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# Benchmarking CMA-ES with Basic Integer Handling on a Mixed-Integer Test Problem Suite

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#### ABSTRACT

We compare the performances of one implementation of CMA-ES (pycma version 3.3.0) for optimizing functions with both continuous and integer variables. The implementation incorporate a lower bound on the variance along the integer coordinates to keep the optimization from stalling. This benchmark will serve as a baseline for further works on pycma. Results shows substantial improvement since the last benchmarked version of pycma. Also this implementation is competitive with other mixed integer algorithms.

## **CCS CONCEPTS**

•Computing methodologies → Continuous space search;

#### KEYWORDS

Benchmarking, Black-box optimization, Mixed-integer optimization

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## 1 INTRODUCTION

Mixed optimization problems are of great importance in real-world applications. Typically, variables include real-valued degrees of freedom that correspond, directly or not, to physical measurements (eg angles, frequencies, forces, etc.) as well as discrete (integer or binary) settings that correspond to categorical choices (eg materials) or service activations (eg radar modes). Therefore, developing algorithmic variants that can handle several types of optimization variable at the same time without impairing the search process will be very useful in practice.

In the context of black box optimization for problems with continuous variables, evolutionary algorithms which update a covariance

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matrix, namely CMA-ES, are studied from more than 20 years [10]. While the CMA-ES was originally not designed to handle also integer variables, it can be employed with integer variables by using the integer part of a continuous variable in the fitness evaluation. This is however expected to lead to integer variables getting stuck in the resulting fitness plateaus, and several versions have been proposed to improve the algorithm in this situation [4, 5].

In order to study mixed integer problems within the COCO framework [9], the bbob-mixint testbed was proposed in [13]. This testbed is based on the 24 functions of the bbob testbed with 80% of the variables to be integer with an arity between 2 and 16.

In order to prevent variables getting stuck on the same integer level, for example in CMA-ES, a lower bound on the variance can be set such that there remains a reasonable probability for an integer variable to "jump" to another integer level, as for example in CMA-ES with margin (CMA-ESwM) [4]. The same principle is implemented in the pycma code with Integer Handling (cma-IH in the benchmark) with a more simplistic approach.

The purpose of this paper is to measure the performance of the current implementation of the widely distributed cma-IH code (version 3.3.0) [6] with different options and compare its performance with previous results and enhancements.

## 2 ALGORITHM PRESENTATION

The general idea behind cma-IH is to set a lower bound for the variance of the integer variables. It prevents integer variables from being trapped in one value. We formulate the bounding using the covariance matrix decomposition from the CMA-ES with diagonal decoding [1]. At each new iteration t+1, new candidate solutions,  $x^{(t+1)}$ , are sampled according to a multivariate normal distribution.

$$x^{(t+1)} \sim \mathcal{N}(m, \sigma^{(t)^2} C^{(t)})$$
$$\sim m + \sigma^{(t)} \sqrt{C^{(t)}} \mathcal{N}(0, 1) ,$$

where C is a covariance matrix and is  $\sigma$  the step size. In order to bound the standard deviation of each integer variable, we introduce the diagonal scaling matrix D,

$$x^{(t+1)} \sim m + \sigma^{(t)} D^{(t)} \sqrt{C^{(t)}} N(0.1)$$
.

where  $D^{(0)}$  is the identity. The update of  $\sigma$  and C are done as in the original CMA-ES algorithm. Then, the diagonal matrix D is updated based on the current standard deviation in each coordinate. The standard deviation of the  $i^{th}$ -th coordinate of x,  $\sigma^{(t)}_{std(i)}$ , is computed with the diagonal elements of C and D:

<sup>\*</sup>Submission deadline: to be announced (likely late March/early April.

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```
import cocoex
import cma
suite = cocoex.Suite ('bbob-mixint', '', '')
for problem in suite :
  up_bound = list(problem.upper_bounds[
     :problem.number_of_integer_variables]) +
  lo_bound = list(problem.lower_bounds[
     :problem.number_of_integer_variables]) +
     [None]
  cma.fmin2(problem , problem.initial_solution, 1,
             {'bounds': [lo_bound, up_bound]
              'CMA_stds ':(problem.upper_bounds

    problem.lower bounds)/5.

              'integer_variables':list(range(
                problem.number_of_integer_variables)),
             restarts =9)}
```

Figure 1: Calling code to benchmark cma.fmin2.

$$\sigma_{\mathrm{std}(i)}^{(t)} = \sigma^{(t)} \, \mathrm{D}_{i,i}^{(t)} \sqrt{\mathrm{C}_{i,i}^{(t)}}$$

This standard deviation has to be compared with a lower bound  $\sigma_{LB}$ . If the standard deviation in the  $i^{\text{th}}$  coordinate is smaller than the threshold value,  $\sigma_{\text{std}(i)}^{(t)} < \sigma_{LB}$ , then the D matrix is scaled up in this coordinate.

$$\mathbf{D}_{i,i}^{(t+1)} \leftarrow \begin{cases} \frac{\sigma_{LB}}{\sigma^{(t)}} & \text{if } 1 \leq i \leq N_{\text{int}} \text{ and } \sigma_{\text{std}(i)}^{(t)} \leq \sigma_{LB} \\ \mathbf{D}_{i,i}^{(t)} & \text{otherwise} \end{cases} \tag{1}$$

where  $N_{\text{int}}$  is the number of integer variables. In the version 3.3.0 of pycma with integer handling (cma-IH), the lower bound is set to:

$$\sigma_{LB} = \frac{1}{2N_{\rm int} + 1} \tag{2}$$

## 3 EXPERIMENTAL PROCEDURE

Figure 1 shows the calling code and options used to run the benchmark for cma-IH. A maximum of nine restarts may be performed and each restart doubles the population size (IPOP-CMA-ES) [2]. The initial step size is chosen to sample solutions mainly within the upper and the lower bound of the problem. The bounds are enforced on the integer variables only. The maximum number of function evaluations allowed per problem is set to 10<sup>4</sup> times the number of dimension of the problem.

This current implementation cma-IH is compared to performance data from the bbob-mixint COCO archive<sup>1</sup>. We show results of the algorithms given in Table 1.

The experiments were performed and the plots were produced with COCO [9], version 2.6.3.

#### 4 CPU TIMING

In order to evaluate the CPU timing of the algorithm, we have run the cma-IH algorithm with restarts on the bbob-mixint test

Table 1: Compared algorithms

	1.52
cma-IH	pycma version 3.3 (current) with the default
	integer handling option
CMA-ES-pycma	previous integer handling of pycma bench-
	marked in [13]
CMA-ESwM	CMA-ES with margin benchmarked in [3]
cma-NoIH	pycma version 3.3 (current) without any in-
	teger handling option
cmaIH1e-1	as cma-IH with a larger coordinate-wise
	lower bound on the sample standard devia-
	tion of $\sigma_{LB} = 10^{-1}$
DE-scipy	Differential Evolution implemented in scipy
	benchmarked in [13]
RANDOMSEARCH	Random Search algorithm for baseline

suite [13] with a maximum budget of  $10^4 \times$  dimensions function evaluations according to [11].

The Python code was run on a Linux machine with 32 cores, Intel ® Xeon ®E7 to T3 v4 processor. The time per function evaluation averaged over all functions in the test bed for dimensions 5, 10, 20, 40, 80 and 160 equals 3.7, 4.9, 5.1, 5.6, 6.4 and  $8.4 \times 10^{-4}$  seconds respectively.

### 5 RESULTS

Results from experiments according to [11] and [8] on the benchmark functions given in [13]. Figures 2 and 3 show summary results for the different function groups. Figure 4 shows the empirical distribution of function evaluations to reach 51 target values on the single functions [9]. Tables 2 and 3 present expected runtimes and statistical tests.<sup>2</sup>

The **expected runtime** (ERT), used in the tables, depends on a given target precision,  $I_{\text{target}} = f_{\text{opt}} + \Delta f$ , and is computed over all relevant trials as the number of function evaluations executed during each trial while the best function value did not reach  $f_{\text{t}}$ , summed over all trials and divided by the number of trials that actually reached  $f_{\text{t}}$  [11, 12]. **Statistical significance** is tested with the rank-sum test for a given target  $\Delta f_{\text{t}}$  using, for each trial, either the number of needed function evaluations to reach  $f_{\text{t}}$  (inverted and multiplied by -1), or, if the target was not reached, the best  $\Delta f$ -value achieved, measured only up to the smallest number of overall function evaluations for any unsuccessful trial under consideration.

Comparing two integer handling versions of pycma. We compare the performance of cma-IH versus CMA-ES-pycma. In comparison, the cma-IH performs increasingly better with increasing dimension and is overall about ten times faster than CMA-ES-pycma in dimension 80 (see Figure 3, lower right). The largest differences we observe on the ill-conditioned and multi-modal functions. The difference on the linear slope function is mainly due to the boundary handling which was applied also to the continuous variables in the CMA-ES-pycma experiment, as we confirmed with additional experiments. The cma-IH performs statistically significantly better on 6, 8, 10, 16 and 15 functions in dimension 5, 10, 20, 40 and 80,

See https://numbbo.github.io/data-archive

<sup>&</sup>lt;sup>2</sup>The entire data can be found at https://trmarty.github.io/MixedIntegerData/

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respectively. The CMA-ES-pycma performs better on the separable ellipsoid function f2 in dimension 20, 40 and 80.

Comparing pycma with and without the integer handling. The cma-IH and CMA-ES-pycma perform very similar overall. The only statistically significant difference we observed is on the separable ellipsoid function f2 in dimension 5 (not shown), where cma-IH is about three times faster than CMA-ES-pycma, probably due to preventing additional restarts before to reach better targets. The default lower bound on the sample standard deviations for integer variables has overall little impact on the performance on this test suite.

A larger threshold for the standard deviations lower bound. In order to understand the impact of the choice of the threshold, we have run experiments with a few different thresholds for the standard deviations and show the results for the lower bound set to 10<sup>-1</sup>. While in the smaller dimensions the effects are minor, in larger dimension the cmaIH1e-1 performs overall best and is three times faster than cma-IH on the ill-conditioned functions in larger dimension for budgets above 100 times dimension. On the 80-dimensional sphere function, cmaIH1e-1 solves the last target ten times quicker than cma-IH and also two times quicker than CMA-ESwM. The cmaIH1e-1 also solves the Ellipsoid separable whereas cma-IH gets stuck at around 20% of targets. The naive cmaIH1e-1 algorithm is slower than CMA-ESWM by a factor of approximately 3 on functions 5, 13 and 14, however it is significantly better than the current version cma-IH on functions 2, 5 or 12 while not being worse on all other functions. For this range of dimensions, bounding the standard deviation to  $10^{-1}$  is a simple yet effective solution.

### 6 CONCLUSION

We have assessed the integer handling implemented in the current pycma module [7] (version 3.3.0). The performance with integer handling is overall superior to a previously benchmarked version, however it behaves quite similar to the version without integer handling. We attribute the latter observation to a suboptimal parameter setting: tests with a lower bound for the sample standard deviations of 1/10, which is considerably larger than the original setting, reveal a remarkably improved performance on a number of functions. In particular in larger dimension, this variant performs overall best.

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	7.1e4(7e4)	7.8e4(7e4)	8.4e4(6e4)	9.1e4(6e4)	9.5e4(6e4)	1.1e5(6e4)	1.3e5(6e4)	15/15	CMA-ES-	00	00	00	00	00	00	00 465	0/15
	3.7e4(3e4)	4.0e4(3e4)	4.3e4(3e4)	4.5e4(3e4)	4.6e4(3e4)	4.9e4(3e4)	5.2e4(3e4)	15/15	CMA-ESw	00	00	00	00	00	00	DO 465	0/15
	1.7e5(2e5)	1.7e5(3e5)	1.8e5(2e5)	1.9e5(2e5)	1.9e5(2e5)	2.0e5(2e5)	2.1e5(2e5)	11/15	DE-scip	00	00	00	00	00	00	00 de5	0/15
cma-NoI	5842(9760)	6491(9902)	7584(1e4)	8730(1e4)	1.0e4(1e4)	1.3e4(1e4)	1.6e4(1e4)	15/15	cma-NoI	5.9e6(7e6)	5.9e6(8e6)	5.9e6(7e6)	5.9e6(7e6)	5.9e6(9e6)	5.9e6(5e6)	6.0e6(6e6)	1/15
cmalH1e	2875(2073)	3260(1858)	4092(1654)	4841(1462)	5596(1310)	7218(1566)	8826(1664)*	15/15	cmalH1e	5.9e6(5e6)	5.9e6(5e6)	5.9e6(9e6)	5.9e6(8e6)	5.9e6(4e6)	5.9e6(8e6)	5.9e6(6e6)	1/15
is sho f <sub>opt</sub> + was r	own for 10 <sup>-8</sup> . T	r the dif he medi	ferent ta an num	arget ∆j ber of co	f-values onducte	as shov d functi	wn in th on evalu	e to <sub>j</sub> iatio	p row. ns is a	#succ i ddition	etween 10 s the nun ally given tly betten	iber of tr	ials that i s, if the ta	reached rget in t	the la	st tar t colu	get mn

Δf<sub>opt</sub> | 1e1

1.0e4(1e4)

3558(3540)

578(136)

578(136) 588(200) 1643(629) 4850(1211) 652(182) 620(134)

2.3e5(6e4)

CMA-ES- 2.9e6(3e6)

DE-scip oo cma-NoI 2.3e5(2e5) cmalH1e 1.4e5(6e4)

malHac f16 cma-IH 4.0e4(5e4) CMA-ES-CMA-ESw 8.7e5(8e5)

cmalH1e 2.8e4(2e4)

cma-IH 9577(1e4) CMA-ES- 1.0e5(1e5) CMA-ESw 3.1e4(3e4) DE-scip 7.0e4(3e4) cma-Nol 1.4e4(1e4) cmalH1e 6473(8852)

cma-IH 1434(678) CMA-ES- 1533(335) CMA-ESw 2825(1204) DE-scip 2.5e4(2e4) cma-NoI 1260(378) cmalH1e 1451(568)

3.0e4(4e4)

9577(1e4)

1434(678)

867(340)

867(340) 979(370) w 4501(6348) 4935(1332) 872(187) 875(148)

4.4e4(4e4)

2.8e5(3e5) 6.6e5(7e5)

CMA-ES- 1,5e5(3e5) CMA-ESw 1.4e5(2e5)

DE-scip 3.6e4(3882) cma-NoI 1.0e5(2e5) cmalH1e 1.0e4(7e4)

CMA-ESv DE-scip

f14

CMA-FS

CMA-ESv DE-scip cma-NoI cmalH1e

f15 cma-IH

CMA-ESw

CMA-ESv DE-scip cma-NoI

f17 na-IH

f18 cma-IH

f19 cma-IH CMA-ES-CMA-ESw

f20 na-IH

cma-IH CMA-ES-CMA-ESw DE-scip cma-NoI cmaIH1e

f21 cma-IH

f22 na-IH

f23

CMA-ES-CMA-ESv DE-scip cma-NoI cmalH1e

f24 cma-IH

HI-e 2.8e5(3e5)

i-IH

#succ

15/15

15/15

13/15

15/15 cma-Nol

15/15 cmalH1e

2/15

8/15

15/15

13/15

0/15

15/15

0/15 0/15 0/15 0/15 0/15 0/15

0/15

0/15

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15/15

15/15

15/15 15/15

0/15

0/15 0/15 0/15 0/15

6/15

4/15

0/15 DE-scip

0/15 cma-Nol

7/15 cmalH1e

9/15

0/15 0/15

0/15 0/15

0/15

0/15

0/15 CMA-ES-

0/15

0/15 DE-scip cma-NoI

0/15

0/15 cmalH1e

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1e-1

1.1e5(9e4) 1.6e4(1e4) 1.1e5(2e5)

2.1e4(3e4)

1.5e4(2e4)

1.5e4(2e4) 6.8e4(7e4) 7015(1e4) 3.1e5(4e5) 2.0e4(4e4) 5783(4326)

2.3e5(6e4)

2.9e6(4e6)

2,6e5(2e5)

1.4e5(6e4)

1.7e4/3e4

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4.1e5(3e5) 8.2e5(1e6)

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1.3e5(2e5)

7.4e5(1e6) 2.0e5(2e5) 6.3e5(6e5)

2.3e5(3e5) 5.9e4(7e4)

1.2e4(8631)

1e0

2.2e4(2e4)

9.3e4(9e4) 1.4e4(1e4) 9.9e4(2e5)

1.8e4(2e4)

7104(7991)

7193(8184)

7193(8184) 6.2e4(6e4) 3018(658) 2.3e4(6259) 5705(8030) 1959(938)

2.3e5(6e4)

2.9e6(4e6)

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1.4e5(6e4)

1.5e4/3e4

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4.0e5(3e5) 6.3e5(7e5)

1.7e6(2e6)

4.0e4(5e4) 4.2e4(5e4)

1012(274)

997(238)

9.4e4(2e5)

3.4e5(4e5) 1.9e5(2e5)

7.9e4(2e5)

1.5e5(3e5) 4.3e4(7e4)

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1e-2

2.9e4(2e4)

1.2e5(8e4) 1.9e4(1e4) 1.2e5(2e5)

2.4e4(3e4)

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2.3e4(2e4)

2.3e4(2e4) 1.1e5(1e5) 9529(1e4) 4.0e5(5e5) 2.7e4(4e4) 1.3e4(1e4)

2.4e5(6e4)

2,9e6(3e6)

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2.0e4(3c4) 2.2e5(1e5) 1.2e5(2e5) 2.7e5(4e5) 3.2e4(3e4) 3.1e4(2e4)

5.2e4(4e4)

4.3e5(3e5) 8.3e5(8e5) 1.7e6(2e6)

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1.4e5(3e5)

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1e-3

Δf <sub>opt</sub>	lel	1e0	1e-1	le-2	1e-3	1e-5	1e-7	#succ	Δf <sub>opt</sub>	le1	1e0	1e-1	1e-2	1e-3	1e-5	1e-7	#succ
		2007460-47	25 44 0			10.16.1	e e . 400 - 30	*****	cma-IH	1.9+0(9+6)	2.3e5(3e5)	2.4e5(3e5)	n c-rin-ri	2,8e5(4e5)	2.5-5(4-5)	40-114-13	11/11
	1586(212)	7261(2e4)	3.5e4(4e4)	3.8e4(4e4)	4.1e4(4e4)	4.8e4(5e4)	5.5e4(5e4)	15/15		1.3e5(3e5)							
	4.8e4(9e4)	3.1e5(3e5)	3.1e5(3e5)	3.2e5(3e5)	3.4e5(3e5)	4.2e5(3e5)	5.2e5(5e5)	13/15		6.7e5(5e5)	7.8e5(7e5)	8.1e5(9e5)	8.4e5(5e5)				0/15
CMA-ESw		1.1e4(3711)	1.3e4(2772)	1.4e4(3119)	1.6e4(2645)	2.1e4(3882)	2.8e4(3508)		CMA-ESw		4.3e4(2e4)	4.7e4(2e4)	5.3e4(2e4)				
DE-scip	2.6e4(3658)	1.7e6(2e6)	1.1e7(2e7)	1.1e7(1e7)	1.1e7(2e7)	1.1e7(1e7)	1.1e7(1e7)	1/15	DE-scip	3.3e6(4e6)	5.5e6(6e6)	5.6e6(5e6)		5.666(666)			
cma-NoI	1653(226)	1.3e4(2e4)	6.5e4(8e4)	6.8e4(8e4)	7.3e4(9e4)	8.3e4(9e4)	9.2e4(1e5)	15/15		5.1e4(8e4)	1.8e5(3e5)	1.9e5(3e5)	2.1e5(3e5)				
cmalH1e	1652(202)	2963(320)	8453(4542)	8650(3904)	8988(3262)	1.1e4(1943)*3	1.3e4(956)*3	15/15	cmalH1e	6941(3740)	4.1e4(9e4)	8.6e4(1e5)	9.5e4(2e5)	1.0e5(2e5)	1.1e5(2e5)	1.2e5(2e5)	15/15
f2	1000 March					SCHOOL ST.		ander.	f14	0.0 0.0							
	3.7e5(2e5)	00	00	00	00	00	on 8e5	0/15	cma-IH	1018(256)	2.1e4(2e4)	2.0e5(3e5)	4.7e5(6e5)	4.9e5(7e5)	5.4e5(8e5)	6.9e5(8e5)	9/15
CMA-ES-	8.3e4(3e4)	3.3e5(1e5)	1.7e6(1e6)	3.8e6(4e6)	1.2e7(9e6)	1.2e7(2e7)	1.2e7(2e7)	1/15	CMA-ES-	1049(213)	8.2e5(8e5)	8.4e5(8e5)	1.9e6(1e6)	1.9e6(2e6)	2.5e6(3e6)	2.7e6(3e6)	4/15
CMA-ESw		2.5e5(2e5)	2.6e5(2e5)	3.8e5(3e5)	3.9e5(3e5)	4.6e5(5e5)	4.7e5(5e5)	13/15	CMA-ESw	3074(863)	5768(832)	8547(1574)	4.1e4(3e4)	4.6e4(3e4)	7.6e4(4e4)	1.1e5(5e4)	15/15
	2.6e4(5618)	1.7e5(4e5)	7.7e5(1e6)	1.0e6(1e6)	1.0e6(Ie6)	1.0e6(1e6)	1.0e6(1e6)	7/15	DE-scip	9388(2766)	6.3e4(3e4)	1.8e6(3e6)		5.3e6(5e6)			
	3.1e5(1e5)	00	00	00	00	00	00 Se5	0/15	cma-NoI	1000(175)	1.1e5(3e5)	2.3e5(3e5)	6.1e5(9e5)				
	2.2e4(9422)		8.1e4(9e4)	1.0e5(9e4)		1.0e5(9e4)	1.1e5(9e4)*	15/15	cmalH1e	1068(308)	3381(575)	8056(3217)		6.0e4(9e4)			
f3	2.2e4(9422)	3.9e4(3e4)	a. 1e4(9e4)	1.065(961)	1.0e5(9e4)	1.062(364)	1.1e5(9e4)	13/13	f15	85 85	85 85	80 70	82. 32	20.00	Vi Vi	8.8	
	na crista na na	and other ed							cma-IH	1.3e6(1e6)	1.8e6(1e6)	2.1e6(2e6)	2.7e6(3e6)	2.7e6(2e6)	3.666(566)	3.6e6(4e6)	3/15
cma-IH	4157(1210)	1.1e6(8e5)	00	00	00	00	00 8e5	0/15	CMA-ES-	00	00	00		00	00	00 8e5	0/15
CMA-ES-	2.5e4(4e4)	1.2e7(9e6)	00			00	00 8e5	0/15	CMA-ESw	00	00	00	00	00	00	on 8e5	0/15
CMA-ESw		3.6e6(4e6)	00	00	00	00	00 8e5	0/15	DE-scip	00	00	00	00	00	00	00 8e5	0/15
DE-scip	5.7e4(1e4)	00	00	00	00	00	oo 8e5	0/15	cma-NoI	1.9e6(2e6)	1.9e6(2e6)	2.9e6(3e6)	5.8e6(8e6)	1.2e7(1e7)	1.2e7(2e7)	1.2e7(1e7)	1/15
	4107(1556)	1.3e6(1e6)					oo 8e5	100	cmalH1e	9.5e5(1e6)	1.1e6(1e6)	1.1e6(1e6)		1.5e6(1e6)			
	4024(749)	1.7e5(2e5)*2	1.2e7(1e7)	00	00	00	oo 8e5	0/15	f16				, ,				
f4									cma-IH	8.2e4(9e4)	00	00	00	00	00	oo 8e5	0/15
cma-IH	3.1e4(2e4)	2.4e6(1e6)	00	00	00	00	00 8e5	0/15		3.0e4(5e4)	00	00	00	00	00	00 8e5	0/15
	1.7e5(2e5)	00	00	00	00	00	00 8e5	0/15	CMA-ESw		00	00	00	00	00	on 8e5	0/15
CMA-ESw	1.5e5(1e5)	5.7e6(5e6)	00	00	00	00	oo 8e5	0/15	DE-scip	00	00	00	00	00	00	00 865	0/15
DE-scip	6.6e4(9802)	00	00	00	00	00	00 Se5	0/15	cma-NoI	5.0e4(4e4)	00	00	00	00	00	00 8e5	0/15
cma-NoI	3.6e4(2e4)	6.0e6(8e6)	00	CCC	00	00	co 8e5	0/15	cmalH1e	9.6e4(1e5)	00	00	00	00	00	00 Se5	0/15
	7833(2775)	8.4e5(1e6)	00	00	00	00	oo 8e5	0/15	f17	,							
f5									cma-IH	7.4e4(1e5)	4.5e5(4e5)	4.7e5(5e5)	4 Re5/Se5)	4.9e5(6e5)	5 le5(5e5)	5.4e5(5e5)	12/15
cma-IH	2535(202)	4.1e4(2e4)	4.1e4(2e4)	4.1e4(2e4)	4.1e4(2e4)	4.1e4(2e4)	4.1e4(2e4)	15/15	CMA-ES-	8.2e5(2e6)	1.2e7(1e7)	00		00	00	00 865	0/15
	1.3e5(1e5)	2.6e6(4e6)	2.6e6(2e6)	2.6e6(3e6)	2.6e6(2e6)	2.6e6(3e6)	2.6e6(4e6)	4/15	CMA-ESw		2.1e6(3e6)	2.1e6(2e6)	The second second	2.1e6(2e6)		2.7e6(2e6)	
CMA-ESw	1363(376)*4	2790(1038)*	2833(1096)*	2847(1104)*	2847(1104)*	2847(1104)*	2847(1104)*	15/15	DE-scip	3.5e6(4e6)	00	00		DO	00	00 8e5	0/15
DE-scip	1.7e5(5e4)	00	00	00	00	00	00 865	0/15	cma-NoI	3.5e4(3e4)	2.9e5(8e5)	3.0e5(4e5)	3.1e5(4e5)				
cma-NoI	2543(220)	8.8e4(2e5)	8.8e4(2e5)	8.8e4(2e5)	8.8e4(2e5)	8.8e4(2e5)	8.8e4(2e5)	15/15		3.1e4(4e4)	2.1e5(3e5)	2.2e5(4e5)	2.5e5(4e5)				
cmalH1e	2530(282)	4704(3582)	4731(3600)	4741(3590)	4741(3590)	4741(3590)	4741(3590)	15/15	f18	J. Ite squery	E. res(ses)	Lizes(ics)	E.Ses(ics)	2.00s(1cs)	2.363(363)	3.103(103)	1,37 1,3
f6	HILLSON WA								cma-IH	3464(1066)	1.7e6(1e6)	1.7e6(1e6)	1 766/166)	1.7e6(2e6)	2.106/306	2 606(406)	4/15
cma-IH	6187(1424)	1.1e7(1e7)	00	00	00	00	oo 8e5	0/15	CMA-ES-	3972(1193)	00	00		00	00	00 865	0/15
CMA-ES-	9.0e4(2e5)	00	00	00	00	00	00 865	0/15	CMA-ESw		00	00	00	00	00	on 8e5	0/15
CMA-ESw	2.7e5(4e5)	00	00	00	00	00	oo 8e5	0/15	DE-scip	9.5e4(5e4)	00	00	00	00	00	00 865	0/15
DE-scip	5.0e4(2e4)	00	00	00	00	00	00 865	0/15	cma-NoI	3215(840)	1.2e6(1e6)	1.6e6(2e6)		1.6e6(2e6)			
cma-NoI	1.2e4(2e4)	5.5e6(7e6)	00	00	00	00	on 8e5	0/15	cmalH1e		1.2e6(2e6)	1.5e6(2e6)		1.6e6(2e6)			
cmalH1e	5491(2723)	3.6e6(3e6)	00	00	00	00	oo 8e5	0/15	f19		Lizeo(zeo)	Incolucto)	1.500(100)	1.000(200)	1.000(.00)	1.000(200)	0,13
<b>f</b> 7									cma-IH	1.2e7(1e7)	00	00	00	00	00	oo 8e5	0/15
cma-IH	00	00	00	00	00	00	oo 8e5	0/15	CMA-ES-	1.2e7(1e/)	00	00	00	00	00	00 8e5	0/15
CMA-ES-	00	00	00	00	00	00	00 865	100000	CMA-ESw	00	00	00	00	00	00	00 8e5	0/15
CMA-ESw	00	00	00	00	00	00	po 8e5	0/15	DE-scip	00	00	00	00	00	00	00 865	0/15
DE-scip	00	00	00	00	00	00	00 865	0/15	cma-NoI	1.2e7(1e7)	00	00	00	00	00	00 865	0/15
cma-NoI	00	00	00	00	00	00	on 8e5	0/15	cmalH1e	1.2e/(1e/)	00	00	00	00	00	00 865	0/15
cmalH1e	00	00	00	00	00	00	00 865	0/15	f20	CO.	CO	w	CO			00 263	0/15
f8							(" 833A:			2142(583)	5990(8398)					oo 8e5	0/15
cma-IH	2.1e4(2e4)	2.5e6(3e6)	00	00	00	00	oo 8e5	0/15				00		00	00		
	2.1e5(3e5)	3.6e6(4e6)	00	00	00	00	00 865	100	CMA-ES-	4095(846) 1.2e5(2e5)	7.6e4(2e5) 1.3e5(2e5)	1.2e7(1e7) 2.5e6(5e6)	00	00	00	00 8e5 00 8e5	0/15 0/15
CMA-ESw	3.5e4(2e4)	1.4e6(2e6)	00	00	00	00	oo 8e5	0/15	CMA-ESw	1.5e4(3040)	1.9e4(4690)	2.500(500)	00	00	00	00 865	0/15
DE-scip	1.7e5(4e5)	5.8e6(Se6)	00	00	00	00	00 865	0/15	DE-scip cma-NoI	2207(552)	2525(621)	1.2e7(2e7)	00	00	00	DO 865	0/15
cma-NoI	7996(2e4)	2.5e6(3e6)	00	00	00	00	oo 8e5	0/15	cmalH1e	2205(238)	2712(1002)	2.4e6(4e6)	00	00	00	00 865	0/15
cmalH1e	2789(492)	5.4e5(6e5)	00	00	00	00	00 865	0/15	f21	2203(230)	2/12(1002)	2.466(460)				00 263	0/15
f9									cma-IH	6,6e4(7e1)	8.1e4(7e4)	4.8e5(9e5)	71.9-0(1-4)	9.6e5(1e6)	1.4-(10-6)	1.4-(19-()	6/15
cma-IH	3.2e4(4e4)	00	00	00	00	00	00 8e5	0/15									
CMA-ES-	1.4e6(1e6)	00	00	00	00	00	00 8e5		CMA-ES-	2.9e5(8e5) 3.8e5(8e5)	8.7e5(9e5) 5.0e5(7e5)	3.6e6(3e6) 6.4e5(1e6)	1.2e7(8e6)	1.2e6(1e6)	1 906(206)	00 8e5 1.8e6(2e6)	0/15 5/15
CMA-ESw	4.8e5(4e5)	00	00	00	00	00	00 8e5	0/15	DE-scip	3,865(865)	5.065(765)	6.465(166)	7.565(965)	1.266(166)	1.8eb(2eb)	1.8eb(2eb) oo 8e5	0/15
DE-scip	3.3e4(5e4)	00	00	00	00	00	oo 8e5	0/15	cma-NoI	1.5e5(4e5)	2.0e5(5e5)	2.4e5(5e5)		9.0e5(9e5)			
	2.6e4(4e4)	00	00	00	00	00	on 8e5	0/15	cmalH1e	1.6e5(4e5)	2.0e5(5e5) 1.6e5(4e5)	1.9e5(4e5)	3.0e5(5e5)				
f10								- Constant	f22	()	(1)		2.00-1(.103)	(363)	(3(3(3)		10,13
cma-IH	00	00	00	00	00	00	oo 8e5	0/15	cma-IH	00	00	00	co	00	00	00 8e5	0/15
CMA-ES-	00	00	00	00	00	00	oo 8e5	0/15	CMA-ES-	00	00	00	00	00	00	00 8e5	0/15
CMA-ESw	00	00	00	00	00	00	00 865	0/15	CMA-ESw		00	00		00	00	on 8e5	0/15
DE-scip	00	00	00	00	00	00	oo 8e5	0/15	DE-scip	00	00	00	00	00	00	00 865	0/15
cma-NoI	00	00	00	00	00	00	oo 8e5	0/15	cma-NoI	00	00	00	00	00	00	00 8e5	0/15
cmalH1e	00	00	00	00	00	00	on 8e5	0/15	cmalH1e	00	00	00		00	00	00 865	0/15
fii								- Avenue	f23	and the second s	- market	- media i					0,13
cma-IH	6954(Ie4)	5.7e6(5e6)	00	00	00	00	oo 8e5	0/15	cma-IH	1.9e5(2e5)	00	00	00	00	000	00 8e5	0/15
CMA-ES-	751(646)	3.7e6(5e6)	00	00	00	00	oo 8e5	0/15	CMA-ES-	1.2e7(1e7)	00	00	00	00	00	00 865	0/15
CMA-ESw	921(738)	00	00	00	00	00	00 865	100000	CMA-ESW		00	00		00	00	00 865	0/15
DE-scip	4009(4052)	00	00	00	00	00	00 865	0/15	DE-scip	00	00	00	00	00	00	00 865	0/15
cma-NoI	7208(Ie4)	2.7e6(3e6)	00	00	00	00	oo 8e5	0/15	cma-NoI	2.3e5(2e5)	00	00	00	00	00	00 865	0/15
cmalH1e	1.8e4(2e4)	5.7e6(6e6)	00	00	00	00	on 8e5	0/15	cma-Not	5.7e6(7e6)	00	00		00	00	00 865	0/15
f12	XXXXXXXXXX	100000000000000000000000000000000000000					47-07076-5	3276-576	f24	3.760(760)	and .	and .				20 003	0/13
	3.2e4(2e4)	2.0e5(3e5)	2.1e5(3e5)	2,1e5(3e5)	2.2e5(3e5)	2.4e5(4e5)	2.7e5(4e5)	13/15	cma-IH	00	00	00	00	00	00	00 8e5	0/15
	4.1e5(4e5)	4.2e5(5e5)	4.4e5(5e5)	4.7e5(5e5)	5.4e5(4e5)	6.7e5(5e5)	7.7e5(4e5)	11/15	CMA-ES-	00	00	00	00			00 8e5	0/15
CMA-ESw		2.6e5(1e5)	2.9e5(2e5)	2.9e5(2e5)	2.9e5(2e5)	3.0e5(2e5)	3.1e5(2e5)		CMA-ES-		00	00		00	00	00 8e5 00 8e5	0/15
DE-scip	7.0e5(8e5)	1.1e6(1e6)	1.2e6(2e6)	1.2e6(1e6)	1.2e6(1e6)	1.5e6(1e6)	1.5e6(2e6)	6/15	DE-scip	000	00	00	00	00	00	00 8e5	0/15
	2.9e4(2e4)	8.2e4(1e5)	8.7e4(1e5)	9.1e4(1e5)	9.6e4(1e5)	1.0e5(1e5)	1.1e5(1e5)	15/15	cma-NoI	5.9e6(8e6)	00	00	00	00	00	00 8e5	0/15
	6361(2626)		1.2e4(7724)*2					100	cmalH1e	3.8e6(5e6)	00	00	00	00	00	00 8e5	0/15
Committee	2020)	Constant)		Lieqieij	z./es(zes)	- Servery	Licey	23,13	SIMILITIE .	J.J.Co(J.Co)	a seed of						Late
	F									Land							

Table 3: Expected runtime (ERT) to reach given targets, measured in number of f-evaluations, in dimension 80. For each function, the ERT and, in braces as dispersion measure, the half difference between 10 and 90%-tile of (bootstrapped) runtimes is shown for the different target  $\Delta f$ -values as shown in the top row. #succ is the number of trials that reached the last target  $f_{\rm opt}+10^{-8}$ . The median number of conducted function evaluations is additionally given in *italics*, if the target in the last column was never reached. Entries, succeeded by a star, are statistically significantly better (according to the rank-sum test) when compared to all other algorithms of the table, with p=0.05 or  $p=10^{-k}$  when the number k following the star is larger than 1, with Bonferroni correction by the number of functions (24). Best results are printed in bold.

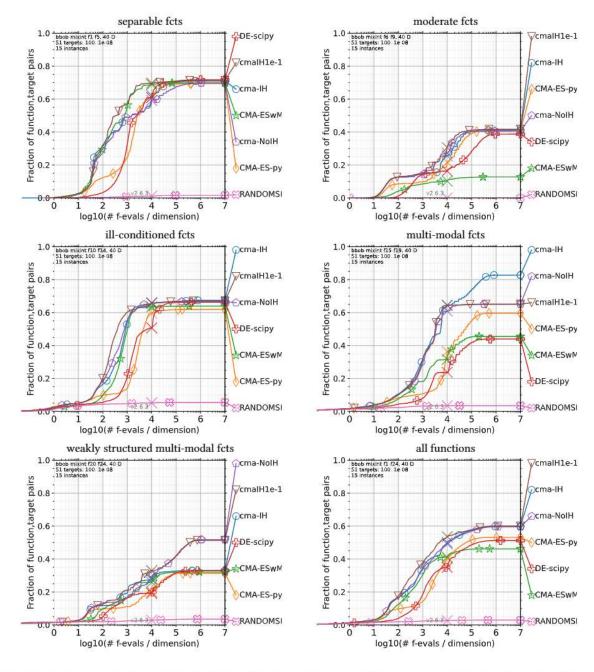


Figure 2: Bootstrapped empirical cumulative distribution of the number of f-evaluations divided by dimension (FEvals/DIM) for 51 targets with target precision in  $10^{[-8..2]}$  for all functions and subgroups in 40-D.

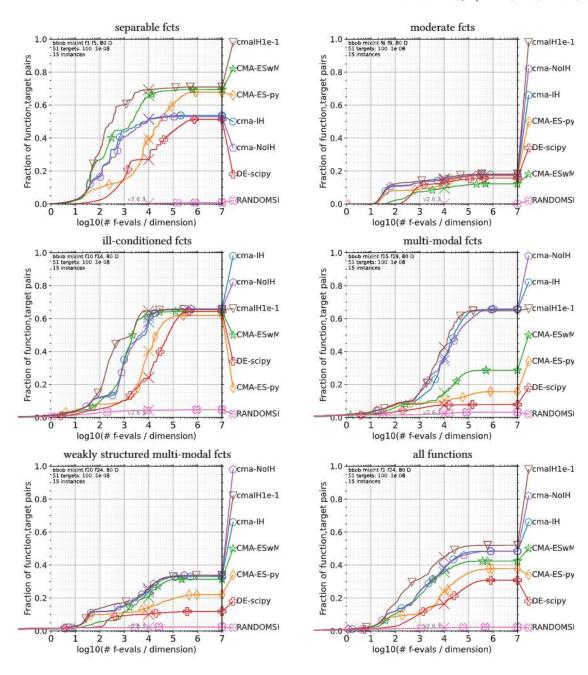


Figure 3: Bootstrapped empirical cumulative distribution of the number of f-evaluations divided by dimension (FEvals/DIM) for 51 targets with target precision in  $10^{[-8..2]}$  for all functions and subgroups in 80-D.

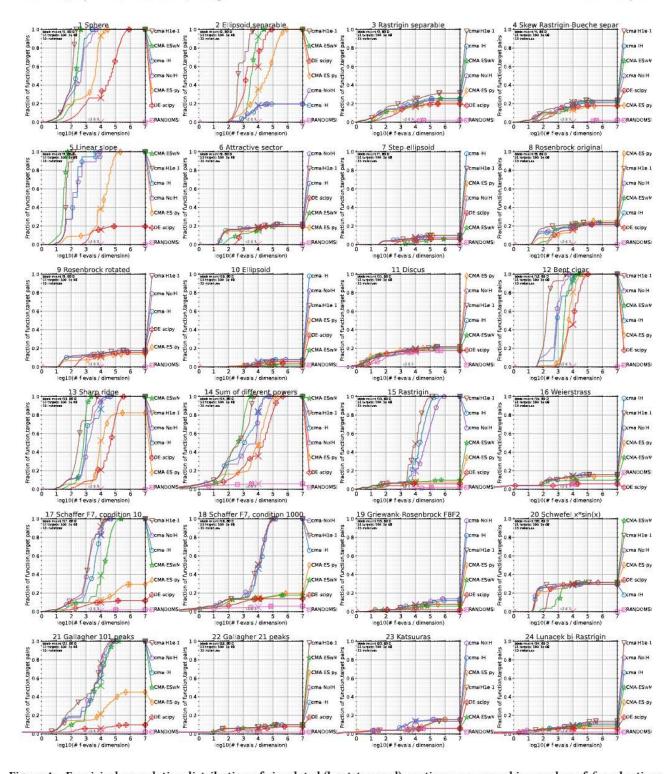


Figure 4: Empirical cumulative distribution of simulated (bootstrapped) runtimes, measured in number of f-evaluations, divided by dimension (FEvals/DIM) for the 51 targets  $10^{[-8..2]}$  in dimension 80.