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# TRUSS OPTIMIZATION WITH NATURAL FREQUENCY CONSTRAINTS USING TIKI-TAKA ALGORITHM

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## ABSTRACT

In this work, the recently-proposed Tiki-Taka algorithm (TTA) is employed for optimal weight design of truss structures with frequency constraints. This kind of problem are very challenging optimization problems, with large number of locally optimization solutions and non-convexity of search space. To evaluate its performance in this engineering area for the first time in the literature, three benchmark truss optimization problems with frequency constraints are studied. Numerical results indicate that TTA is more efficient, stable, and reliable than other metaheuristics algorithms.

## INTRODUCTION

The study of the natural frequencies and mode shapes of structures is a branch of mechanical and civil engineering that has benefited widely from the latest available technologies, especially from advances in computing and from the enormous signal processing power. To avoid the resonance phenomenon and improve the dynamic behavior of a structure these parameters need to be controlled. On the other hand, the construction industry requests design cost-effective (minimal weight) structures that meet the established requirements. However, minimizing the weight of structures can be considered as a difficult problem to solve because the reduction of weight generates conflict with the frequency limits (Millan-Paramo & Filho, 2021). Frequency constraints are highly nonlinear, non-convex, and implicit concerning the design variables (Grandhi, 1993). Hence, proper and powerful optimization methods should be implemented for solving this kind of design problems.

Unlike gradient-based methods, metaheuristic algorithms use mechanisms that allow exploring and exploiting the search space without the need for sensitivity analysis. In recent times, different metaheuristic algorithms have been introduced to solve the problem of optimal design of truss structures with frequency constraints (Cheng & Prayogo, 2017; Gomes, 2011; Ho-Huu, Nguyen-Thoi, Truong-Khac, Le-Anh, & Vo-Duy, 2018; Kaveh & Mahjoubi, 2019; Lieu, Do, & Lee, 2018; Miguel & Fadel Miguel, 2012; Millan-Paramo & Abdalla Filho, 2020; Tejani, Savsani, Patel, & Mirjalili, 2018), however, this area of research has not been fully explored. On the other hand, the No Free Lunch (NFL) theorem (Wolpert & Macready, 1997) indicates that it is not possible to develop a general strategy to solve different types of problems.

The motivation of this study is employed the Tiki-Taka algorithm (TTA) (Ab. Rashid, 2020), for the first time in the literature, for optimal weight design of truss structures with frequency constraints. TTA is inspired by the football playing style introduced by Johan Cruyff and is characterized by short passing, player movement and possession control. The optimal results obtained by TTA are compared with other solutions available in the literature.

This article is organized as follows: In Section 2, the TTA is briefly described. Section 3 presents the general formulation of the size optimization of truss structures with multiple dynamic constraints. Section 4 presents the benchmark truss optimization problems to illustrate the efficiency of the TTA. Finally, in Section 5, our conclusions are presented.

***Tiki-Taka Algorithm (Tta)***

The TTA is a population-based algorithm inspired by two main characteristics in the tiki-taka tactic, which are short passing and player movement (Ab. Rashid, 2020). The following four steps describe the algorithm in detail:

The algorithm starts with *n* randomly generated solutions in the search space. This matrix is called players (P). Additionally, another matrix that represents ball position, B, is established.

To update ball position, the player will pass the ball to the next nearby player.

To update player position, the player moves and finds a better position in the formation
For more details on the parameters that control this algorithm, please see (Ab. Rashid, 2020).

The flowchart of TTA is illustrated in Fig. 1.

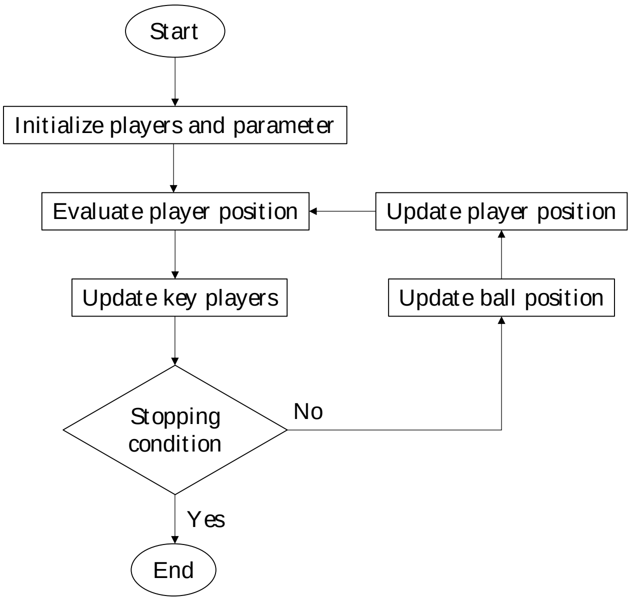


**Figure 1.** The TTA flowchart (Ab. Rashid, 2020).

***truss problems statement***

The goal of the structural optimization problem is to minimize the weight of the structure while satisfying some constraints on the natural frequencies. The numerical equations for size optimization with a number of constraints on the natural frequencies can be formulated as:

$$\begin{aligned} &\text{Find,} \quad X = \{A,\}, \text{where} \quad A = \{A_1, A_2, \dots, A_n \\ &\text{To minimize} \quad W(X) = \sum_{i=1}^{n} \rho_i A_i L_i \\ &\text{Subject to} \quad \begin{cases} f_q - f_q^{min} \geq 0 \\ f_r - f_r^{max} \leq 0 \\ A_i^{min} \leq A_i \leq A_i^{max} \end{cases} \end{aligned} \quad (1)$$

where W is the weight of the structure; n is the total number of members of the structure; $\rho_i$, $A_i$ and $L_i$ stand for the material density, the cross-sectional area and the length of the *ith* member, respectively; $f_q$ and $f_r$ are the *qth* and *rth* natural frequencies of the structure, respectively; the superscripts, “max” and “min” denote the maximum and minimum allowable limits respectively.

***Numerical Examples And Discussion***

In this section, three benchmark problems (Fig. 2) are analyzed to evaluate feasibility and validity of TTA. The design parameters of the problems are given in Table 1. Each problem is solved 30 times independently. The algorithm and the two-node linear bar element for FE analysis are coded in Matlab on a machine with 2.4 GHz and 8 of GB RAM. Three case studies are used, including a 72-bar space truss, a 120 bar dome truss and a 200-bar planer truss. Outcomes of each issue are then compared to those acquired by other methods.

**Table 1.** Design parameters of benchmark truss design problems

| | **200-bar planar truss** | **72-bar space truss** | **120-bar dome truss** |
|---|---|---|---|
| **Young's modulus *E* (GPa)** | 210 | 69.8 | 210 |
| **Material density $\rho$ (kg/m$^3$)** | 7860 | 2770 | 7971.81 |
| **Size variables (cm$^2$)** | $0.1 \leq A \leq 30$ | $0.645 \leq A \leq 30$ | $1 \leq A \leq 129.3$ |
| **Frequency constraints (Hz)** | $f_1 \geq 5$<br>$f_2 \geq 10$<br>$f_3 \geq 15$ | $f_1 = 4$<br>$f_3 \geq 6$ | $f_1 \geq 9$<br>$f_2 \geq 11$ |

***200-bar planar truss structure***

Fig 2a shows the first benchmark problem, which is called the planar truss structure of 200 bars. Elements are grouped in 29 groups as depicted in the figure. Hence, this problem includes 29 independent sizing variables. At the top of the structure, a lumped mass of 100 kg is added at nodes 1 to 5.

Table 2 shows that TTA obtained the lightest design (2160.31 kg) with the fewest number of iterations (8000 NI). Moreover, average and standard deviation attained by TTA is more stable than others and its solutions are less spread.

***72-bar space truss structure***

The second instance is shown in Fig 2b. There are 16 sizing variables and a lumped mass of 2770 kg is attached at all top nodes (nodes 1–4).

Table 3 reveals that the optimal weight achieved by the TTA is 325.97 kg, respectively. Furthermore, the SD obtained by TTA (0.88 kg) is lower than the HSPO, SOS and ISOS. Finally, regarding NI, TTA ranks third among the considered metaheuristics. Natural frequencies optimal obtained by the TTA show that none of the frequency constraints are violated.

***120-bar dome truss structure***

The 120-bar dome truss, as displayed in Fig. 2c, has a non-structural masses at the free nodes as follow: 3000 kg at node one, 500 kg at the nodes 2 through 13 kg, and 100 kg at the rest of the nodes. The elements are categorized into seven groups using geometrical symmetry,

The results obtained are presented in Table 4. As can be seen, the optimum design achieved by TTA is better than other considered metaheuristics. On the other hand, the proposed algorithm also required less structural analyses to converge to the optimal solution. Regarding NI, TTA ranks second among the considered metaheuristics

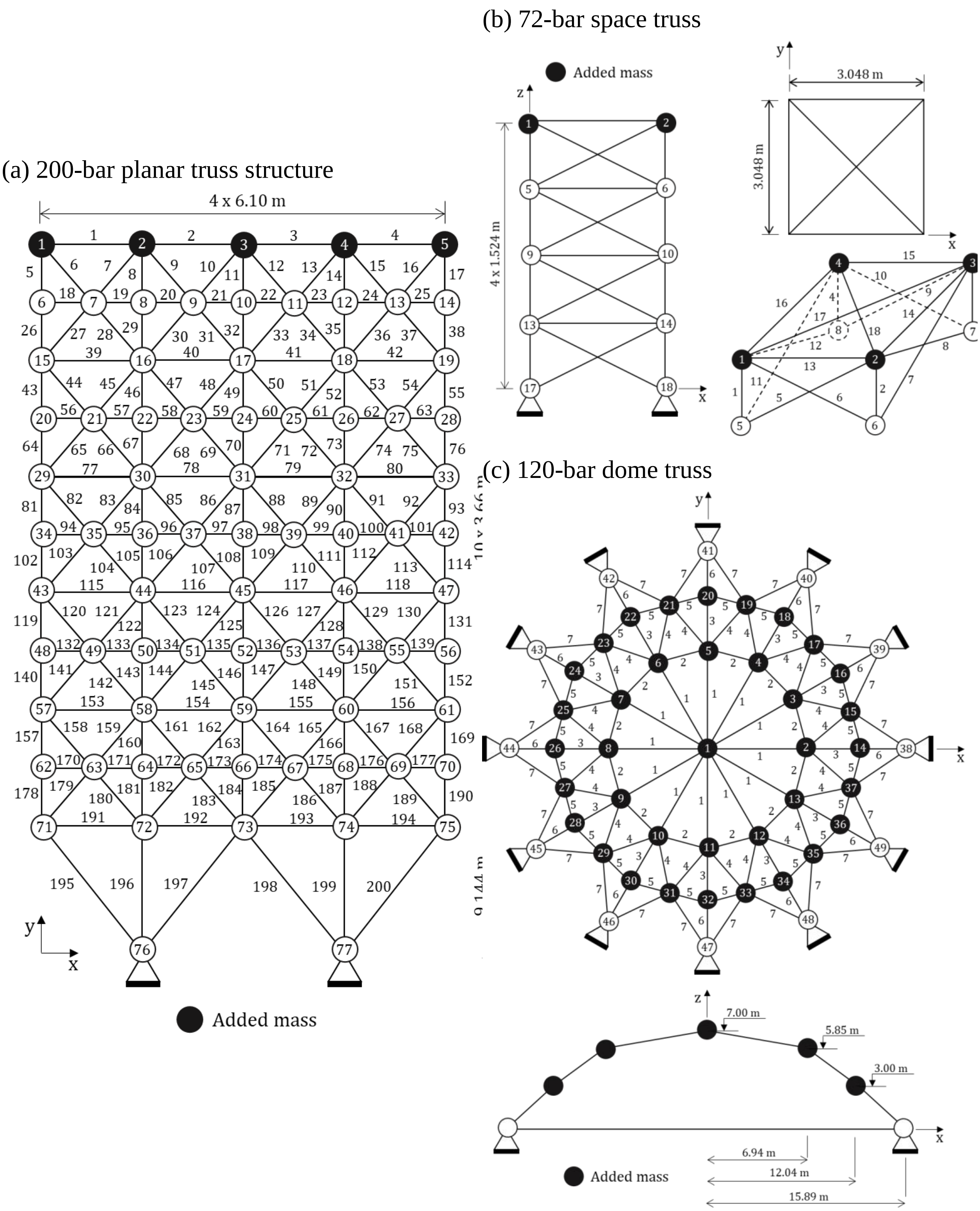


**Figure 2.** Truss optimization problems

**Table 2.** Optimal results obtained by TTA and other metaheuristic algorithms for the 200-bar planar truss

| **Variables ($cm^2$)** | **CSS-BBBC** | **HALC-PSO** | **HSPO** | **SOS** | **ISOS** | **AHEFA** | **This study** |
|---|---|---|---|---|---|---|---|
| | (Kaveh & Zolghadr, 2012) | (Kaveh & Ilchi Ghazaan, 2015) | (Kaveh & Mahjoubi, 2019) | (Tejani, Savsani, & Patel, 2016) | (Tejani et al., 2018) | (Lieu et al., 2018) | **TTA** |
| $A_1$ | 0.2934 | 0.3072 | 0.3014 | 0.4781 | 0.3072 | 0.2993 | 0.3000 |
| $A_2$ | 0.5561 | 0.4545 | 0.4594 | 0.4481 | 0.5075 | 0.4508 | 0.4922 |
| $A_3$ | 0.2952 | 0.1000 | 0.0781 | 0.1049 | 0.1001 | 0.1001 | 0.1000 |
| $A_4$ | 0.1970 | 0.1000 | 0.0983 | 0.1045 | 0.1000 | 0.1000 | 0.1001 |
| $A_5$ | 0.8340 | 0.5080 | 0.5062 | 0.4875 | 0.5893 | 0.5123 | 0.5718 |
| $A_6$ | 0.6455 | 0.8276 | 0.8199 | 0.9353 | 0.8328 | 0.8205 | 0.8105 |
| $A_7$ | 0.1770 | 0.1023 | 0.1000 | 0.1200 | 0.1431 | 0.1011 | 0.1026 |
| $A_8$ | 1.4796 | 1.4357 | 1.3968 | 1.3236 | 1.3600 | 1.4156 | 1.5268 |
| $A_9$ | 0.4497 | 0.1007 | 0.1000 | 0.1015 | 0.1039 | 0.1000 | 0.1000 |
| $A_{10}$ | 1.4556 | 1.5528 | 1.5735 | 1.4827 | 1.5114 | 1.5742 | 1.5148 |
| $A_{11}$ | 1.2238 | 1.1529 | 1.1490 | 1.1384 | 1.3568 | 1.1597 | 1.1670 |
| $A_{12}$ | 0.2739 | 0.1522 | 0.1186 | 0.1020 | 0.1024 | 0.1338 | 0.1320 |
| $A_{13}$ | 1.9174 | 2.9564 | 3.10264 | 2.9943 | 2.9024 | 2.9672 | 2.7903 |
| $A_{14}$ | 0.1170 | 0.1003 | 0.1000 | 0.1562 | 0.1000 | 0.1000 | 0.1058 |
| $A_{15}$ | 3.5535 | 3.2242 | 3.2433 | 3.4330 | 3.4120 | 3.2722 | 3.2372 |
| $A_{16}$ | 1.3360 | 1.5839 | 1.5968 | 1.6816 | 1.4819 | 1.5762 | 1.5789 |
| $A_{17}$ | 0.6289 | 0.2818 | 0.2422 | 0.1026 | 0.2587 | 0.2562 | 0.4348 |
| $A_{18}$ | 4.8335 | 5.0696 | 5.3968 | 5.0739 | 4.8291 | 5.0956 | 4.9853 |
| $A_{19}$ | 0.6062 | 0.1033 | 0.1000 | 0.1068 | 0.149 | 0.100 | 0.3810 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | 9 | 1 | |
| $A_{20}$ | 5.4393 | 5.4657 | 5.2582 | 6.0176 | 5.5090 | 5.4546 | 5.0956 |
| $A_{21}$ | 1.8435 | 2.0975 | 2.1434 | 2.0340 | 2.2221 | 2.0933 | 2.1949 |
| $A_{22}$ | 0.8955 | 0.6598 | 0.8293 | 0.6595 | 0.6113 | 0.6737 | 0.6100 |
| $A_{23}$ | 8.1759 | 7.6585 | 7.3013 | 6.9003 | 7.3398 | 7.6498 | 8.7671 |
| $A_{24}$ | 0.3209 | 0.1444 | 0.1128 | 0.2020 | 0.1559 | 0.1178 | 0.1645 |
| $A_{25}$ | 10.9800 | 8.0520 | 7.9108 | 6.8356 | 8.6301 | 8.0682 | 7.0580 |
| $A_{26}$ | 2.9489 | 2.7889 | 2.8674 | 2.6644 | 2.8245 | 2.8025 | 2.7848 |
| $A_{27}$ | 10.5243 | 10.4770 | 10.8526 | 12.1430 | 10.8563 | 10.5040 | 10.1177 |
| $A_{28}$ | 20.4271 | 21.3257 | 20.8993 | 22.2484 | 20.9142 | 21.2935 | 21.4519 |
| $A_{29}$ | 19.0983 | 10.5111 | 10.7515 | 8.9378 | 10.5305 | 10.7410 | 10.4464 |
| **Best weight (kg)** | 2298.61 | 2156.73 | 2157.77 | 2180.32 | 2169.46 | 2160.74 | 2160.31 |
| **$f_1$ (Hz)** | 5.010 | 5.000 | 5.0000 | 5.0001 | 5.0000 | 5.0000 | 5.0000 |
| **$f_2$ (Hz)** | 12.911 | 12.254 | 12.1499 | 13.4306 | 12.4477 | 12.1821 | 12.2876 |
| **$f_3$ (Hz)** | 15.416 | 15.044 | 15.0004 | 15.2645 | 15.2332 | 15.0160 | 15.0058 |
| **Average weight (kg)** | – | 2157.14 | 2169.05 | 2303.30 | 2244.64 | 2161.04 | 2163.02 |
| **SD (kg)** | – | 0.24 | 10.82 | 83.59 | 43.48 | 0.18 | 3.72 |
| **NI** | – | 13000 | 11640 | 10000 | 10000 | 11300 | 8000 |

**Table 3.** Optimal results obtained by TTA and other metaheuristic algorithms for the 72-bar space truss

| **Variables ($cm^2$)** | **CSS-BBBC** | **TLBO** | **HSPO** | **SOS** | **ReDE** | **ISOS** | **AHEFA** | **This study** |
|---|---|---|---|---|---|---|---|---|
| | (Kaveh & Zolghadr, 2012) | (Farshchin, Camp, & Maniat, 2016) | (Kaveh & Mahjoubi, 2019) | (Tejani et al., 2016) | (Ho-Huu et al., 2018) | (Tejani et al., 2018) | (Lieu et al., 2018) | **TTA** |
| $A_1$-$A_4$ | 2.854 | 3.5491 | 3.4315 | 3.6957 | 3.5327 | 3.3563 | 3.5612 | 3.1016 |
| $A_5$-$A_{12}$ | 8.301 | 7.9676 | 7.8436 | 7.1779 | 7.8303 | 7.8726 | 7.8736 | 7.8981 |
| $A_{13}$-$A_{16}$ | 0.645 | 0.6450 | 0.6450 | 0.6450 | 0.6453 | 0.6450 | 0.6450 | 0.6450 |
| $A_{17}$-$A_{18}$ | 0.645 | 0.6450 | 0.6450 | 0.6569 | 0.6459 | 0.6450 | 0.6451 | 0.6450 |
| $A_{19}$-$A_{22}$ | 8.202 | 8.1532 | 8.0390 | 7.7017 | 8.0029 | 8.5798 | 7.9710 | 9.9797 |
| $A_{23}$-$A_{30}$ | 7.043 | 7.9667 | 7.9306 | 7.9509 | 7.9135 | 7.6566 | 7.8928 | 7.8862 |
| $A_{31}$-$A_{34}$ | 0.645 | 0.6450 | 0.6450 | 0.6450 | 0.6451 | 0.7417 | 0.6450 | 0.6450 |
| $A_{35}$-$A_{36}$ | 0.645 | 0.6450 | 0.6450 | 0.6450 | 0.6451 | 0.6450 | 0.6451 | 0.6465 |
| $A_{37}$-$A_{40}$ | 16.328 | 12.9272 | 12.7040 | 12.3994 | 12.7626 | 13.0864 | 12.5404 | 13.0424 |
| $A_{41}$-$A_{48}$ | 8.299 | 8.1226 | 7.9684 | 8.6121 | 7.9657 | 8.0764 | 7.9639 | 8.0786 |
| $A_{49}$-$A_{52}$ | 0.645 | 0.6452 | 0.6451 | 0.6450 | 0.6452 | 0.6450 | 0.6459 | 0.6450 |
| $A_{53}$-$A_{54}$ | 0.645 | 0.6450 | 0.6450 | 0.6450 | 0.6450 | 0.6937 | 0.6462 | 0.6450 |
| $A_{55}$-$A_{58}$ | 15.048 | 17.0524 | 17.0169 | 17.4827 | 16.9041 | 16.2517 | 17.1323 | 15.6047 |
| $A_{59}$-$A_{66}$ | 8.268 | 8.0618 | 8.0127 | 8.1502 | 8.0434 | 8.1703 | 8.0216 | 8.0024 |
| $A_{67}$-$A_{70}$ | 0.645 | 0.6450 | 0.6450 | 0.6740 | 0.6451 | 0.6450 | 0.6450 | 0.6450 |
| $A_{71}$-$A_{72}$ | 0.645 | 0.6450 | 0.6450 | 0.6550 | 0.6473 | 0.6450 | 0.6451 | 0.6450 |
| **Best weight (kg)** | 327.51 | 327.57 | 324.23 | 325.56 | 324.25 | 325.01 | 324.24 | 325.97 |
| **$f_1$ (Hz)** | 4.0000 | 4.000 | 4.0000 | 4.0023 | 4.0000 | 4.0000 | 4.0000 | 4.0000 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$f_3$ (Hz)** | 6.0040 | 6.000 | 6.0000 | 6.0020 | 6.0001 | 6.0008 | 6.0000 | 6.0000 |
| **Average weight (kg)** | – | 328.68 | 325.42 | 331.12 | 324.32 | 329.47 | 324.41 | 326.78 |
| **SD (kg)** | – | 0.73 | 0.90 | 4.23 | 0.05 | 2.66 | 0.24 | 0.88 |
| **FEs** | – | 15000 | 8820 | 4000 | 10840 | 4000 | 8860 | 5500 |

**Table 4.** Optimal results obtained by TTA and other metaheuristic algorithms for the 120-bar dome truss

| **Variables ($cm^2$)** | **CSS-BBBC** | **DPSO** | **CBO** | **HALC-PSO** | **ISOS** | **This study** |
|---|---|---|---|---|---|---|
| | (Kaveh & Zolghadr, 2012) | (Kaveh & Zolghadr, 2014) | (Kaveh & Mahdavi, 2015) | (Kaveh & Ilchi Ghazaan, 2015) | (Tejani et al., 2018) | **TTA** |
| $A_1$ | 17.478 | 19.607 | 19.6917 | 19.8905 | 19.6662 | 20.1310 |
| $A_2$ | 49.076 | 41.290 | 41.1421 | 40.4045 | 39.8539 | 39.4371 |
| $A_3$ | 12.365 | 11.136 | 11.1550 | 11.2057 | 10.6127 | 14.0635 |
| $A_4$ | 21.979 | 21.025 | 21.3207 | 21.3768 | 21.2901 | 20.6287 |
| $A_5$ | 11.190 | 10.060 | 9.8330 | 9.8669 | 9.7911 | 8.8935 |
| $A_6$ | 12.590 | 12.758 | 12.8520 | 12.7200 | 11.7899 | 14.6434 |
| $A_7$ | 13.585 | 15.414 | 15.1602 | 15.2236 | 14.7437 | 12.9765 |
| **Best weight (kg)** | 9046.34 | 8890.48 | 8889.13 | 8889.96 | 8710.06 | 8712.55 |
| **$f_1$ (Hz)** | 9.000 | 9.0001 | 9.0000 | 9.0000 | 9.0001 | 9.0000 |
| **$f_2$ (Hz)** | 11.007 | 11.0007 | 11.0000 | 11.0000 | 10.9998 | 11.0000 |
| **Average weight (kg)** | – | 8895.99 | 8891.25 | 8900.39 | 8728.56 | 8717.52 |
| **SD (kg)** | – | 4.26 | 1.79 | 6.38 | 14.23 | 4.98 |
| **FEs** | – | 6000 | 6000 | 17000 | 4000 | 5500 |

## CONCLUSIONS

In this paper the TTA is used, for the first time in the literature, in the optimization of truss structure with frequency constraints. Numerical results indicate that the performance of the TTA is comparable to the other state-of-the-art methods in terms of the best weight, average weight, standard deviation (SD) and NI required by the optimization process. Regarding SD, the results show that is more stable than others and its solutions are less spread.

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