Problem Definitions and Evaluation Criteria for the CEC 2017 Competition and Special Session on Constrained Single Objective Real-Parameter Optimization

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Introduction

In real-world applications, most optimization problems contain constraints (ranging from physical, time, geometric, design etc.) which need to be satisfied while finding an optimal solution. However, the presence of constraints alters the shape of the search space making it difficult to solve. In the last few decades, stochastic search algorithms such as evolutionary algorithms have gained popularity due to their effectiveness in solving optimization problems. However, since evolutionary algorithms or most meta-heuristics naturally designed for unconstrained optimization problems require additional mechanisms to solve constrained optimization problems.

Initially, the effectiveness of different penalty functions (both in evolutionary algorithms and in mathematical programming) has been investigated for several decades. However, the penalty functions have, in general, several limitations.For instance, they are not suitable for optimization problems where the optimum is on the boundary connecting the feasible and the infeasible regions or when the feasible region is disjoint.In addition, penalty functions require intensive fine-tuning to identify the most appropriate penaltyfactors to be employed. In the last few decades, a variety approaches have been proposed in conjunction with evolutionary algorithms to handle constraints. Most popular among them are self-adaptive penalty, epsilon constraint handling, superiority of feasible and stochastic ranking. Recently, the idea of ensemble of different constraint handling methods was proposed where each constraint handling method is apt only for a group of problems [1].

For competition in CEC06 [2], 24 benchmark functions with dimensionality varying from 2-20 have been developed. However, the CEC06 benchmark problems are not scalable. In the modern era of Big Data, most optimization problems that are being considered contain few hundreds of variables with a wide variety of constraints. Therefore, it necessary to test the scalability of the optimization algorithms that are being developed on a set of scalable constrained optimization problems. In [3], a test-case generator for constrained parameter optimization problems was proposed. In [4], 18 benchmark functions which are scalable (10- and 30-dimensional) were developed for the competition in CEC2010. However, the optimization problems proposed for competitions in CEC06 and CEC2010 have been successfully solved. In this report, we develop a set of 28 benchmark constrained optimization problems with dimensions 10, 30, 50 and 100. The developed problems contain a wide variety of constraints.

The mathematical formulas and properties of these functions are described in Section 1. In Section 2, the evaluationcriteria are given. A suggested format to present the results is also given in Section 3.

1. Definitions of the Function Suite

In this section, 28 constrained optimization problems are proposedwhich can be transformed into the following format:

$$\text{Minimize: } f(X), \quad X = (x_1, x_2, ..., x_n) \text{ and } X \in S \tag{1}$$

$$\text{Subject to: } \begin{array}{ll} g_i(X) \le 0, & i = 1, ..., p \\ h_j(X) = 0, & j = p+1, ..., m \end{array} \tag{2}$$

Usually equality constraints are transformed into inequalities of the form

$$|h_j(X)| - \varepsilon \le 0 \text{, for } \quad j = p+1, ..., m \qquad \dots (3)$$

A solution X is regarded as feasible if $g_i(X) \le 0$, $for\ i = 1, ..., p$ and $|h_j(X)| - \varepsilon \le 0$, for $j = p+1, ..., m$. In this special session ε is set to 0.0001.

C01: $\text{Min } f(x) = \sum_{i=1}^{D} \left(\sum_{j=1}^{i} z_j \right)^2 \quad z = x - o$

$$g(x) = \sum_{i=1}^{D} \left[z_i^2 - 5000 \cos(0.1\pi z_i) - 4000 \right] \le 0$$

$$x \in [-100, 100]^D$$

C02: $\text{Min } f(x) = \sum_{i=1}^{D} \left(\sum_{j=1}^{i} z_j \right)^2 \quad z = x - o, \ y = M * z$

$$g(x) = \sum_{i=1}^{D} \left[y_i^2 - 5000 \cos(0.1\pi y_i) - 4000 \right] \le 0$$

$$x \in [-100, 100]^D$$

C03: $\text{Min } f(x) = \sum_{i=1}^{D} \left(\sum_{j=1}^{i} z_j \right)^2 \quad z = x - o$

$$g(x) = \sum_{i=1}^{D} \left[z_i^2 - 5000 \cos(0.1\pi z_i) - 4000 \right] \le 0$$

$$h(x) = -\sum_{i=1}^{D} z_i \sin(0.1\pi z_i) = 0$$

$$x \in [-100, 100]^D$$

C04: $\text{Min } f(x) = \sum_{i=1}^{D} \left[z_i^2 - 10 \cos(2\pi z_i) + 10 \right] \quad z = x - o$

$$g_1(x) = -\sum_{i=1}^{D} z_i \sin(2 z_i) \le 0$$

$$g_2(x) = \sum_{i=1}^{D} z_i \sin(z_i) \le 0$$

$$x \in [-10, \ 10]^D$$

C05: Min $f(x)=\sum_{i=1}^{D-1}(100(z_i^2-z_{i+1})^2+(z_i-1)^2)\quad z=x-o,\ y=M_1*z,\quad w=M_2*z$

$$g_1(x)=\sum_{i=1}^{D}\left[y_i^2-50\cos(2\pi y_i)-40\right]\le 0$$

$$g_2(x)=\sum_{i=1}^{D}\left[w_i^2-50\cos(2\pi w_i)-40\right]\le 0$$

$$x\in[-10,\ 10]^{\mathrm{D}}$$

C06: Min $f(x)=\sum_{i=1}^{D}\left[z_i^2-10\cos(2\pi z_i)+10\right]\qquad z=x-o$

$$h_1(x)=-\sum_{i=1}^{D}z_i\sin(z_i)=0$$

$$h_2(x)=\sum_{i=1}^{D}z_i\sin(\pi z_i)=0$$

$$h_3(x)=-\sum_{i=1}^{D}z_i\cos(z_i)=0$$

$$h_4(x)=\sum_{i=1}^{D}z_i\cos(\pi z_i)=0$$

$$h_5(x)=\sum_{i=1}^{D}(z_i\sin(2*\sqrt{|z_i|}))=0$$

$$h_6(x)=-\sum_{i=1}^{D}(z_i\sin(2*\sqrt{|z_i|}))=0$$

$$x\in[-20,\ 20]^{\mathrm{D}}$$

C07: Min $f(x)=\sum_{i=1}^{D}(z_i\sin(z_i))\quad z=x-o$

$$h_1(x)=\sum_{i=1}^{D}(z_i-100\cos(0.5z_i)+100)=0$$

$$h_2(x)=-\sum_{i=1}^{D}(z_i-100\cos(0.5z_i)+100)=0$$

$$x\in[-50,\ 50]^{\mathrm{D}}$$

C08: Min $f(x)=\max(z)\quad z=x-o,\ y_l=z_{(2l-1)},\ w_l=z_{(2l)}\ \ where\ l=1,\ldots,D/2$

$$h_1(x)=\sum_{i=1}^{D/2}\left(\sum_{j=1}^{i}y_j\right)^2=0$$

$$h_2(x)=\sum_{i=1}^{D/2}\left(\sum_{j=1}^{i}w_j\right)^2=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C09: Min $f(x)=\max(z)$ $\quad z=x-o,\ y_l=z_{(2l-1)},\ w_l=z_{(2l)}\ \ where\ l=1,...,D/2$

$$g(x)=\prod_{i=1}^{D/2} w_i \le 0$$

$$h(x)=\sum_{i=1}^{D/2-1}(y_i^2-y_{i+1})^2=0$$

$$x\in[-10,\ 10]^{\mathrm{D}}$$

C10: Min $f(x)=\max(z)$ $\quad z=x-o$

$$h_1(x)=\sum_{i=1}^{D}\left(\sum_{j=1}^{i} z_j\right)^2 = 0$$

$$h_2(x)=\sum_{i=1}^{D-1}(z_i-z_{i+1})^2=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C11: Min $f(x)=\sum_{i=1}^{D}(z_i)$ $\quad z=x\text{ - }o$

$$g(x)=\prod_{i=1}^{D} z_i \le 0$$

$$h(x)=\sum_{i=1}^{D-1}(z_i-z_{i+1})^2=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C12: Min $f(x)=\sum_{i=1}^{D}(y_i^2-10\cos(2\pi y_i)+10)$, $\ y=x-o$

$$g_1(x)=4-\sum_{i=1}^{D}|y_i|\le 0$$

$$g_2(x)=\sum_{i=1}^{D} y_i^2-4=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C13: Min $f(x)=\sum_{i=1}^{D\text{-}1}(100(y_i^2-y_{i+1})^2+(y_i-1)^2)$, $y=x-o$

$$g_1(x)=\sum_{i=1}^{D}(y_i^2-10\cos(2\pi y_i)+10)-100\le 0$$

$$g_2(x)=\sum_{i=1}^{D} y_i-2D\le 0$$

$$g_3(x)=5-\sum_{i=1}^{D} y_i \le 0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C14: Min $f(x) = -20\cdot\exp(-0.2\sqrt{\frac{1}{D}\sum_{i=1}^{D}y_i^2}) + 20 - \exp(\frac{1}{D}\sum_{i=1}^{D}\cos(2\pi y_i)) + e$, $y = x - o$

$$g(x) = \sum_{i=2}^{D} y_i^2 + 1 - |y_1| \le 0$$
$$h(x) = \sum_{i=1}^{D} y_i^2 - 4 = 0$$
$$x \in [-100,\ 100]^{\mathrm{D}}$$

C15: Min $f(x) = \max\{|y_i|, 1 \le i \le D\}$, $y = x - o$

$$g(x) = \sum_{i=1}^{D} y_i^2 - 100D \le 0$$
$$h(x) = \cos f(x) + \sin f(x) = 0$$
$$x \in [-100,\ 100]^{\mathrm{D}}$$

C16: Min $f(x) = \sum_{i=1}^{D}|y_i|$, $y = x - o$

$$g(x) = \sum_{i=1}^{D} y_i^2 - 100D \le 0$$
$$h(x) = (\cos f(x) + \sin f(x))^2 - \exp(\cos f(x) + \sin f(x)) - 1 + \exp(1) = 0$$
$$x \in [-100,\ 100]^{\mathrm{D}}$$

C17: Min $f(x) = \frac{1}{4000}\sum_{i=1}^{D} y_i^2 + 1 - \prod_{i=1}^{D}\cos(\frac{y_i}{\sqrt{i}})$, $y = x - o$

$$g(x) = 1 - \sum_{i=1}^{D}\mathrm{sgn}(|y_i| - \sum_{j=1,2..D,\, j\ne i} y_j^2 - 1) \le 0$$
$$h(x) = \sum_{i=1}^{D} y_i^2 - 4D = 0$$
$$x \in [-100,\ 100]^{\mathrm{D}}$$

C18: Min $f(x)=\sum_{i=1}^{D}(z_i^2-10\cos(2\pi z_i)+10)$, $z_i=\begin{cases} y_i, if\ |y_i|<0.5 \\ 0.5*round(2*y_i), otherwise \end{cases}$, $y=x-o$

$$g_1=1-\sum_{i=1}^{D}\left|y_i\right|\le 0$$

$$g_2=(x)=\sum_{i=1}^{D}y_i^2-100D\le 0$$

$$h(x)=\sum_{i=1}^{D}100(y_i^2-y_{i+1})^2+\prod_{i=1}^{D}\sin^2(y_i-1)\pi=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C19: Min $f(x)=\sum_{i=1}^{D}(|y_i|^{0.5}+2\sin y_i^3)$, $y=x-o$

$$g_1(x)=\sum_{i=1}^{D-1}(-10\exp(-0.2\sqrt{y_i^2+y_{i+1}^2}))+(D-1)\cdot 10/\exp(-5)\le 0$$

$$g_2(x)=\sum_{i=1}^{D}\sin^2(2y_i)-0.5D\le 0$$

$$x\in[-50,50]^D$$

C20: Min $f(x)=\sum_{i=1}^{D-1}g(y_i,y_{i+1})+g(y_D,y_1), g(y_i,y_{i+1})=0.5+\dfrac{(\sin^2(\sqrt{{y_i}^2+{y_{i+1}}^2})-0.5)}{(1+0.001(\sqrt{{y_i}^2+{y_{i+1}}^2}))^2}$,

$y=x-o$

$$g_1(x)=\cos^2(\sum_{i=1}^{D}y_i)-0.25\cos(\sum_{i=1}^{D}y_i)-0.125\le 0$$

$$g_2(x)=\exp(\cos(\sum_{i=1}^{D}y_i))-\exp(0.25)\le 0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C21: Min $f(x)=\sum_{i=1}^{D}(y_i^2-10\cos(2\pi y_i)+10)$, $z=M(x-o)$

$$g_1(x)=4-\sum_{i=1}^{D}\left|z_i\right|\le 0$$

$$g_2(x)=\sum_{i=1}^{D}z_i^2-4=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C22: Min $f(x)=\sum_{i=1}^{D}(100(z_i^2-x_{i+1})^2+(z_i-1)^2)$, $z=M(x-o)$

$$g_1(x)=\sum_{i=1}^{D}(z_i^2-10\cos(2\pi z_i)+10)-100\le 0$$

$$g_2(x)=\sum_{i=1}^{D}z_i-2D\le 0$$

$$g_3(x)=5-\sum_{i=1}^{D}z_i\le 0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C23: Min $f(x)=-20\cdot\exp(-0.2\sqrt{\frac{1}{D}\sum_{i=1}^{D}z_i^2})+20-\exp(\frac{1}{D}\sum_{i=1}^{D}\cos(2\pi z_i))+e$, $z=M(x-o)$

$$g(x)=\sum_{i=2}^{D}z_i^2+1-|z_1|\le 0$$

$$h(x)=\sum_{i=1}^{D}z_i^2-4=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C24: Min $f(x)=\max\{|z_i|, 1\le i\le D\}$, $z=M(x-o)$

$$g(x)=\sum_{i=1}^{D}z_i^2-100D\le 0$$

$$h(x)=\cos f(z)+\sin f(z)=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C25: Min $f(x)=\sum_{i=1}^{D}|z_i|$, $z=M(x-o)$

$$g(x)=\sum_{i=1}^{D}z_i^2-100D\le 0$$

$$h(x)=(\cos f(z)+\sin f(z))^2-\exp(\cos f(z)+\sin f(z))-1+\exp(1)=0$$

$$x\in[-100,\ 100]^{\mathrm{D}}$$

C26: $\text{Min } f(x) = \frac{1}{4000}\sum_{i=1}^{D} y_i^2 + 1 - \prod_{i=1}^{D}\cos(\frac{y_i}{\sqrt{i}})$, $z = M(x-o)$

$$g(x) = 1 - \sum_{i=1}^{D}\text{sgn}(|z_i| - \sum_{j=1,2..D,\, j\neq i} z_j^2 - 1) \le 0$$

$$h(x) = \sum_{i=1}^{D} z_i^2 - 4D = 0$$

$$x \in [-100,\ 100]^{\mathrm{D}}$$

C27: $\text{Min } f(x) = \sum_{i=1}^{D}(z_i^2 - 10\cos(2\pi z_i) + 10)$, $z_i = \begin{cases} y_i, if\ |y_i| < 0.5 \\ 0.5 * round(2 * y_i), otherwise \end{cases}$,

$z = M(x-o)$

$$g_1 = 1 - \sum_{i=1}^{D}\left|y_i\right| \le 0$$

$$g_2 = (x) = \sum_{i=1}^{n} y_i^2 - 100D \le 0$$

$$h(x) = \sum_{i=1}^{D}100(y_i^2 - y_{i+1})^2 + \prod_{i=1}^{D}\sin^2(y_i - 1)\pi = 0$$

$$x \in [-100,\ 100]^{\mathrm{D}}$$

C28: $\text{Min } f(x) = \sum_{i=1}^{D}(|z_i|^{0.5} + 2\sin z_i^3)$, $z = M(x-o)$

$$g_1(x) = \sum_{i=1}^{D-1}(-10\exp(-0.2\sqrt{z_i^2 + z_{i+1}^2})) + (D-1)\cdot 10/\exp(-5) \le 0$$

$$g_2(x) = \sum_{i=1}^{D}\sin^2(2z_i) - 0.5D \le 0$$

$$x \in [-50,\ 50]^{\mathrm{D}}$$

Table 1: Details of 28 test problems. *D* is the number of decision variables, *I* is the number of inequality constraints, *E* is the number of equality constraints

Problem/Search Range	Type of Objective	Number of Constraints	
		E	*I*
C01 $[-100,100]^D$	Non Separable	0	1 Separable
C02 $[-100,100]^D$	Non Separable, Rotated	0	1 Non Separable, Rotated
C03 $[-100,100]^D$	Non Separable	1 Separable	1 Separable
C04 $[-10,10]^D$	Separable	0	2 Separable
C05 $[-10,10]^D$	Non Separable	0	2 Non Separable, Rotated
C06 $[-20,20]^D$	Separable	6	0 Separable
C07 $[-50,50]^D$	Separable	2 Separable	0
C08 $[-100,100]^D$	Separable	2 Non Separable	0
C09 $[-10,10]^D$	Separable	2 Non Separable	0
C10 $[-100,100]^D$	Separable	2 Non Separable	0
C11 $[-100,100]^D$	Separable	1 Non Separable	1 Non Separable
C12 $[-100,100]^D$	Separable	0	2 Separable
C13 $[-100,100]^D$	Non Separable	0	3 Separable
C14 $[-100,100]^D$	Non Separable	1 Separable	1 Separable
C15 $[-100,100]^D$	Separable	1	1
C16 $[-100,100]^D$	Separable	1 Non Separable	1 Separable
C17 $[-100,100]^D$	Non Separable	1 Non Separable	1 Separable
C18	Separable	1	2

$[-100,100]^D$			Non Separable
C19 $[-50,50]^D$	Separable	0	2 Non Separable
C20 $[-100,100]^D$	Non Separable	0	2
C21 $[-100,100]^D$	Rotated	0	2 Rotated
C22 $[-100,100]^D$	Rotated	0	3 Rotated
C23 $[-100,100]^D$	Rotated	1 Rotated	1 Rotated
C24 $[-100,100]^D$	Rotated	1 Rotated	1 Rotated
C25 $[-100,100]^D$	Rotated	1 Rotated	1 Rotated
C26 $[-100,100]^D$	Rotated	1 Rotated	1 Rotated
C27 $[-100,100]^D$	Rotated	1 Rotated	2 Rotated
C28 $[-50,50]^D$	Rotated	0	2 Rotated

2. Performance Evaluation Criteria

Number of Problems: 28

Number or runs/trials: 25

Maximum Function Evaluations (Max_FES) = 20000*D, where D is the dimensionality of the optimization problems

Population Size: You are free to have an appropriate population size to suit your algorithm while not exceeding the Max FES.

2.1 **Presentation of Statistics**

Record the function value of $f(X)$ for the achieved best solution X after 2000D, 10000D and 20000D for each problems. D is the dimensionality of the problem.

For each function, present the following: best, median, worst result, mean value and standard deviationfor the 25 runs. Please indicate the number of violated constraints (including the number of violations by more than 1, 0.01, and 0.0001) and the mean violations $\bar{v}$ at one solution.

$$v = \frac{\left(\sum_{i=1}^{p} G_i(X) + \sum_{j=p+1}^{m} H_j(X)\right)}{m}$$

where

$$G_i(X) = \begin{cases} g_i(X) & if\ g_i(X) > 0 \\ 0 & if\ g_i(X) \leq 0 \end{cases}$$

$$H_j(X) = \begin{cases} \left|h_j(X)\right| & if\ \left|h_j(X)\right| - \epsilon > 0 \\ 0 & if\ \left|h_j(X)\right| - \epsilon \leq 0 \end{cases}$$

2.2 **Feasibility Rate**

Feasible Run: A run during which at least one feasible solution is found in Max FES.
Feasible Rate = (# of feasible runs) / Total runs.
The above quantity is computed for each problem separately.

2.3 **AlgorithmComplexity**

a) $T1 = (\sum_{i=1}^{28} t1i)/28$. *t*1*i* is the computing time of 10000 evaluations for problem *i*.
b) $T2 = (\sum_{i=1}^{28} t2i)/28$. *t*2*i* is the complete computing time for the algorithm with 10000 evaluations for problem *i*.

The complexity of the algorithm is reflected by: *T*1*; T*2*; and* (*T*2-*T*1)*/T*1

2.4 **Parameters**

We discourage participants searching for a distinct set of parameters for each problem/dimension/etc.Please provide details on the following whenever applicable:
a) All parameters to be adjusted.
b) Corresponding dynamic ranges.
c) Guidelines on how to adjust the parameters.
d) Estimated cost of parameter tuning in terms of number of FEs.
e) Actual parameter values used.

2.5 **Encoding**

If the algorithm requires encoding, then the encoding scheme should be independent of the specific problems and governed by generic factors such as the search ranges.

3. Presentation of Results

Participants are suggested to present their results in the following format:

PC Configure:

System: CPU:
RAM: Language:
Algorithm:

Parameters Setting:

a) All parameters to be adjusted.
b) Corresponding dynamic ranges.
c) Guidelines on how to adjust the parameters.
d) Estimated cost of parameter tuning in terms of number of FEs.
e) Actual parameter values used.

Presentation of Results

The simulation results obtained for the different optimization problems should be reported in the specified formats (in the manuscript and for the competition).

Presentation of results in the conference manuscript:

For instance, for a 10D problem the results need to be presented in the following format in the manuscript.

Table 1: Function Values Achieved When FES = 2×10^5 for 10D Problems C01-C06.

FEs		C01	C02	C03	C04	C05	C06
2×10^5	Best	-158.7482					
	Median	-55.7482					
	c	0, 0, 0					
	$\bar{v}$	0					
	Mean	-69.0852					
	worst	38.5729					
	std	64.4877					
	SR	100%					
	$\overline{vio}$	0					

c is the number of violated constraints at the median solution: the sequence of three numbers indicate the number of violations (including inequality and equalities) by more than 1.0, in the range [0.01, 1.0] and in the range [0.0001, 0.01] respectively. $\bar{v}$ is the mean value of the violations of all constraints at the median solution. The numbers in the parenthesis after the fitness value of the best, median, worst solution are the number of constraints which cannot satisfy feasible condition at the best, median and worst solutions respectively. SR is the feasibility rate of the solutions obtained in 25 runs. $\overline{vio}$ is the mean constraint violation value of all the solutions of 25 runs.

*The solution sorting method:

1. Sort feasible solutions in front of infeasible solutions;
2. Sort feasible solutions according to their function values *f(x*)*
3. Sort infeasible solutions according to their mean value of the violations of all constraints.

Presentation of results for the competition:

To compare and evaluate the algorithms participating in the competition, it is necessary that the authors send (through email) the results in the following format to the organizers.

Table 2: Function Values Achieved When FES = 2×10^4 , FES =1×10^5, FES = 2×10^5 for 10D Problems C01-C06.

FEs		C01	C02	C03	C04	C05	C06
2×10^4	Best	237.9718					
	Median	358.3837					
	c	2, 0, 0					
	$\bar{v}$	5.3256					
	Mean	350.3861					
	worst	446.8061					
	std	103.2039					
	SR	80%					
	$\overline{vio}$	9.3985					
1×10^5	Best	152.1540					
	Median	291.1380					
	c	0, 2 ,0					
	$\bar{v}$	4.12E-05					
	Mean	28.1940					
	worst	386.3278					
	std	101.189					
	SR	90%					
	$\overline{vio}$	2.3854					
2×10^5	Best	-158.7482					
	Median	-55.7482					
	c	0, 0, 0					
	$\bar{v}$	0					
	Mean	-69.0852					
	worst	38.5729					
	std	64.4877					
	SR	100%					
	$\overline{vio}$	0					

Algorithm Complexity

Table 8: Computational Complexity

$T1$	$T2$	$(T2-T1)/T1$

4. Rank of algorithms

1) Rank all algorithms on one problem with multiple runs

- The procedure for ranking algorithms based on mean values:

  ① Rank the algorithms based on feasibility rate;

  ② Then rank the algorithms according to the mean violation amounts;

  ③ At last, rank the algorithms in terms of mean objective function value.

- The procedure for ranking the algorithms based on the median solutions:

  ① A feasible solution is better than an infeasible solution;

  ② Rank feasible solutions based on their objective function values;

  ③ Rank infeasible solutions according to their constraint violation amounts.

2) Rank all algorithms on multiple problems

For each problem, algorithm ranks are determined in terms of the mean values and median solutions at the maximum allowed number of evaluations, respectively. The total rank value of each algorithm is calculated as below.

$$\text{Rank value} = \sum_{i=1}^{28} rank_i(\text{using mean value}) + \sum_{i=1}^{28} rank_i(\text{using median solution})$$

The best algorithm will obtain the lowest rank value. The top three winners will be announced. Special attention will be paid to which algorithm has advantages on which kind of problems, considering dimensionality and problem characteristics

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