Table 1: Results of high-dimensional unimodal benchmark functions

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Function | Index | BOA | SSA | GWO | CSA | MISCSA | TFCSA |
|  | Best | 1.45E-14 | 6.00E-09 | 1.56E-73 | 4.30E-03 | 1.54E-32 | **1.13E-102** |
| Worst | 1.81E-14 | 1.50E-08 | 1.08E-69 | 3.78E-02 | 3.01E-30 | 2.69E-90 |
| Mean | 1.66E-14 | 8.98E-09 | 1.21E-70 | 1.43E-02 | 5.13E-31 | 1.27E-91 |
| Std | 9.46E-16 | 1.76E-09 | 2.05E-70 | 8.48E-03 | 7.63E-31 | 5.08E-91 |
| Rank | 4 | 5 | 2 | 6 | 3 | 1 |
|  | Best | 3.09E-12 | 4.30E-04 | 4.59E-42 | 4.01E-01 | 6.41E-17 | **1.28E-50** |
| Worst | 1.11E-11 | 2.07E+00 | 6.01E-40 | 3.39E+00 | 2.37E-15 | 9.02E-46 |
| Mean | 9.05E-12 | 3.37E-01 | 8.79E-41 | 1.48E+00 | 5.54E-16 | 8.82E-47 |
| Std | 2.58E-12 | 4.98E-01 | 1.24E-40 | 8.51E-01 | 5.47E-16 | 2.28E-46 |
| Rank | 4 | 5 | 2 | 6 | 3 | 1 |
|  | Best | 1.04E-11 | 7.30E-01 | 1.29E-19 | 7.75E-01 | 2.82E-17 | **1.07E-50** |
| Worst | 1.28E-11 | 7.18E+00 | 1.23E-16 | 5.40E+00 | 1.23E-15 | 7.63E-45 |
| Mean | 1.17E-11 | 3.56E+00 | 2.17E-17 | 2.40E+00 | 3.61E-16 | 4.87E-46 |
| Std | 6.37E-13 | 1.88E+00 | 3.09E-17 | 1.13E+00 | 3.00E-16 | 1.44E-45 |
| Rank | 4 | 5 | 2 | 6 | 3 | 1 |
|  | Best | 1.48E-14 | 6.43E+00 | 4.98E-26 | 3.89E+02 | 2.04E-28 | **3.33E-98** |
| Worst | 1.85E-14 | 2.12E+02 | 5.22E-19 | 3.47E+03 | 1.60E-27 | 7.43E-89 |
| Mean | 1.68E-14 | 4.61E+01 | 3.50E-20 | 9.56E+02 | 4.59E-30 | 3.92E-90 |
| Std | 8.32E-16 | 4.07E+01 | 1.07E-19 | 5.77E+02 | 3.24E-28 | 1.48E-89 |
| Rank | 4 | 5 | 3 | 6 | 2 | 1 |
|  | Best | 2.34E-04 | 9.07E-03 | 1.35E-04 | 5.54E-03 | 8.74E-06 | **5.15E-06** |
| Worst | 1.12E-03 | 1.29E-01 | 9.59E-04 | 3.89E-02 | 2.34E-04 | 2.44E-04 |
| Mean | 5.62E-04 | 5.43E-02 | 4.33E-04 | 2.38E-02 | 9.31E-05 | 9.79E-05 |
| Std | 2.16E-04 | 2.43E-02 | 2.27E-04 | 8.50E-03 | 5.83E-05 | 6.59E-05 |
| Rank | 4 | 6 | 3 | 5 | 2 | 1 |
|  | Best | 1.33E-14 | 3.42E+03 | 4.19E-72 | 4.62E+02 | 2.66E-30 | **3.92E-97** |
| Worst | 1.88E-14 | 2.53E+04 | 4.17E-69 | 2.48E+03 | 1.72E-26 | 3.20E-88 |
| Mean | 1.63E-14 | 9.60E+03 | 5.07E-70 | 1.35E+03 | 3.22E-27 | 1.29E-89 |
| Std | 1.20E-15 | 5.79E+03 | 8.49E-70 | 4.75E+02 | 4.95E-27 | 5.88E-89 |
| Rank | 4 | 6 | 2 | 5 | 3 | 1 |
|  | Best | 1.56E-14 | 5.64E+04 | 3.04E-70 | 4.21E+03 | 3.91E-29 | **9.19E-98** |
| Worst | 1.93E-14 | 4.11E+05 | 1.82E-67 | 6.15E+04 | 1.42E-26 | 1.77E-82 |
| Mean | 1.77E-14 | 1.61E+05 | 2.52E-68 | 2.38E+04 | 2.29E-27 | 6.23E-84 |
| Std | 9.13E-16 | 7.15E+04 | 4.31E-68 | 1.29E+04 | 3.32E-27 | 3.24E-83 |
| Rank | 4 | 6 | 2 | 5 | 3 | 1 |

Table 2: Results of high-dimensional multimodal benchmark functions

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Function | Index | BOA | SSA | GWO | CSA | MISCSA | TFCSA |
|  | Best | **0.00E+00** | 1.49E+01 | **0.00E+00** | 1.19E+01 | **0.00E+00** | **0.00E+00** |
| Worst | 1.69E+02 | 7.76E+01 | 2.05E+00 | 4.68E+01 | 0.00E+00 | 0.00E+00 |
| Mean | 5.62E+00 | 4.23E+01 | 6.82E-02 | 2.08E+01 | 0.00E+00 | 0.00E+00 |
| Std | 3.08E+01 | 7.76E+01 | 3.74E-01 | 8.33E+00 | 0.00E+00 | 0.00E+00 |
| Rank | 1 | 6 | 1 | 5 | 1 | 1 |
|  | Best | 6.26E-12 | 1.74E-05 | 2.12E-15 | 1.51E+00 | **8.88E-16** | **8.88E-16** |
| Worst | 1.31E-11 | 3.89E+00 | 1.51E-14 | 4.42E+00 | 8.88E-16 | 8.88E-16 |
| Mean | 1.12E-11 | 1.81E+00 | 1.40E-14 | 2.92E+00 | 8.88E-16 | 8.88E-16 |
| Std | 1.53E-12 | 1.05E+00 | 2.12E-15 | 6.96E-01 | 0.00E+00 | 0.00E+00 |
| Rank | 4 | 5 | 3 | 6 | 1 | 1 |
|  | Best | **0.00E+00** | 1.97E-08 | **0.00E+00** | 3.82E-02 | **0.00E+00** | **0.00E+00** |
| Worst | 5.55E-15 | 4.67E-02 | 2.32E-02 | 1.97E-01 | 0.00E+00 | 0.00E+00 |
| Mean | 8.81E-16 | 9.10E-03 | 2.25E-03 | 1.08E-01 | 0.00E+00 | 0.00E+00 |
| Std | 1.13E-15 | 1.21E-02 | 6.27E-03 | 3.89E-02 | 0.00E+00 | 0.00E+00 |
| Rank | 1 | 5 | 1 | 6 | 1 | 1 |
|  | Best | 1.11E-15 | 3.63E-01 | 1.38E-41 | 7.25E-03 | 4.15E-18 | **3.45E-52** |
| Worst | 3.53E-13 | 4.77E+00 | 3.37E-04 | 8.47E-01 | 1.34E-16 | 3.33E-47 |
| Mean | 2.27E-14 | 1.94E+00 | 1.60E-05 | 1.20E-01 | 3.85E-17 | 5.68E-48 |
| Std | 6.49E-14 | 1.25E+00 | 6.16E-05 | 1.64E-01 | 3.55E-17 | 8.98E-48 |
| Rank | 4 | 6 | 2 | 5 | 3 | 1 |
|  | Best | 1.04E-14 | 1.06E-01 | 6.68E-09 | 1.57E-01 | 1.09E-34 | **8.77E-103** |
| Worst | 1.62E-14 | 1.20E+00 | 5.08E-06 | 2.09E+00 | 3.64E-31 | 8.90E-91 |
| Mean | 1.39E-14 | 3.94E-01 | 1.41E-06 | 8.05E-01 | 5.31E-32 | 3.44E-92 |
| Std | 1.08E-15 | 2.71E-01 | 1.23E-06 | 4.41E-01 | 7.67E-32 | 1.63E-91 |
| Rank | 3 | 5 | 4 | 6 | 2 | 1 |
|  | Best | 1.69E+00 | 2.69E-01 | 6.33E-01 | 3.18E-01 | 9.05E-01 | **2.25E-04** |
| Worst | 2.69E+00 | 1.02E+01 | 1.27E+00 | 4.44E+00 | 2.00E+00 | 2.47E-01 |
| Mean | 2.00E+00 | 5.26E+00 | 9.40E-01 | 1.10E+00 | 1.49E+00 | 1.78E-02 |
| Std | 2.03E-01 | 2.88E+00 | 1.66E-01 | 8.79E-01 | 2.69E-01 | 6.17E-02 |
| Rank | 6 | 2 | 4 | 3 | 5 | 1 |
|  | Best | 2.48E-01 | 4.02E-10 | **6.51E-03** | 9.66E+00 | 1.50E+00 | 7.00E-03 |
| Worst | 9.11E-01 | 2.10E-02 | 4.06E-02 | 6.95E+01 | 4.26E+00 | 2.16E+00 |
| Mean | 4.75E-01 | 5.46E-03 | 2.53E-02 | 2.49E+01 | 3.12E+00 | 7.74E-01 |
| Std | 1.51E-01 | 6.20E-03 | 1.03E-02 | 1.18E+01 | 8.15E-01 | 4.59E-01 |
| Rank | 4 | 1 | 2 | 6 | 5 | 3 |

Table 3: Results of fixed-dimensional multimodal benchmark functions

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Function | Index | BOA | SSA | GWO | CSA | MISCSA | TFCSA |
|  | Best | 5.55E-17 | 1.60E-14 | **0.00E+00** | **0.00E+00** | **0.00E+00** | **0.00E+00** |
| Worst | 1.05E-02 | 9.72E-03 | 9.72E-03 | 9.72E-03 | 0.00E+00 | 0.00E+00 |
| Mean | 7.86E-03 | 9.72E-04 | 2.91E-03 | 2.46E-03 | 0.00E+00 | 0.00E+00 |
| Std | 4.00E-03 | 2.96E-03 | 4.53E-03 | 4.20E-03 | 0.00E+00 | 0.00E+00 |
| Rank | 5 | 6 | 1 | 1 | 1 | 1 |
|  | Best | 1.01E-05 | 3.25E-18 | 7.41E-10 | 5.87E-28 | **0.00E+00** | **0.00E+00** |
| Worst | 3.71E-01 | 3.18E-15 | 7.61E-08 | 5.66E-24 | 9.87E-30 | 0.00E+00 |
| Mean | 4.84E-02 | 4.96E-16 | 1.88E-08 | 6.40E-25 | 1.19E-30 | 0.00E+00 |
| Std | 9.27E-02 | 7.06E-16 | 1.71E-08 | 1.22E-24 | 2.37E-30 | 0.00E+00 |
| Rank | 6 | 4 | 5 | 3 | 1 | 1 |
|  | Best | 0.00031 | 0.00031 | **0.00030** | **0.00030** | 0.00031 | **0.00030** |
| Worst | 0.00050 | 0.00122 | 0.02036 | 0.00122 | 0.00166 | 0.02036 |
| Mean | 0.00035 | 0.00077 | 0.00237 | 0.00034 | 0.00053 | 0.00101 |
| Std | 0.00004 | 0.00027 | 0.00610 | 0.00017 | 0.00038 | 0.00366 |
| Rank | 5 | 5 | 1 | 1 | 5 | 1 |
|  | Best | 1.93E-19 | 8.38E-18 | **0.00E+00** | 3.01E-27 | 2.06E-43 | 6.17E-178 |
| Worst | 2.97E-17 | 5.23E-15 | 0.00E+00 | 1.41E-24 | 7.59E-40 | 6.90E-168 |
| Mean | 4.27E-18 | 1.19E-15 | 0.00E+00 | 2.58E-25 | 3.31E-41 | 2.77E-169 |
| Std | 5.36E-18 | 1.64E-15 | 0.00E+00 | 3.40E-25 | 1.38E-40 | 0.00E+00 |
| Rank | 5 | 6 | 1 | 4 | 3 | 2 |
|  | Best | **0.398** | **0.398** | **0.398** | **0.398** | **0.398** | **0.398** |
| Worst | 0.649 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 |
| Mean | 0.410 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 |
| Std | 0.047 | 1.65E-15 | 0 | 0 | 0 | 0 |
| Rank | 1 | 1 | 1 | 1 | 1 | 1 |
|  | Best | **3.00E+00** | **3.00E+00** | **3.00E+00** | **3.00E+00** | **3.00E+00** | **3.00E+00** |
| Worst | 3.14E+00 | 3.00E+00 | 3.00E+00 | 3.00E+00 | 3.00E+00 | 3.00E+00 |
| Mean | 3.03E+00 | 3.00E+00 | 3.00E+00 | 3.00E+00 | 3.00E+00 | 3.00E+00 |
| Std | 3.72E-02 | 7.28E-14 | 5.18E-06 | 1.63E-15 | 1.54E-15 | 9.37E-16 |
| Rank | 1 | 1 | 1 | 1 | 1 | 1 |

Table 4: Wilcoxon rank sum test and *p-value*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Function | TFCSA/BOA | TFCSA/SSA | TFCSA/GWO | TFCSA/CSA | TFCSA/MISCSA |
| *f1* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f2* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f3* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f4* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f5* | 3.69E-11 | 3.02E-11 | 8.89E-10 | 3.02E-11 | **9.12E-01** |
| *f6* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f7* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f8* | 1.21E-12 | 1.21E-12 | 2.03E-13 | 1.21E-12 | NA |
| *f9* | 6.19E-10 | 1.21E-12 | 4.19E-02 | 1.21E-12 | NA |
| *f10* | 4.19E-02 | 1.21E-12 | 5.56E-03 | 1.21E-12 | NA |
| *f11* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f12* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f13* | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 | 3.02E-11 |
| *f14* | 3.67E-03 | 1.21E-10 | 5.97E-09 | 3.02E-11 | 4.98E-11 |
| *f15* | 1.21E-12 | 1.21E-12 | 1.37E-03 | 1.45E-04 | NA |
| *f16* | 1.21E-12 | 1.21E-12 | 1.21E-12 | 1.21E-12 | 1.94E-09 |
| *f17* | 7.97E-07 | 3.86E-10 | 2.70E-07 | 8.51E-07 | 1.21E-07 |
| *f18* | 3.02E-11 | 3.02E-11 | 1.21E-12 | 3.02E-11 | 3.02E-11 |
| *f19* | 1.21E-12 | 3.62E-08 | 1.21E-12 | NA | NA |
| *f20* | 1.43E-11 | 9.30E-12 | 1.43E-11 | 3.36E-06 | 1.91E-04 |

Table 5: Test results of different algorithms for Speed Reducer Design

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | TFCSA | CSO [27] | Gandomi et al [28] | ABC [29] | Akhtar et al [30] | Montes and Coello [31] |
| Best | **2896.26** | 2996.60 | 3000.98 | 2997.06 | 3008.08 | 3025.01 |
|  | 3.500000 | 3.500000 | 3.501500 | 3.499999 | 3.506122 | 3.506163 |
|  | 0.700000 | 0.700000 | 0.700000 | 0.700000 | 0.700006 | 0.700831 |
|  | 17.00000 | 17.00000 | 17.00000 | 17.00000 | 17.00000 | 17.00000 |
|  | 7.300000 | 7.308000 | 7.605000 | 7.300000 | 7.549126 | 7.460181 |
|  | 7.800000 | 7.802000 | 7.818100 | 7.800000 | 7.859330 | 7.962143 |
|  | 2.900000 | 3.350000 | 3.352000 | 3.350215 | 3.365576 | 3.362900 |
|  | 5.286683 | 5.287000 | 5.287500 | 5.287800 | 5.289773 | 5.309000 |