^3), ultimately resulting in the structural weight of truss structures. Meanwhile, the cross-sectional area for the truss members is obtained through optimization and the gross structural weight of the truss is noted from the point of convergence. The number of generations after which the optimum result is obtained is also noted.

It is found that the gross structural weight of the optimized truss is at least 25% less than that of manually designed truss. From Table 7, it is evident that the above mentioned results can be derived for any plane truss structures used for industrial purposes. Also, the proposed approach is a rapid and time saving design process. These results justify the need for optimization and robustness of the differential evolution algorithm.

CONCLUSIONS

In this paper, a standard differential evolution algorithm (DEA) to optimize any plane truss structure is developed. Through several trial runs, by varying combinations of F and CR values in the range (0.5 - 0.8 for F) and (0.1 - 0.4 for CR), it is found that "F= 0.5 and CR= 0.3" gives the best optimized result consistently in most of the trials. These best mutation and cross-over factors can be used for efficient exploration of search space of truss design as 0.5 and 0.3, respectively. On executing several trials with various values for different population sizes, it is concluded that the population size of 20 or 30 for plane truss holds good for quick convergence to the optimal results. Also, for any truss, the best optimized result gives 25% less gross weight compared with manually designed trusses. It is also observed that the developed differential evolution algorithm program is able to converge on the best optimized result within 1000 generations. Thus, the proposed approach performs well with the design examples in terms of quality of the results generated and in terms of number of analyses required.

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