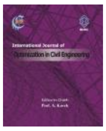
INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2016; 6(4):xxx-xxx



Technical Report

STRUCTURAL OPTIMIZATION PROBLEMS OF THE ISCSO 2011-2015: A TEST SET

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ABSTRACT

Beginning in 2011 an international academic contest named as International Student Competition in Structural Optimization (ISCSO) has been organized by the authors to encourage undergraduate and graduate students to solve structural engineering optimization problems. During the past events on the one hand a unique platform is provided for a fair comparison of structural optimization algorithms; and on the other hand it is attempted to draw the attention of students to the interesting and joyful aspects of dealing with optimization problems. This year, after five online events successfully held with support and help of our advisory and scientific committee members from different universities all around the world, the authors decided to gather the test problems of the ISCSO in this technical report as an optimization test set. Beside the well-known traditional benchmark instances, the provided test set might also be used for further performance evaluation of future structural optimization algorithms.

Keywords: structural optimization; student competition; ISCSO; optimization test set; truss structures; optimal design.

Received: 23 February 2016; Accepted: 28 April 2016

1. INTRODUCTION

Recently an extensive research work has been devoted to development of efficient structural optimization algorithms for practical applications. Typically, traditional benchmark structural optimization examples are employed for performance evaluation of the developed optimization algorithms. This trend of testing the new algorithms with traditional benchmarks may result in an abundance of optimization algorithms capable of solving only

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traditional instances, some of which are not challenging anymore. An efficient remedy for this problem is to produce and tackle new test examples for performance evaluation of structural optimization algorithms.

In addition to a need for new design optimization instances, another important concern in structural optimization is to perform a fair comparison of optimization algorithms. It is generally conceived that reliable and fair comparisons of the algorithms can be carried out through design optimization competitions judged by the experts of the field. Optimization competitions can be fruitful because all the algorithms can be tested based on a unique implementation of a test instance or a test set. In 2011 an international contest named as International Student Competition in Structural Optimization (ISCSO) [1] has been organized by the authors to encourage undergraduate and graduate students to tackle structural optimization instances. During the past events on the one hand a unique platform is provided for a fair comparison of structural optimization algorithms; and on the other hand it is attempted to draw the attention of students to the interesting and joyful aspects of solving optimization problems. This year, after five online events successfully held with support of our advisory and scientific committee members from different universities, the authors decided to gather the test instances of the ISCSO as an optimization test set. Along with the well-known traditional benchmark problems, the provided test set can be also employed for further investigation of new algorithms.

The remaining parts of this technical report is organized as follows. The second section provides the statement of truss optimization problem. The third section covers the test problems of ISCSO 2011-2015 and corresponding optimum designs reported by the winners. A brief conclusion of the this technical report is provided in the last section.

2. STATEMENT OF THE OPTIMIZATION PROBLEM

Design optimization of truss structures can be formulated as follows:

$$\text{Find } \mathbf{X} = \{x_1, x_2, ..., x_d\}, \quad x_{\min,n} \le x_n \le x_{\max,n} \quad n = 1,2,...,D \tag{1}$$

$$\text{to minimize } f(\mathbf{X}) = W(\mathbf{X}) + P(\mathbf{X}) \tag{2}$$

$$\text{subject to} \quad g_i(\mathbf{X}) = \left|\frac{\sigma_i}{\sigma_{ai}}\right| - 1 \le 0 \quad i = 1,2,...,NM \tag{3}$$

$$d_j(\mathbf{X}) = \left|\frac{\delta_j}{\delta_{aj}}\right| - 1 \le 0 \quad j = 1,2,...,ND \tag{4}$$

In Eq. (1), **X** is a candidate design, $x_{\min,n}$ and $x_{\max,n}$ are the lower and upper bounds of the *n*-th design variable x_n, and *D* is the total number of design variables. In Eq. (2), $f(\mathbf{X})$ is the objective function (penalized weight of the structure), $W(\mathbf{X})$ is the net weight of the structure and $P(\mathbf{X})$ is the penalty function employed for handling the constraints. In Eqs. (3) and (4), $g_i(\mathbf{X})$ and $d_j(\mathbf{X})$ are the stress and displacement constraints respectively, σ_i

and σ_{ai} are the computed axial stress in the *i*-th member and its allowable value, respectively, d_j and d_{aj} are the computed displacement in the direction of the *j*-th degree of freedom and its allowable value, respectively, *NM* is the total number of truss members and *ND* is the total number of active degrees of freedom.

3. STRUCTURAL OPTIMIZATION PROBLEMS OF THE ISCSO 2011-2015

3.1 ISCSO (2011) test problem: 45-bar truss structure

Optimal sizing of the 45-bar planar truss structure shown in Fig. 1 was considered in ISCSO (2011). The geometry and topology of the truss is assumed to be fixed. Nine vertical loads are applied simultaneously to the structure as follows: five loads of P_1 = 20 kips are applied at nodes 3, 7, 11, 15 and 19; also four loads of P_2 = 15 kips are applied at nodes 5, 9, 13 and 17. The stress limit is 30 ksi in both tension and compression for all the members. The displacement of all nodes in both horizontal and vertical directions is limited to ± 2.0 in. The material density is 0.283 lb/in.^{3} and the modulus of elasticity is 30,000 ksi. The truss members are linked, according to the symmetry of the structure, into 23 groups, considered as 23 sizing variables. The cross-sectional areas of truss members should be selected from the list A = {0.1, 0.2, 0.3,…, 14.8, 14.9, 15} in.^{2} Thus, the available cross-sectional areas are from 0.1 to 15 in.^{2} (including both 0.1 and 15) with 0.1 in.^{2} increments.

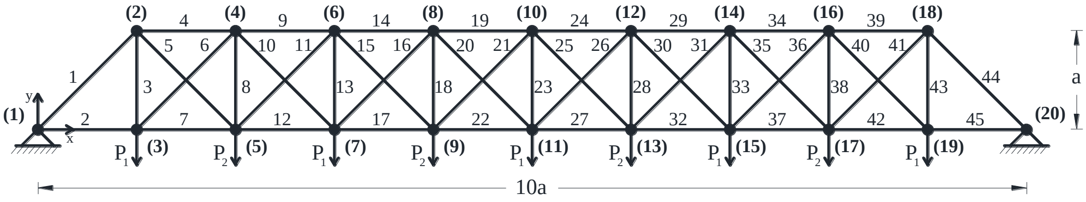


Figure 1. Test problem of ISCSO (2011): 45-bar truss, a = 200 in

For sizing optimization of the given truss, find the sizing variables (G1 to G23) which minimize the weight of the structure according to the given constraints. The member grouping as well as the solution reported by the winner, Saartje Arnout [2] from K. U. Leuven, is given in Table 1. As presented in the table, a minimum design weight of 14341.21 (lb) was reported for this test problem.

Table 1: The solution reported by the winner of ISCSO (2011) [2]

Variables	Members	Sections (in.^{2})
G_1	1, 44	9.1
G_2	2, 45	6.8
G_3	3, 43	4.6
G_4	4, 39	8.2
G_5	5, 41	2.5

G_6	6, 40	5.2
G_7	7, 42	3.1
G_8	8, 38	0.1
G_9	9, 34	15
G_{10}	10,36	5.1
G_{11}	11, 35	1.7
G_{12}	12, 37	0.1
G_{13}	13, 33	0.1
G_{14}	14, 29	15
G_{15}	15, 31	1.8
G_{16}	16, 30	3.2
G_{17}	17, 32	6
G_{18}	18, 28	0.1
G_{19}	19, 24	15
G_{20}	20, 26	2.9
G_{21}	21, 25	0.1
G_{22}	22, 27	7.6
G_{23}	23	0.6
Weight (lb)		14341.21

3.2 ISCSO (2012) test problem: 38-bar truss structure

Sizing optimization of the 38-bar planar truss structure shown in Fig. (2) was tackled in ISCSO (2012). The geometry and topology of the truss is assumed to be fixed. A vertical load of P = 15 kips is applied to the structure at node 21. The stress limit is 30 ksi in both tension and compression for all the members. The displacement of all nodes in both horizontal and vertical directions is limited to ± 4 in. The material density is 0.283 lb/in.^{3} and the modulus of elasticity is 30,000 ksi. The cross-sectional areas of truss members are considered as 38 sizing variables which should be selected from the list A = {0.1, 0.2, 0.3, …, 14.8, 14.9, 15} in.^{2}; hence, the available cross-sectional areas are from 0.1 to 15 in.^{2} (including both 0.1 and 15) with 0.1 in.^{2} increments. For sizing optimization of the given truss, find the 38 sizing variables which minimize the weight of the structure according to the given constraints.

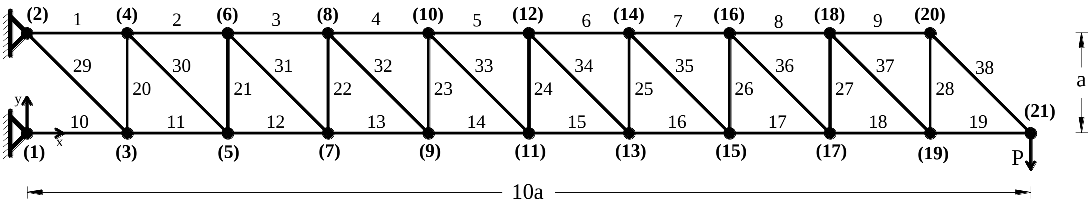


Figure 2. Test problem of ISCSO (2012): 38-bar truss structure, a = 100 in

For this test example, the solution found by the winner MunichOpt team (Simon Rudolph and Jakob Schmidt from Technical University of Munich) [3] is given in Table 2. As depicted in the table, a minimum design weight of 5889.99 (lb) was reported by MunichOpt.

Table 2: The solution reported by the winner of ISCSO (2012) [3]

Variables	Sections (in.^{2})	Variables	Sections (in.^{2})
A_1	14.6	A_{20}	1.6
A_2	12.9	A_{21}	1.6
A_3	11.3	A_{22}	1.6
A_4	9.7	A_{23}	1.6
A_5	8.2	A_{24}	1.6
A_6	6.5	A_{25}	1.6
A_7	4.9	A_{26}	1.6
A_8	3.3	A_{27}	1.6
A_9	1.7	A_{28}	1.6
A_{10}	15	A_{29}	2.3
A_{11}	14.6	A_{30}	2.3
A_{12}	12.9	A_{31}	2.3
A_{13}	11.3	A_{32}	2.3
A_{14}	9.7	A_{33}	2.3
A_{15}	8.2	A_{34}	2.3
A_{16}	6.5	A_{35}	2.3
A_{17}	4.9	A_{36}	2.3
A_{18}	3.3	A_{37}	2.3
A_{19}	1.7	A_{38}	2.3
Weight (lb)			5889.99

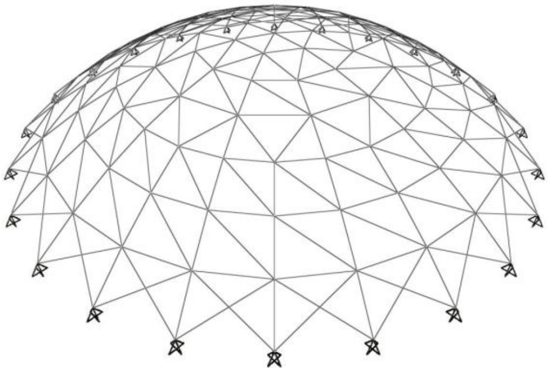


Figure 3. Test problem of ISCSO (2013): 354-member truss dome

3.3 ISCSO (2013) test problem: 354-member truss dome

Discrete sizing optimization of the 354-member steel truss dome shown in Fig. 3 was considered as the test problem of ISCSO (2013). The truss members were selected from a discrete set of 37 ready sections. For the sake of simplicity the objective function of this optimization problem was provided and the participants were asked to minimize the function using discrete solution variables. It was asked to terminate the optimization process for an objective function value smaller than 15000. A solution of this test problem could be in form of a vector (***x***) as: ***x***= (x_1, x_2, x_3,..., x_{354}), where x_1 to x_{354} can take only integer values ranging from 1 through 37 (including both 1 and 37). This test example has also been investigated in

Ref. [4] using different approaches. Therein, a more detailed description of the problem has been provided as follows. The dome is composed of 354 members and 127 joints. No member grouping is performed and a challenging design optimization problem including 354 sizing design variables is considered.

Table 3: The solution reported by the winner of ISCSO (2013) [5]

Group index	Design variable index	Group size	Optimal value
1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68, 70, 72	48	13
2	25, 27, 29, 31, 33, 35, 37, 39, 41, 43, 45, 47, 49, 51, 53, 55, 57, 59, 61, 63, 65, 67, 69, 71	24	18
3	73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96	24	9
4	97, 99, 101, 103, 105, 107, 109, 111, 113, 115, 117, 119, 121, 123, 125, 127, 129, 131, 133, 135, 137, 139, 141, 143	24	17
5	98, 100, 102, 104, 106, 108, 110, 112, 114, 116, 118, 120, 122, 124, 126, 128, 130, 132, 134, 136, 138, 140, 142, 144	24	5
6	145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168	24	12
7	169, 171, 173, 175, 177, 179, 181, 183, 185, 187, 189, 191, 193, 195, 197, 199, 201, 203, 205, 207, 209, 211, 213, 215	24	17
8	170, 172, 174, 176, 178, 180, 182, 184, 186, 188, 190, 192, 194, 196, 198, 200, 202, 204, 206, 208, 210, 212, 214, 216	24	7
9	217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240	24	13
10	241, 244, 247, 250, 253, 256, 259, 262, 265, 268, 271, 274	12	14
11	242, 243, 245, 246, 248, 249, 251, 252, 254, 255, 257, 258, 260, 261, 263, 264, 266, 267, 269, 270, 272, 273, 275, 276	24	15
12	277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288	12	1
13	289, 291, 293, 295, 297, 299, 301, 303, 305, 307, 309, 311	12	20
14	290, 292, 294, 296, 298, 300, 302, 304, 306, 308, 310, 312	12	7
15	313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324,	12	9
16	325, 328, 331, 334, 337, 340	6	21
17	326, 327, 329, 330, 332, 333, 335, 336, 338, 339, 341, 342	12	15
18	343, 344, 345, 346, 347, 348	6	32
19	349, 350, 351, 352, 353, 354	6	37
Obj.func. value	14938.2		

For design purpose, downward loads of 15 kN are applied at all the unsupported nodes. In addition to these loads, a single downward load of 100 kN is also acting at the tip of the dome. The vertical displacement of the dome tip is limited to 2 cm. It is worth mentioning that nodal coordinates, member connectivity and discrete set of ready sections for this example can be provided upon request for further studies.

For this test problem, the solution found by the winner LLBo Juniors team [5] (Markus Schatz and Qian Xu from Technical University of Munich) is given in Table 3. As shown in the table, an objective function value of 14938.2 was reported by LLBo Juniors. Although no member grouping limitation is imposed to this problem, the grouping approach used by *LLBo Juniors* has reduced the dimension of the design space from 354 to 19. Their member grouping strategy is based on a deterministic and numeric approach which does not need any structural system information and uses only the objective function value to identify the groups.

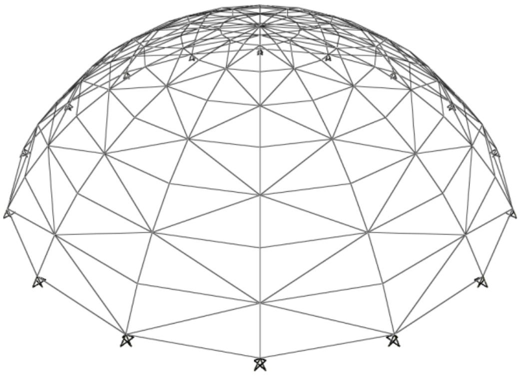


Figure 4. Test problem of ISCSO (2014): 368-member truss dome

3.4 ISCSO (2014) test problem: 368-member truss dome

Discrete sizing optimization of the 368-member steel truss dome shown in Fig. 4 was considered as the test problem of ISCSO (2014). The truss members were selected from a discrete set of 37 ready sections. For the sake of simplicity the objective function of this optimization problem was provided and the participants were asked to minimize the function using discrete solution variables. It was asked to terminate the optimization process for an objective function value smaller than 4900. A solution of this test problem could be in form of a vector ($\boldsymbol{x}$) as: $\boldsymbol{x}= (x_1, x_2, x_3,..., x_{368})$, where x_1 to x_{368} can take only integer values ranging from 1 through 37 (including both 1 and 37). This test example has also been investigated in Ref. [6] using different approaches. Therein, a more detailed description of the problem has been provided as follows. The steel truss dome is composed of 368 members and 129 joints. No member grouping is allowed to generate a challenging design optimization problem with 368 sizing design variables. The dome is sized under three independent load cases, where the loads are applied at all unsupported nodes of the truss in the following cases: (i) horizontal loads of 15 kN applied in positive x-direction, (ii) horizontal loads of 15 kN applied in positive y-direction, (iii) vertical loads of 15 kN applied in negative z-direction. The displacements of all nodes in x, y, and z directions are limited to a maximum value of 1.5 cm.

For this test problem, the winner Born Bright team [7] (Erik Günther form Technical University of Munich, Morten M. Kaastrup from Technical University of Denmark, and Thomas Lumpe from Technical University of Munich) reported an objective function value of 4897.62. Their reported solution vector, as well as nodal coordinates, member connectivity and discrete set of ready sections for this example can be provided upon request.

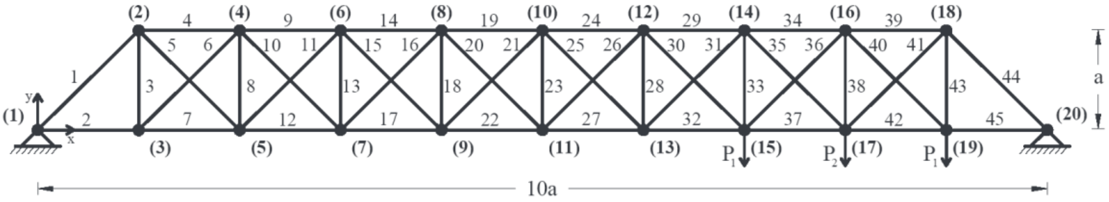
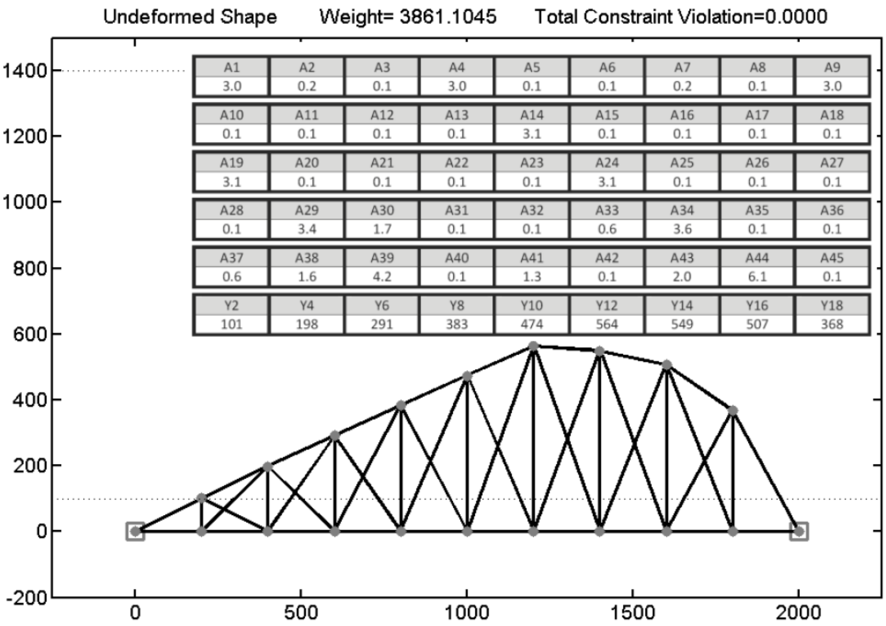


Figure 5. Test problem of ISCSO (2015): 45-bar truss, a = 200 in

3.5 ISCSO (2015) test problem: sizing and shape optimization of 45-bar truss structure

Simultaneous sizing and shape optimization of the of the 45-bar planar truss structure shown in Fig. 5 was considered as the test problem of ISCSO (2015). The topology of the truss is assumed to be fixed. Three vertical loads are applied simultaneously to the structure as follows: two loads of P_1 = 60 kips are applied at nodes 15 and 19 and a single load of P_2 = 80 kips is applied at node 17. The stress limit is 30 ksi in both tension and compression for all the members. The displacement of all nodes in both horizontal and vertical directions is limited to ± 2.0 in. The material density is 0.283 lb/in.^{3} and the modulus of elasticity is 30,000 ksi. The cross-sectional areas of truss members should be selected from the list A = {0.1, 0.2, 0.3,…, 14.8, 14.9, 15} in.^{2} . Thus, the available cross-sectional areas are from 0.1 to 15 in.^{2} (including both 0.1 and 15) with 0.1 in.^{2} increments.



A1	A2	A3	A4	A5	A6	A7	A8	A9
3.0	0.2	0.1	3.0	0.1	0.1	0.2	0.1	3.0

A10	A11	A12	A13	A14	A15	A16	A17	A18
0.1	0.1	0.1	0.1	3.1	0.1	0.1	0.1	0.1

A19	A20	A21	A22	A23	A24	A25	A26	A27
3.1	0.1	0.1	0.1	0.1	3.1	0.1	0.1	0.1

A28	A29	A30	A31	A32	A33	A34	A35	A36
0.1	3.4	1.7	0.1	0.1	0.6	3.6	0.1	0.1

A37	A38	A39	A40	A41	A42	A43	A44	A45
0.6	1.6	4.2	0.1	1.3	0.1	2.0	6.1	0.1

Y2	Y4	Y6	Y8	Y10	Y12	Y14	Y16	Y18
101	198	291	383	474	564	549	507	368

Figure 6. The solution reported by the winner of ISCSO (2015) [7]

This test problem includes 45 sizing variables (cross-sectional areas of members) and 9 shape variables namely the vertical coordinates of nodes 2, 4, 6, 8, 10, 12, 14, 16, and 18), resulting in 54 design variables. Here, the aim of optimization is to find the sizing variables (A_1 to A_{45}) as well as shape variables (y_2, y_4, y_6, y_8, y_{10}, y_{12}, y_{14}, y_{16}, y_{18}) which minimize the weight of the structure according to the given constraints. For the shape variables, only using discrete integer values is permitted. The lower and upper bounds on the shape variables are 100 and 1400 in., respectively. In the ISCSO (2015), the maximum number of structural analyses was limited to 7000 analyses.

For this test instance, the solution reported by the winner Team COME [8] (Péter Zénó Korondi, Dionysios Panagiotopoulos, Efthymios Papoutsis, Tobias Teschemacher, and Sebastian Thelemann from Technical University of Munich) is shown in Fig. 6. As shown in the figure, for this test example a design weight of 3861.1045 (lb) was reported by Team COME. Further details related to the investigated test examples and reported results can be found in Ref. [1].

4. CONCLUDING REMARKS

Since 2011 an international academic contest so called International Student Competition in Structural Optimization (ISCSO) has been organized by the authors to encourage undergraduate and graduate students to solve structural design optimization problems. During the past events on the one hand a unique platform is provided for a fair comparison of structural optimization algorithms; and on the other hand it is attempted to draw the attention of students to the interesting and joyful aspects of dealing with engineering optimization problems. After five online events successfully held with support and help of our advisory and scientific committee members from different universities all around the world, the authors decided to gather the test problems of the ISCSO as an optimization test set. Together with the well-known traditional benchmark examples, the provided test set can be used for further performance evaluation of new optimization algorithms. Last but not least, it is worth mentioning that engineering optimization competitions offer the students important chances to improve their design optimization skills, receive financial benefits of the competition prize, and show their talents in an international academic level.

Acknowledgments: Sponsorship of MİTAŞ Engineering INC., MİTAŞ Telecom Systems INC., OPTENG Project Engineering, as well as support and sincere cooperation of advisory and scientific committee members of the ISCSO are highly acknowledged.

REFERENCES

1. International Student Competition in Structural Optimization (ISCSO), http://www.brightoptimizer.com/
2. Arnout S. *The First International Student Competition in Structural Optimization*, ISCSO, 2011.
3. Rudolph S, Schmidt J, MunichOpt team. *The Second International Student Competition in Structural Optimization*, ISCSO, 2012.

4. Kazemzadeh Azad S, Hasançebi O, Saka MP. Guided stochastic search technique for discrete sizing optimization of steel trusses: A design-driven heuristic approach, *Computers and Structures* 2014; **134**: 62-74.
5. Schatz M, Xu Q, LLBo Juniors team, *The Third International Student Competition in Structural Optimization*, ISCSO, 2013.
6. Kazemzadeh Azad S, Hasançebi O. Discrete sizing optimization of steel trusses under multiple displacement constraints and load cases using guided stochastic search technique, *Structural and Multidisciplinary Optimization* 2015; **52**: 383-404.
7. Günther E, Kaastrup MM, Lumpe T. *Born Bright Team, the Fourth International Student Competition in Structural Optimization*, ISCSO, 2014).
8. Korondi PZ, Panagiotopoulos D, Papoutsis E, Teschemacher T, Thelemann S. Team COME, *The Fifth International Student Competition in Structural Optimization*, ISCSO, 2015.