

A Constrained ITGO Heuristic Applied to Engineering Optimization

Matheus Pedroza Ferreira^a, Marcelo Lisboa Rocha^{a,*}, Antônio J. Silva Neto^b,
Wagner F. Sacco^c

^a*Departamento de Ciência da Computação, Universidade Federal do Tocantins, Quadra 109 Norte,
Avenida NS-15, ALCNO-14, Palmas, Tocantins, Brazil*

^b*Departamento de Engenharia Mecânica e Energia, Instituto Politécnico, Universidade do Estado do Rio
de Janeiro, IPRJ/UERJ, RJ, Brazil*

^c*Instituto de Engenharia e Geociências, Universidade Federal do Oeste do Pará, PA, Brazil*

Point-to-point changes

Reviewer #1

Some important points in the experimental part of the revised paper still however persist. They regard the adopted comparison strategy between deterministic and metaheuristic algorithms. When I said "(please take into account that the number of function evaluations is to be multiplied by the number of runs of a metaheuristic method - 25 in this paper)" this did not mean to use a particular "type of comparison" as authors replied. This just means that to obtain the reported numbers of function evaluations the authors needed to perform 25 (or 100 in new experiments) launches of their method for each test function and then to average the results. Thus, while the competitors used, let us say, a thousand evaluations, the authors claimed to use, in average, 500 evaluations (which is apparently better!) but, in fact, they used, in average, 25*500 (or 100*500) evaluations of a test function (which is much worse!). Thus, if we have a practical problem to solve, the competitors solve this problem in 1000 evaluations, while the authors' method can solve it in 10 evaluations in a particular run, in 500 evaluations in another run, or probably does not solve the problem at all. To have a higher possibility to solve the problem, a higher number of launches of the

*Corresponding authors

Email addresses: matheuspedrozaferreira@uft.edu.br (Matheus Pedroza Ferreira),
mlisboa@uft.edu.br (Marcelo Lisboa Rocha), ajsneto@iprj.uerj.br (Antônio J. Silva Neto),
wagner.sacco@ufopa.edu.br (Wagner F. Sacco)

method is needed or a careful tuning of the multiple parameters of the method has to be done thus increasing the required computational costs.

Therefore, I still do not find the reported numerical results to be fair. As I could understand, the methodology reported in Sergeyev et al. (2018) aimed at considering all these worst, best, and average cases in a unique diagram. The authors instead have just taken results from this paper and mixed them with their own ones thus producing superficial and misleading conclusions. Maybe I am wrong but neither from the revised paper nor from the authors' brief reply I could see the opposite conclusion.

The methodology used to achieve the results presented in the paper may be not very clear, so we now make a thorough discussion about the methods used.

Engineering Design Problems

We consider eight engineering design problems, consisting of continuous, integer and mixed-integer constrained optimization problems. We compared the results achieved by C-ITGO against 19 competitive meta-heuristic methods, with some of them reporting state of the art results for the problems considered.

For each of the eight engineering design problems, we run the C-ITGO algorithm 25 times, saving all the statistics of each run. The choice of the number of runs for each problem is completely arbitrary. We chose the number 25 to match the results of one of the most competitive methods considered, the IAPSO (Guedria, 2016). However, as the only statistic considered is the Mean Number of Function Evaluations (MNFEs), we can safely compare C-ITGO against the other meta-heuristics, even if they execute a different number of runs for each problem.

For each of the 25 runs for a problem, we restarted the random number generator with a different seed, so as to couple with the stochastic nature of C-ITGO. If the same seed is used for each run, the exactly same results are achieved, which is obviously not wanted.

However, the same sequence of seeds was used for all problems. Specifically, we started with the seed number 270001 (this is an arbitrary value used by some authors (Silva et al., 2013)) for problem 1 and increased the seed value by 1 for each run. That is, for run 1, we used seed number 270001, for run 2, the seed number is 270002, and so on.

Any other sequence of seeds could be used. In fact, we could choose a particular

sequence of seeds for each problem that would give the best results on average. This, of course, would bias the results. This was not the case with C-ITGO, as we used the same arbitrary sequence of seeds for all the eight problems.

The statistics currently reported for each problem are: the function value of the best solution found among the 25 runs (**Best**), the mean function value of the 25 solutions found (**Mean**), the function value of the worst solution found among the 25 runs (**Worst**), the standard deviation of the function value of the 25 solutions (**SD**) and the mean number of function evaluations needed to achieve convergence (**MNFES**), also calculated among the 25 runs.

The convergence criteria are discussed in the text and are specific to each problem (see page 23). We chose to adopt these criteria because the problems being solved present very different characteristics, like the results presented by the competing methods. Still, the C-ITGO algorithm achieves very small standard deviation for the function value in all problems considered (smaller than most competing methods for all problems).

We also note, again, that all solutions found by C-ITGO for all the engineering problems are completely feasible (they respect all imposed constraints on all runs), as stated in page 23, paragraph 3. So, we can consider that every run of the C-ITGO method is successful, having no failed runs given the convergence criteria.

Considering the methodology used, the authors consider that the comparison of the C-ITGO method against the competing meta-heuristics is completely clear, valid and fair. Of course, all the methodology presented here can be found in the main text.

GKLS

For the GKLS class of problems, we used exactly the same methodology used in Sergeyev et al. (2018) for meta-heuristics. We considered 100 different problems for each of the eight classes, ranging from 2 to 5 dimensions, each consisting of an easy and a hard case. For each problem, C-ITGO was executed 100 times, saving the statistic for all runs.

The first thing to consider is that every single run of C-ITGO was successful. That is, none of the 80,000 runs (8 classes, 100 problems, 100 runs for each problem) required more than 10^6 function evaluations to achieve convergence. That is, not even a single run has failed.

For all classes, we fed the random number generator with the seed value 270001

for problem 1, 270002 for problem 2, and so on, up to 270100 for problem 100. For each problem, we save the number of function evaluations required to achieve convergence.

Table 18 in the main text shows the mean number of function evaluations required to achieve convergence for all the eight classes. This table presents the same results as the Table 1 of Sergeyev et al. (2018), when comparing deterministic and meta-heuristics.

According to the reviewer’s opinion, the results presented in the main text are ‘misleading’ and ‘superficial’, even considering the fact that the results presented were achieved in the exactly same way as described in Sergeyev et al. (2018). So, the authors decided to include some more data for the comparison of the developed method.

We added to the main text, in the appendix section, plots showing the *Operational Zones* of the C-ITGO method, together with the *Operational Characteristics* of the competing deterministic methods, for the easy and hard cases of the 5-dimensional class.

Also, a new table with some more statistics regarding the number of function evaluations was added. We included the minimum, maximum and the standard deviation for all the 10,000 runs for each class of problems and also after averaging all the 100 runs of the same problem (Table 19, page 54).

We hope that all those additions to the text convince the reviewer that the methods and comparison that were used in this work are completely fair.

Reviewer #2

Although the authors made a significant improvement in the revised paper, there remain some important questions that I would ask the authors to consider. They mainly concern a newly added section (Appendix) where results on test classes are reported.

1) Please indicate the number of evaluations executed in local searches. Are these numbers currently included in the numbers of Table 18?

Yes, the number of function evaluations executed in the local searches are included in the calculations of the mean number of function evaluations.

Actually, the local searches are responsible for the most part of the function calls, as stated in page 17, paragraph 3, where we comment about the impact of the maximum number of function calls allowed for each call of the local search procedure.

2) When several runs are executed by a stochastic method for solving a particular problem, some of them can be unsuccessful and for them maximal allowed number of evaluations can be reached. If these runs are excluded from calculating the averages, the results can be falsely advantageous for the considered method with respect to the other compared algorithms. Please comment upon this aspect and indicate the percentage of unsolved problems (as done for example in doi 10.1016/j.amc.2017.05.014 - Metaheuristic vs. deterministic global optimization algorithms: The univariate case). It is also a good practice to indicate other statistics (for example, standard deviations) for the results given by stochastic methods.

When considering the engineering design problems, all solutions found by C-ITGO were completely feasible, respecting all imposed constraints (see page 23, paragraph 3). Also, the execution of C-ITGO is halted only when the best-found solution in a run is considerably close to the global optimum, as described in Table 2, page 23. The standard deviation achieved by C-ITGO is very small in all problems, with the fitness of the worst solution being very close to the fitness of the best solution. In fact, it is one of the methods with smallest standard deviation in all cases when compared to the other methods considered. So, we believe we can consider that all runs of the C-ITGO method were successful for all the eight engineering design problems.

When it comes to the GKLS class of problems, a run is considered successful if it satisfies the criteria described in Kvasov & Sergeyev (2012), which was also emphasized in the appendix of the text, more specifically in page 52, equation 3. If a method executes 10^6 function evaluations and do not achieve convergence, its execution is stopped and that run is marked as unsuccessful (as displayed in Table 18 in the same fashion as Sergeyev et al. (2018)).

We used the same approach as described in Sergeyev et al. (2018) to apply C-ITGO to the GKLS class of problems, running the algorithm 100 times for each of the 100 problems of each class (with 8 classes, this means 800 different problems, with a total of 80,000 runs), as described in page 52. We then average the number of

function/gradient calls for each problem, that is, we take the mean of the 100 runs for each of the 800 problems. Every run of C-ITGO (every one of the 80,000 runs) was successful and achieved convergence under 10^6 function calls.

Now we also included in the text the minimum, maximum and the standard deviation for all the 10,000 runs for each class of problems and also after averaging all the 100 runs of the same problem (Table 19, page 54). We again emphasize that none of the 80,000 runs (which are all successful) exceeded 10^6 function/gradient calls. We then conclude that every run of C-ITGO for all the 800 problems of the GKLS class of problems was successful, with none of them exceeding the maximum number of function evaluations allowed (10^6).

Please do not use term unconstrained optimization for box-constrained problems to avoid misunderstanding (unconstrained optimization problems have no any constraints while the problems in Appendix do have them).

We agree with the reviewer. Using the term unconstrained optimization for bound constrained optimization is misleading and wrong. The current version of the paper was modified accordingly.

Highlights: The developed method can solve real, integer and mixed-integer constrained problems -> but only continuous problems are considered.

That is not correct. Integer and mixed-integer constrained problems were also considered. The Gear Train (GT) and the Multiple Disk clutch brake (MD) are examples of integer constrained optimization problems, while the Speed Reducer (SRII and SRII) and Pressure Vessel (PV) are mixed-integer constrained optimization problems.

We kindly ask the reviewer to reread the section **3. Computational Results**, where we comment about each problem, explicitly stating in both the text and in the mathematical formulation whether it is a continuous, integer, or mixed-integer constrained problem.

Finally, bibliography is needed to be polished: please check the references Gavano et al. (2003), Paulavcius and Zilinskas (2014), Paulavcius and Zilinskas (2016), Sergeyev and Kvasov (2006), Sergeyev et al. (2013), Sergeyev et al. (2018), that are either incorrect or contain errors.

This was already solved and the references were double checked. They are corrected now on the current version of the paper.

Abstract

Nonlinear optimization is an active line of research, given the wide range of scientific fields that benefit from its development. In the last years, the meta-heuristics proved to be one of the most effective methods to tackle difficult optimization problems, providing an alternative in cases where exact methods would be unfeasible. In this work, we present a method based on the Iterative Topographical Global Optimization meta-heuristic, which we call C-ITGO, incorporating specific mechanisms to solve nonlinearly constrained optimization problems. We use the method developed in this work to optimize eight complex engineering design problems and compare the results obtained here against those obtained with several other methods found in the literature. In the tests performed, C-ITGO outperforms all competing methods, achieving state of the art results for the problems considered.

Keywords: Meta-heuristics, ITGO, Optimization, Engineering Problems.

1. Introduction

In recent years, there has been an increase in the interest of applying meta-heuristics to solve difficult numerical optimization problems, mainly due to the impossibility of obtaining good quality solutions to some complex problems using standard local optimization methods. It is usual to find nonlinear constrained real-world problems which are not smooth or not even continuous, ruling out the possibility to apply any gradient-based optimization procedure.

Even when the problem at hand has continuous derivatives, it may be multimodal, having many local optima. Any deterministic local procedure is confined to finding

sub-optimal solutions for any multimodal problem of reasonable size. Many modern meta-heuristics, on the other hand, are capable of finding an optimal or nearly optimal solution to these problems within a feasible amount of time.

Along with the meta-heuristics, there exist a class of deterministic global optimization methods that can tackle multimodal optimization problems, assuring convergence to the global optimum with predefined tolerance. These methods are in general more complex than meta-heuristics, having rigorous convergence proofs and requiring certain mathematical background to be correctly understood and implemented (Sergeyev et al., 2013; Paulavičius & Žilinskas, 2014; Sergeyev et al., 2018). Some examples include the well known DIRECT (DIviding RECTangles) method (Jones et al., 1993), its locally biased variant (Gablonsky & Kelley, 2001), the ADC (Adaptive Diagonal Curves) algorithm (Sergeyev & Kvasov, 2006), and some more recent methods Kvasov & Sergeyev (2012); Fok et al. (2017); Paulavičius & Žilinskas (2016). A thorough comparison between meta-heuristics and deterministic global optimization algorithms is made in Sergeyev et al. (2018), using some novel methods.

Among the most recent meta-heuristics used to solve nonlinear constrained optimization problems, we can cite some well known methods, such as Particle Swarm Optimization (PSO) (Machado-Coelho et al., 2017; Guedria, 2016; Liang et al., 2010), Artificial Bee Colony (ABC) (Brajevic, 2015; Long et al., 2017), Differential Evolution (DE) (Sarker et al., 2014; Takahama & Sakai, 2010; Melo & Carosio, 2013), Genetic Algorithms (GA) (Saha et al., 2010) and many other new methods, being some of them nature inspired (Gandomi et al., 2013; Eskandar et al., 2012; Sadollah et al., 2013).

The objective is to find the best solution in a search space that satisfies some criteria, expressed in the form of constraints, whose value is rated according to a function. For minimization, a general nonlinearly constrained optimization problem can be defined as follows:

$$\begin{aligned}
& \arg \min_{\mathbf{x}} f(\mathbf{x}) \\
& \text{s.t. } g_j(\mathbf{x}) \leq 0, \quad j = 1, \dots, p \\
& \quad h_k(\mathbf{x}) = 0, \quad k = 1, \dots, q \\
& \quad l_i \leq x_i \leq u_i, \quad i = 1, \dots, n
\end{aligned} \tag{1}$$

where $f(\cdot)$ is the objective function or fitness function, $\mathbf{x} = (x_1, \dots, x_n)$ is a solution vec-

tor containing n continuous or discrete values, $g_j(\cdot)$, $j = 1, \dots, p$, and $h_k(\cdot)$, $k = 1, \dots, q$, are the inequality and equality constraints respectively, where both can be nonlinear. The vectors \mathbf{l} and \mathbf{u} define the lower and upper bounds of the solution space. We also define the sum of constraint violation as:

$$v(\mathbf{x}) = \sum_{j=1}^p \max\{g_j(\mathbf{x}), 0\} + \sum_{k=1}^q |h_k(\mathbf{x})| \quad (2)$$

so a solution \mathbf{x} is feasible only when $v(\mathbf{x}) = 0$.

In this work, we develop some modifications over a successful meta-heuristic for continuous optimization, known as Iterative Topographical Global Optimization (ITGO) (Törn & Viitanen, 1996). The modifications consist of adapting ITGO to work with constrained optimization issues, calling this new algorithm as the Constrained version of ITGO (C-ITGO). We compare the results obtained for eight complex constrained engineering design problems, used as a benchmark against several state-of-the-art methods. We show that C-ITGO outperforms the best competing techniques from literature, mainly relative to the number of function evaluations that characterize the execution effort of the technique.

The structure of the paper is as follows. Section 2 presents the C-ITGO method, as well as the details of its implementation and the parameters used in the tests. We compare the developed algorithm against the competing methods in Section 3 and make the final conclusions in Section 4.

2. The Constrained Topographical Global Optimization Algorithm

The TGO algorithm, which stands for *Topographical Global Optimization*, is a meta-heuristic developed by Törn & Viitanen (1992) for solving continuous optimization problems, possibly non-smooth and multimodal. The method has three steps: (i) the random uniform generation of a population of solutions over the domain of the problem; (ii) the selection of some of the individuals of the population based on the topography of the function to be optimized; and (iii) the application of some sort of local search in the selected elements.

Initially, the TGO creates a population of size M denoted by $P = \{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_M\}$, uniformly distributed in the solution space. The TGO performance depends directly on the algorithm used in the generation of the population, and, consequently, on the

pseudo-random number generator. In this work, we used the Sobol sequences (Sobol, 1967; Henderson et al., 2015), which has a significantly more uniform distribution than a state-of-the-art pseudorandom number generator. Figure 1 shows the distribution of 300 points in the domain $[0, 1]^2$, with 150 of them (blue dots) generated by the pseudo-random generator Mersenne Twister proposed by Matsumoto & Nishimura (1998). The other points (red dots) are the 150 first elements of a Sobol sequence. From Figure 1 it is possible to observe that the points generated by the Sobol sequence cover the space more uniformly than those of Mersenne Twister.

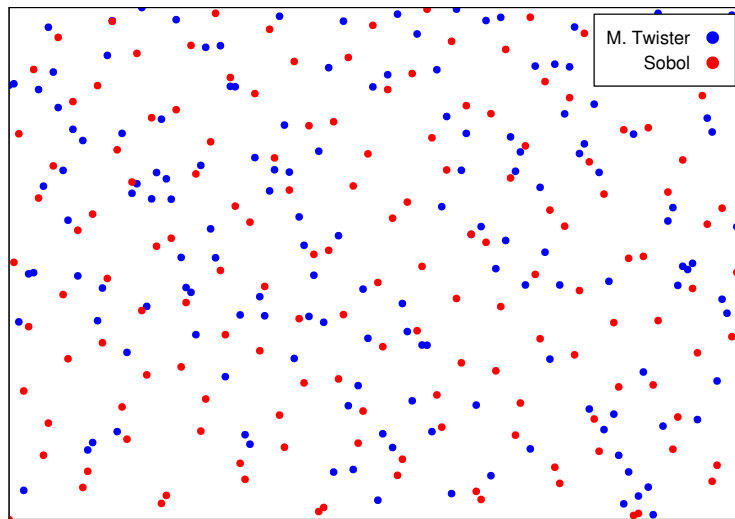


Figure 1: Example showing the distribution of points in the domain $[0, 1]^2$ by the Mersenne Twister generator (blue points) and by a Sobol sequence (red points).

The next step is the construction of a graph over possible solutions that incorporate information regarding the topography of the function $f(\cdot)$. Consider now a integer $K > 0$. We define the $KNN_K(x)$ neighborhood as the set of the K elements of the population P , different of x , that have the smallest euclidean distance from x .

A directed graph is then defined, having a vertex for every solution in the population. For each individual x , a directed edge is created pointing to every element x' of the population P such that $x' \in KNN_K(x)$ and $f(x) \leq f(x')$. With this construction, every vertex has at most K outgoing edges. A topography matrix $A \in \mathbb{R}^{M \times M}$ is created based on this graph, defined as:

$$A_{i,j} = \begin{cases} 1, & \text{if } f(\mathbf{x}_i) \leq f(\mathbf{x}_j) \text{ and } \mathbf{x}_j \in KNN_K(\mathbf{x}_i) \\ 0, & \text{otherwise} \end{cases}$$

The matrix A tells us if the element \mathbf{x}_i has better fitness than the element \mathbf{x}_j , given that \mathbf{x}_j is in the KNN set of \mathbf{x}_i . The graph defined previously has a direct link with the topography matrix: a directed edge between elements \mathbf{x}_i and \mathbf{x}_j only exists if $A_{i,j} = 1$. We have then created an ordering of the elements of the population based on the position in space, the objective function value, and the neighborhood defined by K .

The topographic heuristic is based on selecting every individual \mathbf{x}_i such that $\sum_j^M A_{i,j} = K$, that is, every individual that has better fitness than every element of its KNN set. Likewise, every vertex that has K outgoing edges. These elements are considered local optimal points based on the estimated topography of the function $f(\cdot)$.

As there is no guarantee that the individuals selected are really local optimal points (as we only have an estimate of the function's surface given by the topography created), the application of some algorithm for fine-tuning is necessary.

The last step of the TGO method consists in applying some sort of local search in every local optimal point based on the topographic heuristic. Regarding the local search, many procedures used in the TGO are found in the literature, such as pattern search algorithms (Sacco et al., 2014), derivative-based (Henderson et al., 2015) and derivative-free (Jardim et al., 2015) optimization methods. The local search algorithm depends directly on the properties of the function to be optimized and is of significant impact in the overall performance of the method.

We consider now a simple example. Let the function $f(\cdot)$ be defined by $f(x, y) = \sin(x^2) + \sin(y^2)$, in the domain $[-1, 3]^2$, the population P composed by the 10 elements:

$$\begin{aligned} \mathbf{x}_1 &= (-0.2, 0.16), & \mathbf{x}_2 &= (1.2, -0.3), & \mathbf{x}_3 &= (-0.6, 1.2) \\ \mathbf{x}_4 &= (-0.9, 2.4), & \mathbf{x}_5 &= (2.0, 2.0), & \mathbf{x}_6 &= (2.7, 0.3) \\ \mathbf{x}_7 &= (0.3, 2.2), & \mathbf{x}_8 &= (2.0, -0.2), & \mathbf{x}_9 &= (1.3, 2.8), & \mathbf{x}_{10} &= (1.3, 1.2) \end{aligned}$$

and the KNN set determined by the $K = 3$ closest neighbors. Figure 2 shows the

contour plot of the function and the directed graph created by the population. The topography matrix and the sum of each row are the following:

$$A = \left(\begin{array}{cccccccccc|c} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & \mathbf{3} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{1} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{0} \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & \mathbf{2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & \mathbf{3} \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & \mathbf{2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & \mathbf{2} \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & \mathbf{3} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & \mathbf{1} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{0} \end{array} \right)$$

According with the graph and the topography matrix created, it is easy to observe that only the elements x_1 , x_5 and x_8 are local optimum, that is, has K outgoing edges, satisfying $\sum_j^M A_{1,j} = \sum_j^M A_{5,j} = \sum_j^M A_{8,j} = K = 3$.

Even after the application of local search, there is no guarantee that the global optimum was found. It is common to successively apply the TGO method many times, with new elements at each iteration. This procedure is called *ITGO (Iterative Topographical Global Optimization)*, and consists simply in the iterative application of the TGO method, returning the best element found during all the process.

2.1. Space Reduction

In Jardim et al. (2015) a heuristic for space reduction is proposed for the ITGO. After the individual selection step, a sub-space is created around every element, with space reduced in each dimension by $\phi \in (0, 1)$. A new population is generated for every space created, and new elements are selected, for each population. The process is repeated for a defined number of iterations until the execution of local search on selected elements of the last space reduction.

An example involving the application of this heuristic is presented in Figure 3, again for the function $f(x, y) = \sin(x^2) + \sin(y^2)$, in the domain $[-1, 3]^2$, with the first

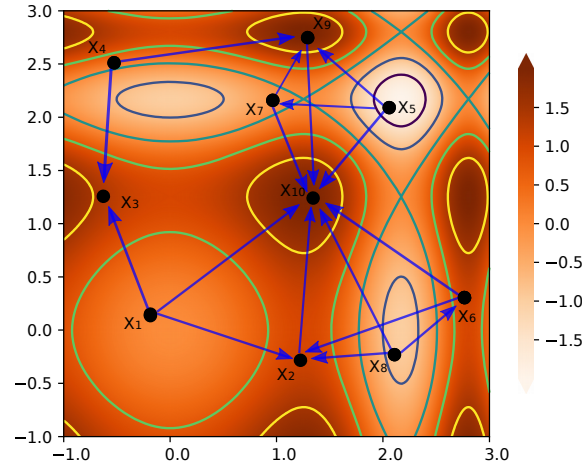


Figure 2: Contour plot of the function $f(x, y) = \sin(x^2) + \sin(y^2)$, and the graph based on the population.

population composed by the same 10 points described previously. Figure 3a shows the selection of the points x_1 , x_5 and x_8 , with a space reduced by $\phi = 0.25$. Figure 3b we can observe the generation of populations for each new subspace. The red points are the individuals considered local optimum based on the topographic heuristic. It is worth noting that the local optimal points of the previous population are kept in the next population.

At each iteration, a new population size is set, along with a new value for K , which is usually smaller than in the previous iteration.

2.2. Constrained Optimization

Up to this point, the ITGO algorithm has been presented only for unconstrained optimization problems. ITGO was applied previously to constrained optimization problems (Sacco et al., 2014; Henderson et al., 2015), handling constraints by using a specific local search procedure or by penalizing unfeasible individuals.

In this work, we propose a different approach, adopting a mechanism for comparing solutions proposed in Deb (2000), and used in some very competitive meta-heuristics, especially on differential evolution algorithms (Sarker et al., 2014; Takahama & Sakai, 2010; Montes et al., 2006). As in this work we propose a constrained

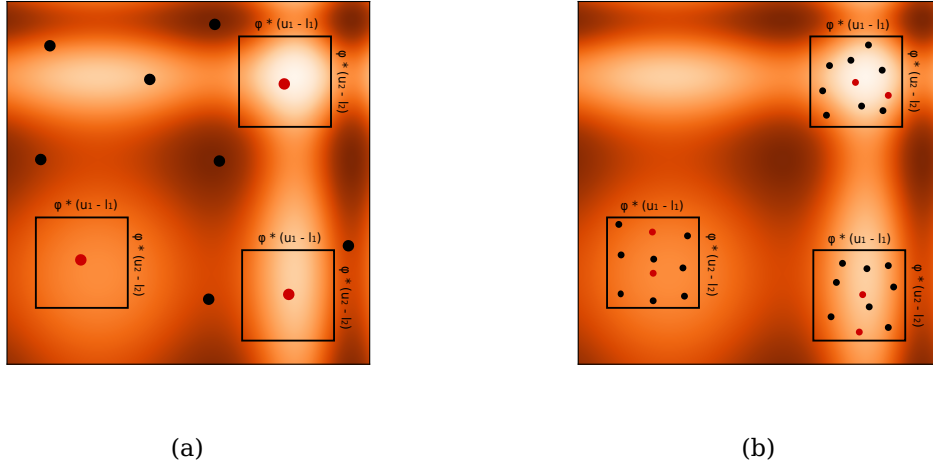


Figure 3: Example showing the application of the space reduction heuristic. In (a) we have the space reduction around the three individuals of Figure 2 (x_1 , x_5 and x_8) in red. In (b) are the respective populations generated in each restricted space to apply ITGO, with the local optimal points in red.

version of ITGO, in the rest of the paper it is named as C-ITGO, standing for Constrained ITGO. The method for comparison used in this work hereafter comprises the following three steps criteria:

- Between two feasible solutions, the fittest one is better.
- A feasible solution is always preferred over an unfeasible solution, irrespectively of its fitness.
- Between two unfeasible solutions, the one with the smallest sum of constraint violation (equation 2) is better.

In the topographical heuristic step, we compare two solutions using this three steps criteria with probability α , and otherwise, we compare only the fitness value. What we try to achieve with this heuristic is keeping promising solutions with small violation of constraints for further exploration with the local search step.

We generate a symmetric matrix of random numbers R , with $R_{i,j} = R_{j,i} \in [0, 1]$. If $R_{i,j} < \alpha$, then we compare elements x_i and x_j using the three steps criteria. Otherwise, only the fitness value is compared. In general, with this configuration, the

number of local optimal points selected by the topographical heuristic is smaller, especially on problems with a small feasible area.

It is important to observe that some distributions of the individuals, with populations of small size and a high value for K , may not generate any local optimum in the topographical heuristic. In the case of none of the individuals being selected as a local optimum in the current population, we take the best individual according to the three steps criteria previously presented as the only local optimum of that population. In practice, however, it is rather unusual to happen.

The best individual in the whole search is always selected using the three steps criteria already mentioned since feasible solutions are generally preferred. In addition to this new topographical selection method, we also use local search algorithms for constrained optimization.

2.3. Implementation

We now present an overview of the implementation of the method, along with pseudocodes describing all necessary steps. Algorithm 1 shows the general procedure for the C-ITGO algorithm.

The parameters are the functions $f(\cdot)$ and $v(\cdot)$, which return the function value and the sum of constraints violation respectively, as defined in equations 1 and 2, the lower and upper bound vectors \mathbf{l} and \mathbf{u} , the vector of population sizes \mathbf{PS} , the vector of the K values \mathbf{KS} , the maximum number Max_LS of elements to execute the local search, the maximum number of function calls allowed in the local search, LS_1 and LS_2 , the space reduction factor ϕ and the probability for the three steps comparison α .

Algorithm 1 C-ITGO($f(\cdot)$, $v(\cdot)$, \mathbf{l} , \mathbf{u} , \mathbf{PS} , \mathbf{KS} , Max_LS , LS_1 , LS_2 , ϕ , α)

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1:  $\mathbf{best} \leftarrow \text{random}(\mathbf{l}, \mathbf{u})$ ;
2: while  $\text{Converged}(\mathbf{best}) = \text{False}$  do
3:    $\text{Populations} \leftarrow \{\mathbf{x} = \mathbf{x}^1, \dots, \mathbf{x}^{\mathbf{PS}(1)} : \mathbf{x} \in \text{random}(\mathbf{l}, \mathbf{u})\}$ ;
4:    $\text{TopoBest} \leftarrow \{\}$ ;
5:   for  $p \in \{1, \dots, |\mathbf{PS}|\}$  do
6:      $\text{NewPops} \leftarrow \{\}$ ;
7:     for  $\text{pop} \in \text{Populations}$  do
8:        $\text{Topo}_p \leftarrow \text{TopographicalHeuristic}(f(\cdot), v(\cdot), \text{pop}, \mathbf{KS}(p), \alpha)$ ;
9:       if  $p < |\mathbf{PS}|$  then
10:        for  $\mathbf{x} \in \text{Topo}_p$  do
11:           $\text{NewPops} \leftarrow \text{NewPops} \cup \text{CreatePop}(\mathbf{x}, \mathbf{l}, \mathbf{u}, \mathbf{PS}(p+1), \phi^p)$ ;
12:       else
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13:          $TopoBest \leftarrow TopoBest \cup Topo_p$ ;
14:     if  $p < |PS|$  then
15:          $Populations \leftarrow NewPops$ ;
16:      $TopoBest \leftarrow \{x = x^1, \dots, x^{\min(|TopoBest|, Max\_LS)} : x \in sort(TopoBest)\}$ ;
17:     for  $x \in TopoBest$  do
18:          $x \leftarrow LocalSearch(f(\cdot), v(\cdot), x, LS_1)$ ;
19:         if  $Compare(f(\cdot), v(\cdot), x, best)$  or  $f(x) < f(best)$  then
20:              $x \leftarrow LocalSearch(f(\cdot), v(\cdot), x, LS_2)$ ;
21:         if  $Compare(f(\cdot), v(\cdot), x, best)$  then
22:              $best \leftarrow x$ ;
23: return  $best$ ;

```

The first line initializes the vector $best$ randomly within the range $[l, u]$, which is the variable that saves the best element found in the search. The main loop starts at line 2, where we check for convergence. The function *Converged* is problem dependent and may take into account the number of iterations, the number of function calls, the convergence of the best individual or any other stopping criteria.

Line 3 initializes the vector of current populations, with all the $PS(1)$ elements inside the bounds of the problem ($[l, u]$). We use *random* here to denote the generation of a random scalar or vector for simplicity, although in the implementation we used Sobol sequences for the generation of the individuals. The set $TopoBest$ at line 4 comprises the best local optimum elements found in all populations and is initialized empty.

For each population size (line 5), which is the number of space reductions plus one, we generate new populations, starting from the empty set at line 6. Here, we use $|\cdot|$ to denote the number of elements inside a set or a vector. Line 7 loops through all the populations and execute the topographical heuristic (*TopographicalHeuristic* function), with $K = KS(p)$. The variable $Topo_p$, at line 8, saves the local optimal points selected from the current population.

If the current space reduction is not the last ($p < |PS|$, line 9), we create a new population around every point in the $Topo_p$ set, with size $PS(p+1)$ and space reduced at every dimension by ϕ^p (lines 10 and 11). Otherwise, if it is the last space reduction, we have to save the local optimal points in the set $TopoBest$ (lines 12 and 13) to apply local search.

The *CreatePop* procedure is shown in algorithm 2. Given an individual x_b (a selected local optimum), the function returns a new randomly generated population with

$popSize - 1$ individuals around this solution, in the original space reduced by the fraction ϕ . If the point is closer than $0.5 * (u_i - l_i)$, $i = 1, \dots, n$, from the lower or upper bounds at dimension i , the limits of that new population are taken to be the original bounds. The *min* and *max* operations are executed element by element. The solution x_b is also added to the new population.

Algorithm 2 CreatePop($x_b, l, u, popSize, \phi$)

```

1:  $l' \leftarrow \max(l, x_b - (0.5 * \phi) * (u - l));$ 
2:  $u' \leftarrow \min(u, x_b + (0.5 * \phi) * (u - l));$ 
3:  $Population \leftarrow \{x_b\} \cup \{x = x^1, \dots, x^{popSize-1} : x \in \text{random}(l', u')\};$ 
4: return Population;

```

Going back to algorithm 1, at line 14, we check again if the current space reduction is not the last, and update the current populations at line 15, if the condition holds. Line 16 selects the *Max_LS* best elements of the set *TopoBest*, using the three steps criteria comparison as the sorting criteria. If $|TopoBest| < Max_LS$, we keep all the elements.

We loop through all the elements of the now sorted *TopoBest* set at line 17, and apply local search, with at maximum LS_1 function evaluations, at line 18. The function *Compare* (line 19) is the three steps comparison, returning true if the first solution (third argument) is better than the second solution (fourth argument), and returns false otherwise. The element returned by the local search procedure is compared against the best element found in the whole search at line 19. If it is better than the best element found (according to the three steps criteria), or if its fitness is better, a new local search procedure is applied, now with LS_2 iterations, at line 20.

The number of function calls is usually the determining performance factor. So, we wish to do as few local search iterations as possible, since a call to the local search algorithm typically makes hundreds or thousands of function evaluations. Here, we set $LS_2 > LS_1$, so every element undergoes LS_1 function evaluations in the local search, but we only search finely for promising solutions, setting higher values for LS_2 . Usually, the second local search is only necessary for problems where very finely tuned solutions are required.

At line 21 we compare again the solution generated by the second local search (x) against the best element found in the whole search (*best*) using the three steps criteria. If the new solution is better, we set *best* to that solution at line 22 and continue the loop for applying local search in the other elements. At the end of the

execution, when *Converged* in the outer loop returns true, we return the best solution found in the whole search on line 23. In practice, however, we may stop the algorithm as soon as the optimal solution is found or when the maximum number of function evaluations is reached.

Finally, let us explain the *TopographicalHeuristic* procedure, shown in Algorithm 3. The function takes as parameters: the objective function $f(\cdot)$, the sum of constraints function $v(\cdot)$, the current population to be evaluated, the value K for the KNN set, and the probability α , for the three steps comparison.

Algorithm 3 TopographicalHeuristic($f(\cdot)$, $v(\cdot)$, $Population$, K , α)

```

1:  $M \leftarrow |Population|$ ;
2:  $best \leftarrow Population(0)$ ;
3:  $KNN_K \leftarrow Build\_KNN(Population, K)$ ;
4:  $R \leftarrow random([0, 1]^{M \times M})$ ;
5:  $TopoBest \leftarrow \{\}$ ;
6: for  $i \in \{1, \dots, |Population|\}$  do
7:    $insert \leftarrow \text{True}$ ;
8:   for  $j \in \{1, \dots, |Population|\} \cap \{x_j \in KNN_K(x_i)\}$  do
9:     if  $R_{i,j} < \alpha$  then
10:       $insert \leftarrow insert \ \& \ Compare(f(\cdot), v(\cdot), x_i, x_j)$ ;
11:     else
12:       $insert \leftarrow insert \ \& \ (f(x_i) < f(x_j))$ ;
13:   if  $insert = \text{True}$  then
14:      $TopoBest \leftarrow TopoBest \cup \{x_i\}$ ;
15:   if  $Compare(f(\cdot), v(\cdot), x_i, best)$  then
16:      $best \leftarrow x_i$ ;
17: if  $|TopoBest| = 0$  then
18:    $TopoBest \leftarrow \{best\}$ ;
19: return  $TopoBest$ ;

```

Lines 1-5 of Algorithm 3 simply initialize the necessary structures. Namely, the number of elements M in $Population$, the *best* vector, which is the best element of the entire population based on three steps comparison (initially set to any individual of the population), the KNN_K structure based on the elements of the population, which is a mapping from a solution vector x to a set of the vectors that belong to the KNN_K of x , the random symmetric matrix R , with every element in the range $[0, 1]$, and the *TopoBest* set, containing the local optimal points, initially empty.

At line 6 we loop through all indices of $Population$, and set the *insert* flag to *True* at line 7, which indicates if the individual x_i is a local optimal point. For every index j ,

such that x_j is in the set $KNN_K(x_i)$ (line 8), we compare x_j with x_i . If $R_{i,j} < \alpha$, then we set the flag *insert* to the boolean result of the *and* operator (&) to *insert* and the result of *Compare* (lines 9-10). That is, if *Compare* returns false at least one time for any j , *insert* will also be false for the index i . If $R_{i,j} \geq \alpha$, then we execute the same procedure, but now using fitness only comparison, at lines 11-12.

At line 13 we check if *insert* = *True*, and, if so, x_i is a local optimum, and we insert it in the *TopoBest* set, at line 14. Lines 15-16 select the best element found in the whole population based on the three steps comparison, and stores that solution in the variable *best*. In case of no solution being selected as a local optimum, the set *TopoBest* is composed only of the *best* element (lines 17-18). At line 19 we return the *TopoBest* set, containing all the local optimal points (or the *best* element).

2.4. Local Search

In this section, we discuss the three different methods of local search we have chosen in the present work to be used in C-ITGO, and their implications on the final performance.

As we used Matlab to implement C-ITGO, a natural choice for the local search step is the use of the optimization toolbox. In the case of real non-linearly constrained problems, we used the *SQP* (Sequential Quadratic Programming), present in the *fmincon* package (MathWorks, 2017). The basic SQP algorithm is described in Chapter 18 of Nocedal & Wright (2006), although the actual implementation used in *fmincon* uses some additional heuristics.

A very successful method, also implemented in Matlab, that uses that same package (SQP of *fmincon*) is the *MVMO* (Mean-Variance Mapping Optimization) (Rueda & Erlich, 2016), winner of two different categories of the IEEE Congress on Evolutionary Computation competition on real optimization in 2016.

For mixed integer problems with nonlinear constraints, we used the *OPTI* toolbox (Currie, 2014), which has many algorithms specialized for mixed integer programming. Specifically, we used the *BONMIN* (Basic Open-source Nonlinear Mixed INteger programming) (Biegler et al., 2015) and the *NOMAD* (Nonlinear Optimization with the MADS algorithm) solvers (Le Digabel, 2011).

We emphasize here that any kind of local search can be used in conjunction with C-ITGO. We could use for example a specialized local search for a given problem. In

this work, both problems on continuous and integer domains are treated in the same way, changing only the local search procedure.

It is true that some simpler problems can be solved solely by using an exact method such as those cited above, for example by calling the procedure at different random points. However, in multimodal objective functions with nonlinear constraints, it is usually not possible to find the global optimum. Even if a problem can be solved by an exact method, the number of function evaluations may be very large.

The objective is not to rely heavily on the local search procedure. Rather, what we want to achieve with the topographical heuristic is to provide solutions that are close to a local or global optimum, so that any reasonably good local search can converge with relative ease. In this work, the maximum number of function evaluations allowed in the first call to the local search procedure is kept as small as possible, and, in most cases, it is enough to find optimal or nearly optimal solutions.

2.5. Parameters chosen for the engineering design problems

Given the differences in the number of variables, constraints, size of the space, number of function calls to converge reported by competing methods, and general complexity of the problems considered in this work, we selected experimentally specific parameters for each problem aiming to obtain the best performance of C-ITGO. This is a general approach taken for most of the optimization methods compared here. The parameters were selected so as to find optimal or near-optimal solutions while minimizing the number of function evaluations (NFEs).

Table 1 shows the choice of the parameters for the eight engineering design problems we consider: Welded Beam (WB), Tension/Compression Spring (TC), Three-Bar truss (TB), Speed Reducer I and II (SRI and SRII), Pressure Vessel (PV), Gear Train (GT) and Multiple Disk clutch brake (MD). We will comment each problem and the results obtained by C-ITGO and other competing methods in Section 3.

<i>Prob/ Param</i>	<i>PS₁</i>	<i>PS₂</i>	<i>K₁</i>	<i>K₂</i>	α	ϕ	<i>LS1</i>	<i>LS2</i>	<i>MaxLS</i>	<i>LSType</i>
WB	100	10	10	3	0.5	0.2	100	200	5	SQP
TC	50	10	8	3	0.5	0.2	100	200	5	SQP
TB	30	5	5	2	0.5	0.2	20	70	5	SQP
SRI	150	10	10	3	0.5	0.2	100	200	5	BONMIN
SRII	100	10	10	3	0.5	0.2	50	100	5	SQP
PV	50	10	8	3	0.5	0.5	30	100	5	BONMIN
GT	20	5	5	2	0.5	0.7	30	100	5	NOMAD
MD	20	5	7	2	0.5	0.7	100	200	5	NOMAD

Table 1: Parameters of C-ITGO for each engineering design problem.

For all problems, we only use a single space reduction, which generates two populations and two values for K , namely PS_1 (first population size, before space reduction) and PS_2 (second population size, after space reduction), K_1 and K_2 (also before and after space reduction, respectively). For problems with a considerably large number of variables, it may be beneficial to use more than one space reduction.

The first population size is generally chosen to be proportional to the problem's domain size. For problems with a larger number of variables, we set PS_1 to 100 or above. The second population size, PS_2 , was defined based on the first population size. For $PS_1 \geq 50$, we set $PS_2 = 10$, and for $PS_1 < 50$, PS_2 is set to 5.

The values of K_1 and K_2 also were chosen experimentally, but were based on the values of PS_1 and PS_2 , respectively. K_1 was set to a maximum of 10 for larger problems, and for a minimum of 5 for small problems. For $PS_2 = 10$, K_2 was set to 3, and for $PS_2 = 5$, K_2 is 2.

The value for the probability α was kept constant at 0.5 for all problems. The α parameter controls the probability of executing the three steps comparison in the topographical heuristic step. For problems which the feasible area is small compared to the whole domain, increasing the value of α have the effect of reducing the number of local optimum points. However, the C-ITGO algorithm is not too sensitive to specific values of α , and the value of 0.5 seems to be a good choice.

The maximum number of elements to execute the local search, $MaxLs$, was also set to a default value for all problems, namely 5. It acts as a filter, selecting only the best solutions to undergo the local search procedure. For problems with a large number of local optima, setting $MaxLs$ to higher values may improve C-ITGO performance. However, if $MaxLs$ is too large, many unnecessary runs of the local search will be executed.

The value of ϕ was set to smaller values for problems defined on entirely continuous domains and assumed higher values for mixed integer problems. If we reduce the space too much for integer problems, we may end up with some dimensions having a very small domain, possibly excluding the global optimum.

The LS_1 and LS_2 parameters control the maximum number of allowed function evaluations in the local search in the first and second calls, respectively. We tried to set LS_1 as small as possible while attaining convergence to the required precision (which is specific for each problem). LS_2 assumed higher values for more difficult problems, where convergence is achieved only for solutions very close to the global

optimum.

Finally, *LSType* represents the algorithm used in the local search. The type of local search was determined based on the properties of each problem. For problems with only continuous variables, we used the SQP method (WB, TC, and TB). For problems with only discrete variables, we used the NOMAD solver (GT, MD), and for mixed integer problems, we used the BONMIN solver (SRI and PV). The only exception was SRII, in which we used the SQP algorithm rounding the variables that are required to be integers. In tests with this specific problem (SRII), it resulted in better solutions with a smaller number of function evaluations (NFEs) than using the mixed integer solvers.

3. Computational Results

The C-ITGO was implemented using Matlab, and the experiments were accomplished on a machine with the Intel i3-3110M CPU @2.40GHz processor with 4GB of RAM, running Windows 7. Also, we provide a free library for using C-ITGO for optimizing any user-defined function, being it constrained or not. The library uses by default the Matlab *fmincon* solver for continuous problems and the OPTI toolbox (currently only readily available for Windows, but can be compiled for Linux and Mac as well) for mixed integer problems. Also, the user has the option to easily incorporate other local search algorithms, if desired.

To evaluate the performance of the developed method to solve real-world problems, we use eight difficult constrained engineering optimization problems from the literature, whose objective functions and constraints are diverse (quadratic, cubic, polynomial and nonlinear) with many numbers and types of design variables (continuous, mixed and integer).

In all tests, given the stochastic characteristic of C-ITGO, we run it 25 times, saving the Best and Worst feasible solutions, as well as the mean value (Mean) and standard deviation (SD) of the fitness after all runs. Given the great variability between the results found in the literature for most problems, we stop the execution of C-ITGO as soon as the best solution found in a run is considerably close to the optimum (the optimum solution for each of the eight engineering design problems considered is known). That is, the condition for stopping C-ITGO, when the fitness reaches a certain value, is problem dependent. At the end, the mean number of function evaluations

(MNFEs) is reported for all runs.

Table 2 shows the values that determine the convergence of C-ITGO for each problem. The values in row *GAP* represent the minimum Euclidean distance to the optimum that the fitness of a solution needs to be in order to stop the execution of C-ITGO. These values were chosen based on the results found by the competing methods, considering the variability of the precision of the reported solutions.

	WB	TC	TB	SRI	SRII	PV	GT	MD
GAP	1E-6	1E-6	1E-5	1E-8	1E-7	1E-4	1E-10	1E-5

Table 2: Minimum distance to optimum to determine C-ITGO convergence for each problem.

The Gear Train (GT) was the only problem where we specified a maximum number of function evaluations. For this problem, if the NFEs reaches 800, we stop immediately and return the best solution found. It was necessary since the convergence requirements for this problem is very tight ($10E - 10$). All other problems converged to at least *GAP* of the optimum without the requirement to specify a maximum NFEs.

In our tests, all solutions reported by C-ITGO are completely feasible for all problems. So, unless specified, we exclude from comparison methods that violate any constraint (unfeasible).

We compare 20 different optimization methods against C-ITGO. The most common meta-heuristic for solving the problems considered in this work is the Particle Swarm Optimization (PSO), including PSO-DE (Lio et al., 2010), a hybrid PSO method combined with Differential Evolution (DE); the HPSO (He & Wang, 2007b), another hybridized particle swarm method in combination with simulated annealing; a co-evolutionary PSO denominated CPSO (He & Wang, 2007a); the hybridized PSO with Nelder-Mead simplex (NM-PSO) (Zahara & Kao, 2009); the Unified PSO (UPSO) (Parsopoulos & Vrahatis, 2005), a PSO variant that balances exploration and exploitation; the APSO, standing for Accelerated PSO (Yang, 2010); the Gaussian Quantum-Behaved Particle Swarm Optimization methods, named QPSO and G-QPSO (Coelho, 2010); and the IPSO (Machado-Coelho et al., 2017), which incorporates an interval reducing procedure. More recently, and among the best PSO methods for constrained global optimization, we can cite the Improved Accelerated PSO algorithm (IAPSO) (Guedria, 2016), which proposes some modifications and improves the APSO method.

Many other different optimization methods were also used for comparison in this

work: the Mine Blast Algorithm (MBA) (Sadollah et al., 2013), a population-based optimization method based on the mine bomb explosion concept; the League Championship Algorithm (LCA) (Kashan, 2011), which models a league championship environment with artificial teams; the Crossover-Based Artificial Bee Colony (CB-ABC) (Brajevic, 2015), applying modified search operators over the regular ABC algorithm; the Differential Evolution with Level Comparison (DELC) (Wang & Li, 2009), which converts a constrained problem into an unconstrained one by means of a level comparison mechanism; a Multi-View Differential Evolution (MVDE) (Melo & Carosio, 2013), which uses several different mutation strategies at every iteration; the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) method (Melo & Iacca, 2014), which builds a distribution model of the population; the Water Cycle Algorithm (WCA) (Es-kandar et al., 2012), a nature-inspired method based on the water cycle process; and the Cuckoo Search algorithm (CS) (Gandomi et al., 2013), another nature-inspired method based on the cuckoo bird species behavior. Recently, reporting state-of-the-art results for some problems, we can cite the Improved Artificial Bee Colony with Modified Augmented Lagrangian (IABC-MAL) (Long et al., 2017), which integrates the Modified Augmented Lagrangian method to handle constraints with the Improved ABC algorithm (Liang et al., 2017), and the Self-Adaptive Multi-Population based Jaya (SAMP-Jaya) algorithm (Rao & Saroj, 2017), a multi-population scheme of the Jaya method (Rao, 2016).

Following, the engineering optimization problems that will be tackled in this work will be briefly explained, as well as the solutions obtained by C-ITGO against the solutions of the best previously cited competing techniques of the literature. Further information on the Welded Beam (WB), Tension/Compression Spring (TC), Speed Reducer (SRI and SRII), Pressure Vessel (PV), Gear Train (GT) and Multiple Disk clutch brake (MD) problems can be found in the work of Guedria (2016). The Three-Bar truss (TB) problem and additional information on Welded Beam (WB), Tension/Compression Spring (TC), Speed Reducer (SRI), Pressure Vessel (PV) and Gear Train (GT) can be seen in the work of Sadollah et al. (2013).

We also decided to add in the appendix the initial results of applying the developed method to the GKLS class of problems (Gaviano et al., 2003). We compared the results achieved by C-ITGO against a number of efficient deterministic global optimization methods, using the guidelines described in Sergeyev et al. (2018) to compare deterministic and meta-heuristic methods. At the end, we executed a nonparametric

statistical test to analyze the results, proving that C-ITGO is at least as good as the deterministic methods considered in this work in the GKLS class of problems. We plan to improve C-ITGO further in a future work to better tackle unconstrained smooth optimization problems.

3.1. Welded beam design problem

The welded beam design (Ragsdell & Phillips, 1976) is the problem of minimizing the fabrication cost of a welded beam, subject to seven inequality constraints, being two linear and five nonlinear. The constraints include shear stress (τ), bending stress in the beam (σ), buckling load on the bar (Pc), end deflection on the beam (δ) and some more side constraints. The four design variables are continuous. The feasible best known objective value is $f(\mathbf{x}^*) = 1.7248523$. Figure 4 presents the schematic of the welded beam design problem. The mathematical formulation of the problem is expressed as follows:

Minimize:

$$f(\mathbf{x}) = 1.10471x_1^2x_2 + 0.04811x_3x_4(14 + x_2)$$

subject to:

$$g_1(\mathbf{x}) = \tau(\mathbf{x}) - 13,600 \leq 0$$

$$g_2(\mathbf{x}) = \sigma(\mathbf{x}) - 30,000 \leq 0$$

$$g_3(\mathbf{x}) = x_1 - x_4 \leq 0$$

$$g_4(\mathbf{x}) = 0.10471x_1^2 + 0.04811x_3x_4(14 + x_2) - 5 \leq 0$$

$$g_5(\mathbf{x}) = 0.125 - x_1 \leq 0$$

$$g_6(\mathbf{x}) = \delta(\mathbf{x}) - 0.25 \leq 0$$

$$g_7(\mathbf{x}) = 6,000 - Pc(\mathbf{x}) \leq 0$$

where:

$$\tau(\mathbf{x}) = \sqrt{\tau^2 + \frac{(2\tau'\tau''x_2)}{2R}} + \tau''/2$$

$$\tau' = \frac{6,000}{(\text{sqr}t{2x_1x_2})}$$

$$\tau'' = \frac{(MR)}{J}$$

$$M = 6,000(14 + \frac{x_2}{2})$$

$$R = sgrt \frac{x_2^2}{4} + (x_1 + \frac{x_3}{2})^2$$

$$J = 2x_1x_2\sqrt{2}(\frac{x_2^2}{12} + (x_1 + \frac{x_3}{2})^2)$$

$$\sigma(\mathbf{x}) = 504,000/(x_4x_3^2)$$

$$\delta(\mathbf{x}) = \frac{65,856,000}{(30 \times 10^6 x_4 x_3^3)}$$

$$Pc(\mathbf{x}) = \frac{4.013(30 \times 10^6)}{196} \sqrt{x_3^2 \frac{x_4^6}{36}} \left(1 - \frac{x_3}{28} \sqrt{\frac{30 \times 10^6}{4(12 \times 10^6)}} \right)$$

with bounds:

$$0.1 \leq x_1, x_4 \leq 2$$

$$0.1 \leq x_2, x_3 \leq 10$$

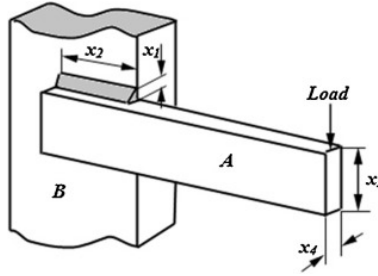


Figure 4: Schematic view of the welded beam design problem.

We compare the results obtained by C-ITGO against a number of state-of-the-art methods used to solve this problem, including PSO-DE, HPSO, UPSO, MBA, CMA-ES, MVDE, CPSO, LCA, IPSO, CB-ABC, DELC, IABC-MAL, NM-PSO, APSO, WCA, IAPSO and SAMP-Jaya. Table 3 shows the comparison of the statistical results obtained by all cited methods to solve the welded beam design problem. All the methods, with exception of CMA-ES, SAMP-Jaya and C-ITGO, took more than 10,000 iterations to achieve good quality solutions. C-ITGO achieved optimal solutions with a very small standard deviation of 3.65E-12, using ten times fewer function evaluations on average

than most of the methods.

We write the statistics for the C-ITGO method in bold simply to highlight the reported results, not because it always presents the best statistics for all problems.

Method	Best	Mean	Worst	SD	MNFes
PSO-DE	1.724852	1.724852	1.724852	6.70E-16	66,600
HPSO	1.724852	1.814295	1.749040	4.01E-02	81,000
UPSO	1.921990	2.837210	N/A	6.83E-01	100,000
MBA	1.724853	1.724853	1.724853	6.94E-19	47,340
CMA-ES	1.7248523	1.7248523	1.7248523	1.66E-09	4,658
MVDE	1.7248527	1.7248621	1.7249215	7.88E-06	15,000
CPSO	1.728024	1.748831	1.782143	1.29E-02	240,000
LCA	1.7248523	1.7248523	1.7248523	7.11E-15	15,000
IPSO	1.724852	1.7248787	1.7250002	3.28E-05	20,000
CB-ABC	1.724852	1.724852	N/A	2.38E-11	15,000
DELIC	1.724852	1.724852	1.724852	4.10E-13	20,000
IABC-MAL	1.724852	1.724852	1.724852	2.31E-12	15,000
NM-PSO	1.724717	1.726373	1.733393	3.50E-03	80,000
APSO	1.736193	1.877851	1.993999	0.076118	50,000
WCA	1.724856	1.726427	1.744697	4.29E-03	46,450
IAPSO	1.7248523	1.7248528	1.7248624	2.02E-06	12,500
SAMP-Jaya	1.724852	1.724852	1.724852	6.7E-16	3,618.25
C-ITGO	1.7248523	1.7248523	1.7248523	3.65E-12	940.68

Table 3: Statistical results of different methods for the Welded beam problem.

The results for C-ITGO and SAMP-Jaya are very similar, with the former having a slightly worse standard deviation, but converging in less than one-third of the number of function evaluations. We note here that the best solution achieved by NM-PSO is slightly unfeasible, so it should not be directly compared to the other methods.

3.2. Tension/compression spring design problem

This problem was introduced by Belegundu (1982), and the objective is the minimization of the weight of a tension/compression spring (Figure 5). The problem has three continuous design variables, being them the diameter of spring wire ($x_1 = D$), the diameter of spring mean coil ($x_2 = d$) and the number of active coils ($x_3 = P$). It is subject to three nonlinear and one linear inequality constraints. The objective function value at the known global optimum is $f(\mathbf{x}^*) = 0.01266523$. The full mathematical formulation of the problem follows:

Minimize:

$$f(\mathbf{x}) = (x_3 + 2)x_2x_1^2$$

subject to:

$$g_1(\mathbf{x}) = 1 - \frac{x_2^3x_3}{7.1785x_1^4} \leq 0$$

$$g_2(\mathbf{x}) = \frac{4x_2^2 - x_1x_2}{12,566(x_2x_1^3) - x_1^4} + \frac{1}{5.108x_1^2} - 1 \leq 0$$

$$g_3(\mathbf{x}) = 1 - \frac{140.45x_1}{x_2^2x_3} \leq 0$$

$$g_4(\mathbf{x}) = \frac{x_2 + x_1}{1.5} - 1 \leq 0$$

with bounds:

$$0.05 \leq x_1 \leq 2, \quad 0.25 \leq x_2 \leq 1.3, \quad 2 \leq x_3 \leq 15$$

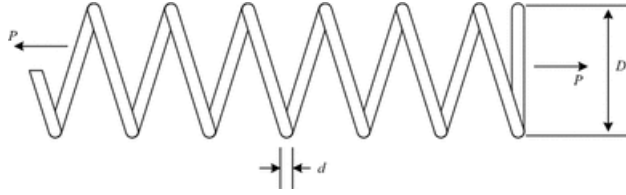


Figure 5: Schematic view of the tension/compression spring design problem.

A variety of methods were used in literature to solve the tension/compression spring design problem. Between them, we can cite CPSO, HPSO, NM-PSO, MBA, UPSO, PSO-DE, LCA, CB-ABC, QPSO, G-QPSO, APSO, CMA-ES, MVDE, DELC, WCA, IPSO, IAPSO, IABC-MAL and SAMP-Jaya. Table 4 shows the statistical results of all methods, along with the number of function evaluations taken to achieve such results.

Method	Best	Mean	Worst	SD	MNFes
CPSO	0.0126747	0.012730	0.012924	5.20E-04	240,000
HPSO	0.012665	0.012719	0.012707	1.58E-05	81,000
NM-PSO	0.012630	0.012633	0.012631	8.47E-07	80,000
MBA	0.012665	0.012713	0.012900	6.30E-05	7,650
UPSO	0.013120	0.022940	N/A	7.20E-03	100,000
PSO-DE	0.012665	0.012665	0.012665	1.20E-08	24,950
LCA	0.01266523	0.01266541	0.01266667	3.88E-07	15,000
CB-ABC	0.012665	0.012671	N/A	1.42E-05	15,000
QPSO	0.012669	0.018127	0.013854	1.34E-03	2,000
G-QPSO	0.012665	0.017759	0.013524	1.27E-03	2,000
APSO	0.012700	0.013297	0.014937	6.85E-04	120,000
CMA-ES	0.01266524	0.01266861	0.01269335	6.30E-06	19,445
MVDE	0.01266527	0.01266732	0.01271906	2.45E-06	10,000
DELC	0.012665	0.012666	0.012665	1.30E-07	20,000
WCA	0.012665	0.012746	0.012952	8.06E-05	11,750
IPSO	0.01266567	0.012671486	0.01268312	3.89E-06	20000
IAPSO	0.01266523	0.013676527	0.01782864	1.573E-3	2,000
IABC-MAL	0.01266523	0.01266525	0.01266539	6.78E-08	15,000
SAMP-Jaya	0.012664	0.013193	0.012714	9.25E-05	6,861
C-ITGO	0.01266523	0.01266523	0.01266525	2.81E-9	535.08

Table 4: Statistical results of different methods for tension/compression spring design problem.

The methods vary greatly in the number of function evaluations required to converge to good quality solutions. Only three of the methods (QPSO, G-QPSO and IAPSO) achieved convergence with 2,000 function evaluations, while some methods required more than 100,000. The best solution achieved by all methods have the same fitness value up to five decimal places, with the exception of CPSO, UPSO, APSO and NM-PSO.

The best solution reported by NM-PSO is again unfeasible, so we do not compare it against other methods. The SAMP-Jaya method also seems to report a slightly unfeasible best solution, differing from the optimal value reported by other methods. However, the result achieved by SAMP-Jaya differs only at the sixth decimal place, and the difference may be due to wrong rounding. We cannot state this for sure since we do not have access to the solution vector found by the method. Given the differences between the precision in the solutions reported by the methods, we consider $f(x) = 0.012665$ to be the fitness at the global optimum.

The C-ITGO method performed remarkably well on this problem, converging to the best solution found in 535.08 function evaluations on average, almost four times less than the second best competing method. Also, the standard deviation is very small, in the order of $2.81\text{E-}9$.

Given the relatively small domain of the problem, we believe that the C-ITGO method was able to cover the space efficiently, providing hot starting points for the local search method, which proved to be very effective in this case.

3.3. Three-bar truss design problem

The three-bar truss design problem (Ragsdell & Phillips, 1973) consists in minimizing the volume of a statically loaded three-bar truss. There are two continuous design variables and three nonlinear inequality constraints, based on the stress on each of the truss members (σ), with $f(x^*) = 263.895843$. Figure 6 shows the schematic view of the problem. The full problem statement follows:

Minimize:

$$f(x) = 2\sqrt{2}x_1 + lx_2$$

subject to:

$$g_1(x) = \frac{\sqrt{2}x_1 + x_2}{\sqrt{2}x_1^2 + 2x_1x_2}P - \sigma \leq 0$$

$$g_2(\mathbf{x}) = \frac{x_2}{\sqrt{2x_1^2 + 2x_1x_2}}P - \sigma \leq 0$$

$$g_3(\mathbf{x}) = \frac{1}{\sqrt{2x_2 + x_1x_2}}P - \sigma \leq 0$$

where:

$$l = 100\text{cm}, \quad P = 2\text{kN/cm}^2, \quad \sigma = 2\text{kN/cm}^2$$

with bounds:

$$0 \leq x_1, x_2 \leq 1$$

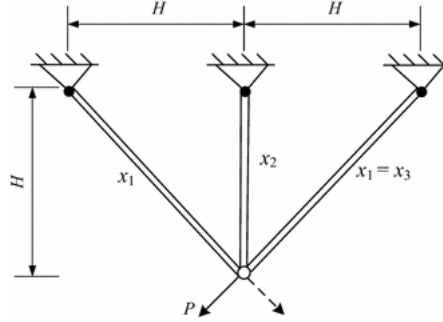


Figure 6: Schematic view of the three-bar truss design problem.

Here we present only the five best-performing methods used to solve this problem since the solutions found in the literature have very small variance from each other. These methods are PSO-DE, CMA-ES, MVDE, DELC, MBA and IABC-MAL. We present the statistical results for this problem in Table 5.

Method	Best	Mean	Worst	SD	MNFES
PSO-DE	263.895843	263.895843	263.895843	4.50E-12	17,600
CMA-ES	263.895843	263.895843	263.895843	2.7E-09	1,706
MVDE	263.895843	263.895843	263.895855	2.58E-07	7,000
DELC	263.895843	263.895843	263.895843	4.3E-14	10,000
MBA	263.895852	263.897996	263.915983	3.93E-03	13,280
IABC-MAL	263.895843	263.895843	263.895843	0.0	15,000
C-ITGO	263.895843	263.895843	263.895843	2.0E-12	136.48

Table 5: Statistical results of different methods for three-bar truss design problem.

From Table 5 it is possible to note that all methods have very similar results, differing mainly in the number of function calls. This is not surprising, given that the problem is simpler, has fewer variables and consequently has a smaller domain than

any other engineering design problem considered in this work.

C-ITGO achieved convergence quickly, taking 136.48 function evaluations on average. In this problem, we have set a small population, as well as a small number of function calls allowed in the local search procedure. Thus, we obtained the lowest MNFEs than any of the competing techniques, at least ten times lower. It seems that the solutions found by the topographical heuristic were already close to the optimum, so the local search converged in very few iterations. However, the C-ITGO method has a slightly worse standard deviation than DELC and IABC-MAL.

3.4. Speed reducer design problem

In this problem, the total weight of the speed reducer (Figure 7) is to be minimized. The problem has seven design variables: face width (b), teeth module (m), number of teeth on the pinion (z), first and second length of shafts between bearings (l_1 and l_2) and first and second shafts diameter (d_1 and d_2) (Golinski, 1973). The problem has 11 nonlinear constraints, and the third variable is constrained to be an integer. A second version of the problem is also found in literature, where the only difference is in the lower bound of the fifth variable (7.8 for SR1 and 7.3 for SR2). The objective function value at the optimal is $f(\mathbf{x}^*) = 2996.34816497$ for the first version (SR1), and $f(\mathbf{x}^*) = 2994.471066$ for the second version (SR2). The mathematical formulation of the problem follows:

Minimize:

$$\begin{aligned} f(\mathbf{x}) = & 0.7854x_1x_2^2(3.333x_3^2 + 14.9334x_3 - 43.0934) \\ & - 1.508x_1(x_6^2 + x_7^2) + 7.4777(x_6^3 + x_7^3) \\ & + 0.7854(x_4x_6^2 + x_5x_7^2) \end{aligned}$$

subject to:

$$\begin{aligned} g_1(\mathbf{x}) &= \frac{27}{x_1x_2^2x_3} - 1 \leq 0 \\ g_2(\mathbf{x}) &= \frac{397.5}{x_1x_2x_3^2} - 1 \leq 0 \\ g_3(\mathbf{x}) &= \frac{1.93x_4^3}{x_2x_3x_6^4} - 1 \leq 0 \\ g_4(\mathbf{x}) &= \frac{1.93x_5^3}{x_2x_3x_7^4} - 1 \leq 0 \end{aligned}$$

$$\begin{aligned}
g_5(\mathbf{x}) &= \frac{1}{110x_6^3} \sqrt{\left(\frac{745x_4}{x_2x_3}\right)^2 + 16.9 \times 10^6} - 1 \leq 0 \\
g_6(\mathbf{x}) &= \frac{1}{85x_7^3} \sqrt{\left(\frac{745x_5}{x_2x_3}\right)^2 + 157.5 \times 10^6} - 1 \leq 0 \\
g_7(\mathbf{x}) &= \frac{x_2x_3}{40} - 1 \leq 0 \\
g_8(\mathbf{x}) &= \frac{5x_2}{x_1} - 1 \leq 0 \\
g_9(\mathbf{x}) &= \frac{x_1}{12x_2} - 1 \leq 0 \\
g_{10}(\mathbf{x}) &= \frac{1.5x_6 + 1.9}{x_4} - 1 \leq 0 \\
g_{11}(\mathbf{x}) &= \frac{1.1x_7 + 1.9}{x_5} - 1 \leq 0
\end{aligned}$$

with bounds:

$$\begin{aligned}
2.6 \leq x_1 \leq 3.6, \quad 0.7 \leq x_2 \leq 0.8, \quad 17 \leq x_3 \leq 28, \quad x_3 \in \mathbb{Z} \\
7.3 \leq x_4 \leq 8.3, \quad 7.8 \leq x_5 \leq 8.3 \text{ (or } 7.3 \leq x_5 \leq 8.3) \\
2.9 \leq x_6 \leq 3.9, \quad 5.0 \leq x_7 \leq 5.5
\end{aligned}$$

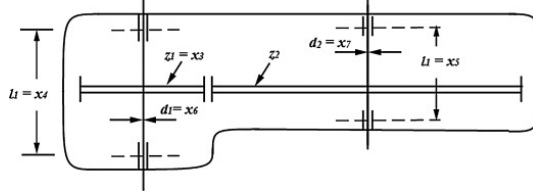


Figure 7: Schematic view of the speed reducer design problem.

For SRI, we compare C-ITGO results against four optimization methods, namely LCA, IPSO, APSO and IAPSO, shown in Table 6.

The LCA, IPSO, IAPSO and C-ITGO present similar results, all finding the constrained global optimum solution and having very low standard deviation.

The first three methods take at least 20,000 iterations to converge to good quality solutions, while IAPSO takes only 6,000 NFES. C-ITGO outperforms the other methods by a large margin, converging in 858.40 function calls on average while maintaining negligible higher standard deviation than IAPSO and IPSO.

Method	Best	Mean	Worst	SD	MNFes
LCA	2996.34816497	2996.34816497	2996.34816497	2.63E-12	24,000
IPSO	2996.34816497	2996.3481	2996.34816509	2.43E-18	20,000
APSO	3177.530771	3855.581557	4677.005187	473.767	30,000
IAPSO	2996.34816497	2996.34816497	2996.34816497	6.88E-13	6,000
C-ITGO	2996.34816497	2996.34816497	2996.34816497	7.5E-13	856.40

Table 6: Statistical results of different methods for the speed reducer design problem I.

For this problem, we used considerably greater populations, of sizes 150 (PS_1) and 10 (PS_2), while maintaining the number of allowed function evaluations of the local search relatively small (100 and 200). For the worst case, C-ITGO took 3 full iterations to converge, while in most cases it converged in the first iteration.

For SR11, the methods used for comparison were PSO-DE, WCA, DELC, CB-ABC, CMA-ES, MVDE, IABC-MAL, LCA, APSO, MBA, IPSO, IAPSO and SAMP-Jaya. The reported results for the SAMP-Jaya method seems to violate the integer constraint at variable three, but it is included to show that even in harder situations the C-ITGO algorithm can still produce state-of-the-art results.

From Table 7, we can see that DELC, CMA-ES, MVDE, IABC-MAL, LCA, IAPSO, SAMP-Jaya and C-ITGO are the only methods that converged to the optimum in every run, having very small standard deviation. Although similar results are observed regarding the quality of the solutions, C-ITGO converges much faster than any competing method, using seven times fewer function evaluations than SAMP-Jaya. The standard deviation achieved by C-ITGO is also only worse than the standard deviation reported by IABC-MAL (the difference is in the order of 1E-13), which took 15,000 function evaluations to converge.

Method	Best	Mean	Worst	SD	MNFes
PSO-DE	2996.348167	2996.348174	2996.348204	6.40E-06	54,350
WCA	2994.471066	2994.474392	2994.505578	7.4E-03	15,150
DELC	2994.471066	2994.471066	2994.471066	1.90E-12	30,000
CB-ABC	2994.471066	2994.471066	N/A	2.48E-07	15,000
CMA-ES	2994.471066	2994.471066	2994.471066	8.98E-10	12,998
MVDE	2994.471066	2994.471066	2994.471066	2.82E-07	30,000
IABC-MAL	2994.471066	2994.471066	2994.471066	8.51E-13	15,000
LCA	2994.471066	2994.471066	2994.471066	2.66E-12	24000
APSO	3187.630486	3822.640624	4443.017639	366.146	30,000
MBA	2994.482453	2996.769019	2999.652444	1.56	6300
IPSO	2994.471067	2994.47108	2994.4711	9.27E-06	20,000
IAPSO	2994.471066	2994.471066	2994.471066	2.65E-09	6,000
SAMP-Jaya	2760.673988	2760.673988	2760.673988	2.54E-11	3744.66
C-ITGO	2994.471066	2994.471066	2994.471066	9.28E-13	491.24

Table 7: Statistical results of different methods for the speed reducer design problem II.

For this specific problem, we used the SQP algorithm as local search and rounded the value of the third variable. In this case, this approach proved to converge much

faster than using a mixed integer local search. Also, the first population size is considerably smaller than the one used in SRI (100 in this problem).

3.5. Pressure vessel design problem

In the pressure vessel design problem, the objective is to minimize the total manufacturing cost, including the cost of the material, forming and welding costs (Sandgren, 1990). The problem is subject to three linear and one nonlinear inequality constraint, and its structure is shown in Figure 8. The four variables are the thickness of the shell ($x_1 = T_s$), the thickness of the head ($x_2 = T_h$), the inner radius ($x_3 = R$), and the length of the cylindrical section of the vessel ($x_4 = L$). This is an example of a mixed integer problem, where the first and second variables are constrained to be integers. The value of the objective function at the best known feasible solution is around $f(\mathbf{x}^*) = 6059.7143$. The mathematical formulation for the pressure vessel problem can be expressed as follows:

Minimize:

$$f(\mathbf{x}) = 0.6224z_1x_3x_4 + 1.7781z_2x_3^2 + 3.1661z_1^2x_4 + 19.84z_1^2x_3$$

subject to:

$$g_1(\mathbf{x}) = -z_1 + 0.193x_3 \leq 0$$

$$g_2(\mathbf{x}) = -z_2 + 0.00954x_3 \leq 0$$

$$g_3(\mathbf{x}) = -\pi x_3^2 x_4^2 - \frac{4}{3}\pi x_3^3 + 1,296,000 \leq 0$$

$$g_4(\mathbf{x}) = x_4 - 240 \leq 0$$

where:

$$z_1 = 0.0625x_1$$

$$z_2 = 0.0625x_2$$

with bounds:

$$1 \leq x_1, x_2 \leq 99, \quad 10 \leq x_2, x_3 \leq 200, \quad x_1, x_2 \in \mathbb{Z}$$

We compare C-ITGO against the UPSO, QPSO, G-QPSO, CMA-ES, MVDE, CB-ABC, PSO-DE, HPSO, WCA, LCA, APSO, CPSO, MBA, IPSO, DELC, IABC-MAL, SAMP-Jaya

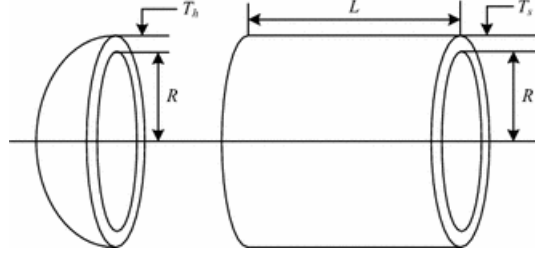


Figure 8: Schematic view of pressure vessel design problem.

and IAPSO methods. The statistical results are shown in Table 8. Some of the methods used to solve this problem report unfeasible results (PSO-DE, WCA, MBA and SAMP-Jaya), probably either because the integer constraints are ignored or due to wrong rounding. Nevertheless, we still use the results of these methods to prove the superior convergence of C-ITGO, even in constrained mixed integer problems.

Method	Best	Mean	Worst	SD	MNFes
UPSO	6544.2700	9032.5500	N/A	9.95E+02	100,000
QPSO	6059.7209	8017.2816	6440.3786	4.79E+02	8,000
G-QPSO	6059.7208	7544.4925	6440.3786	4.48E+02	8,000
CMA-ES	6059.7143	6170.25055	6410.08676	140.4843	30,018
MVDE	6059.7144	6059.99724	6090.53353	2.9103	15,000
CB-ABC	6059.7143	6126.6237	N/A	1.14E+02	15,000
PSO-DE	6059.7140	6059.7140	N/A	N/A	42,100
HPSO	6059.7143	6099.9323	6288.6770	86.2000	81,000
WCA	5885.3327	6198.6172	6590.2129	213.0490	27,500
LCA	6059.8553	6070.5884	6090.6114	11.37534	24,000
APSO	6059.7242	6470.7156	7544.4927	326.9688	200,000
CPSO	6061.0777	6147.1332	6363.8041	86.4500	240,000
MBA	5889.3216	6200.64765	6392.5062	160.34	70,650
IPSO	6059.7143	6059.7155	6059.7257	0.00232	20,000
DELC	6059.7143	6059.7143	6059.7143	2.10E-11	30,000
IABC-MAL	6059.7143	6072.5972	6089.2720	1.88E-06	15,000
SAMP-Jaya	5872.2129	5872.2129	5872.2129	5.0E-12	6513.33
IAPSO	6059.7143	6068.7539	6090.5314	14.0057	7,500
C-ITGO	6059.7143	6059.7143	6059.7143	9.8E-13	1101.64

Table 8: Statistical results of different methods for the pressure vessel design problem.

The algorithms CMA-ES, CB-ABC, HPSO, IABC-MAL, IPSO, DELC, IAPSO and C-ITGO are the only who found the feasible optimal solution. All other methods presented relatively poor performance, with much higher NFEs on average. C-ITGO takes less than five times the number of function evaluations to converge than the best competing method, SAMP-Jaya, which reported a result of 6513.33 MNFEs. Also, C-ITGO achieves the smallest standard deviation among all methods. All runs of C-ITGO converged quickly to the known global optimum, showing unarguably better results than any other method compared in this problem.

3.6. Gear train design problem

In this problem, the objective is to minimize the cost of the gear ratio of the gear train (Sandgren, 1990). An example is shown in Figure 9. The problem has four variables, representing the number of teeth for the four gears ($x_1 = A$, $x_2 = B$, $x_3 = D$, and $x_4 = F$), with $f(\mathbf{x}^*) = 2.700857E-12$. The only constraint of the problem is that all variables must be integers. The full problem statement follows:

Minimize:

$$f(\mathbf{x}) = \left(\left(\frac{1}{6.931} \right) - \left(\frac{x_2 x_3}{x_1 x_4} \right) \right)^2$$

with bounds:

$$12 \leq x_i \leq 60, \quad i = 1, 2, 3, 4$$

$$x_i \in \mathbb{Z}, \quad i = 1, 2, 3, 4$$

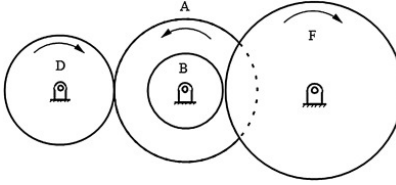


Figure 9: Gear train design problem structure.

We compare the C-ITGO results, shown in Table 9, against other five methods: MBA, UPSO, CS, APSO and IAPSO. In general, all methods compared achieved similar results, having found the global optimal solution for the problem. The main difference relies on the number of function calls, varying from 100,000 for UPSO to 800 for IAPSO.

Method	Best	Mean	Worst	SD	MNFes
MBA	2.700857E-12	2.062904E-08	2.47E-09	3.94E-09	1,120
UPSO	2.700857E-12	3.80562E-08	N/A	1.09E-07	100,000
CS	2.7009E-12	1.9841E-9	2.3576E-9	3.55E-9	5,000
APSO	2.700857E-12	4.781676E-07	7.072678E-06	1.44E-06	8,000
IAPSO	2.700857E-12	5.492477E-09	1.827380E-08	6.36E-09	800
C-ITGO	2.700857E-12	4.6504232E-09	2.7264505E-08	6.85E-09	773.0

Table 9: Statistical results of different methods for the gear train design problem.

Since this is an integer optimization problem, we used the mixed integer local search based on the NOMAD solver. In this problem, the solver had some difficulty in some runs, achieving 6.85E-09 of standard deviation, more than IAPSO, CS and MBA. The mean fitness value, however, is just worse than the CS method, which takes 5,000 function calls to converge. Besides this drawbacks, C-ITGO was the fastest method to achieve convergence, taking only 773.0 function calls on average.

3.7. Multiple disk clutch brake design problem

This is also an example of a problem where all variables are discrete. The Multiple disk clutch brake design problem aims at minimizing the mass of a multiple disk clutch brake Osyczka (2002). There are five integer variables: the inner radius (x_1), outer radius (x_2), thickness of the disk (x_3), actuating force (x_4) and number of friction surfaces (x_5) (Figure 10). The problem is also constrained by nine nonlinear inequalities. The objective function at the optimal solution is $f(\mathbf{x}^*) = 0.313656$. The mathematical formulation of the problem follows:

Minimize:

$$f(\mathbf{x}) = \pi(x_2^2 - x_1^2)x_3(x_5 + 1)\rho$$

subject to:

$$g_1(\mathbf{x}) = x_2 - x_1 - \Delta R \geq 0$$

$$g_2(\mathbf{x}) = L_{max} - (x_5 + 1)(x_3 + \delta) \geq 0$$

$$g_3(\mathbf{x}) = p_{max} - p_{rz} \geq 0$$

$$g_4(\mathbf{x}) = p_{max} * Vsr_{max} - p_{rz} * Vsr \geq 0$$

$$g_5(\mathbf{x}) = Vsr_{max} - Vsr \geq 0$$

$$g_6(\mathbf{x}) = T_{max} - T \geq 0$$

$$g_7(\mathbf{x}) = M_h - sM_s \geq 0$$

$$g_8(\mathbf{x}) = T \geq 0$$

where:

$$M_h = \frac{2}{3} \mu x_4 x_5 \frac{x_2^3 - x_1^3}{x_2^2 - x_1^2} N \cdot mm$$

$$\omega = \frac{\pi n}{30} rad/s$$

$$\begin{aligned}
A &= \pi(x_2^2 - x_1^2)mm^2 \\
p_{rz} &= \frac{x_4}{A}N/mm^2 \\
V_{sr} &= \frac{\pi R_{sr} n}{30}mm/s \\
R_{sr} &= \frac{2}{3} \frac{x_2^3 - x_1^3}{x_2^2 x_1^2}mm \\
\Delta R &= 20mm, \quad L_{max} = 30mm, \quad \mu = 0.6 \\
p_{max} &= 1MPa, \quad \rho = 0.0000078kg/mm^3 \\
V_{sr_{max}} &= 10m/s, \quad \delta = 0.5mm, \quad s = 1.5; \\
T_{max} &= 15s, \quad n = 250rpm, \quad I_z = 55Kg \cdot m^2 \\
M_s &= 40Nm, \quad M_f = 3Nm
\end{aligned}$$

with bounds:

$$\begin{aligned}
60 &\leq x_1 \leq 80, \quad 90 \leq x_2 \leq 110, \quad 1 \leq x_3 \leq 3 \\
0 &\leq x_4 \leq 1000, \quad 2 \leq x_5 \leq 9 \\
x_i &\in \mathbb{Z}, \quad i = 1, 2, 3, 4, 5
\end{aligned}$$

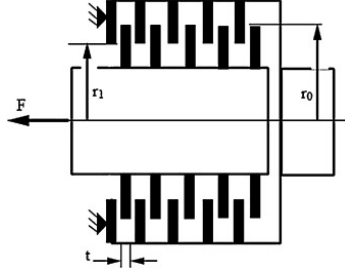


Figure 10: Schematic view of the multiple disk clutch brake design problem.

To compare the results, we used only methods who achieved close performance to the obtained by C-ITGO, since some methods in literature have very diverging results. The methods compared are WCA, IPSO, APSO and IAPSO. The WCA, IPSO, and IAPSO methods achieved good performance in this problem, finding the global optimal solution and having very small variance, as shown in Table 16. The WCA and IAPSO took very few function evaluations to converge, respectively 500 and 400. IPSO took long

more, with 20,000 function evaluations. However, the reported standard deviation for IPSO was 0.0.

Method	Best	Mean	Worst	SD	MNFEs
WCA	0.313656	0.313656	0.313656	1.69E-16	500
IPSO	0.313656	0.313656	0.313656	0.0	20,000
APSO	0.337181	0.506829	0.716313	0.09767	2,000
IAPSO	0.313656	0.313656	0.313656	1.13E-16	400
C-ITGO	0.313656	0.313656	0.313656	1.13E-16	286.48

Table 10: Statistical results of different methods for the multiple disk clutch break design problem.

The C-ITGO clearly outperforms the other methods, having a standard deviation of 1.13E-16, while converging with only 286.48 function evaluations on average. For this problem, we used very small populations, of sizes 20 (PS_1) and 5 (PS_2). The number of function evaluations in the first step was 100, and most runs converged in much less, enjoying the quality of initial solutions provided by the topographical heuristic step. Some runs, however, took more than 1,000 function evaluations, bringing the mean NFEs up.

3.8. Best Solutions to the Engineering Problems

Table 11 shows the fitness value, the values of the variables and the values of the constraints for the best solution found by C-ITGO for all problems. The precision of the results of each problem was set to match the results reported by the competing methods cited in this work. However, to the best of our knowledge, the best solution found by C-ITGO for each problem is equal to, or negligibly worse (up to several decimal places) than the best solutions reported by state-of-the-art methods.

3.9. Statistical Tests To Analyse the Computational Results

We now prove the significant improvement of C-ITGO over the competing methods by means of a nonparametric statistical test, where no assumptions are made regarding the underlying distribution of the data. Since no other algorithm than C-ITGO solves all the eight engineering design problems presented in this paper, we cannot apply typical statistical methods, such as the Friedman test (Derrac et al., 2011).

Instead, we use the Skillings-Mack test (Skillings & Mack, 1981), which is a Friedman-type statistical test that can be used when there are missing data, and that reduces to the Friedman test when the data has no missing entries. Just as in the Friedman test, the Skillings-Mack test finds the rank of the competing algorithms for each

Prob.	WB	TC	TB	SRI	SRII	PV	GT	MD
$f(\cdot)$	1.7248523	0.01266523	263.895843	2996.34816497	2994.471066	6059.7143	2.700857E-12	0.313656
x_1	0.2057296	0.05168906	0.788675	3.5	3.5	13.0	43	70
x_2	3.4704886	0.35671774	0.408248	7.0	0.7	7.0	16	90
x_3	9.0366239	11.28896574		17	17	41.5984	19	1
x_4	0.2057296			7.3	7.3	176.6366	49	830
x_5				7.8	7.715320			3
x_6				3.35021467	3.350215			
x_7				5.28668323	5.286654			
g_1	0.0	0.0	0.0	-0.07391528	-0.073915	-2.6645E-15		0.0
g_2	0.0	0.0	-1.464102	-0.19799853	-0.197999	-0.0359		-24.0
g_3	0.0	-4.05378563	-0.535898	-0.49917225	-0.499172	-4.4238E-09		-0.917438
g_4	-3.4329838	-1.09159320		-0.90147170	-0.904644	-63.3634		-9.826183
g_5	-0.0807296			-8.846257E-13	-2.220446E-16			-7.894697
g_6	-0.2355403			-4.885758E-12	0.0			-0.173855
g_7	-1.818989E-12			-0.7025	-0.7025			-40.118750
g_8				-1.887379E-15	0.0			-14.826145
g_9				-0.58333333	-0.583333			
g_{10}				-0.05132575	-0.051326			
g_{11}				-0.01085237	0.0			

Table 11: Results for the best solution found by C-ITGO for each engineering design problem.

problem and then calculates the mean or average rank. The lower the mean rank, the better is the performance of the algorithm. The Skillings-Mack statistical test is also useful when there are many ties or equal ranks, as well as for small samples.

The method reports a *p-value*, the probability that, when the null hypothesis is assumed to be true (in this case, no difference between the performance of the optimization methods), the results observed by the experiments at hand are at least of the same magnitude that the true values that would be observed in the limit of an infinite number of samples. Thus, a small *p-value*, say less than 0.05, represents a high chance that the null hypothesis is false.

In this work, the mean number of function evaluations (MNFEs) is used as the comparing metric. We used the *Skillings.Mack* package (Srisuradetchai, 2015) of the R language (R Dev. Core Team, 2008) to report the following results.

In Table 12 we show the results of applying the statistical test to all the methods that solved at least three of the eight engineering design problems considered in this work. The mean rank of C-ITGO is 1.0, given that it has the smallest MNFEs for all problems. That is much less than IAPSO and SAMP-Jaya, which have a mean rank of 2.75. The mean ranks are also shown in the form of a bar plot for all methods in Figure 11.

As shown in Table 12, the value of the Skillings-Mack statistic is 63.66813949 with an approximate *p-value* of 1.2469E-07 calculated from the chi-squared distribution with 16 degrees of freedom, which strongly implies that the null hypothesis does not hold true at the critical level of $\alpha = 0.05$ or $\alpha = 0.01$. That is, there is at least one

Algorithms	Skillings-Mack ranks
C-ITGO	1.0
IAPSO	2.75
SAMP-Jaya	2.75
IABC-MAL	5.125
PSO-DE	8.625
HPSO	7.9375
MBA	5.875
CPSO	8.9375
LCA	5.8125
CB-ABC	4.875
DELC	7.0
CMA-ES	5.0
MVDE	5.0625
IPSO	6.5
WCA	5.875
UPSO	8.5625
APSO	9.25
Skillings-Mack Statistic	63.66813949
p-value	1.2469E-07
χ^2	26.296

Table 12: Skillings-Mack test for methods solving at least three problems.

method that is significantly better than the others.

We also show in Table 13 the results of applying the Skillings-Mack test to the methods that solved at least five problems. For this case, the value of the Skillings-Mack statistic is 44.23462786 with an approximate p-value of 7E-06 calculated from the chi-squared distribution with 11 degrees of freedom. The difference between the results reported in Table 12 is mainly due to the reduction of the number of methods, and the exclusion of some methods that performed well, but in four or fewer problems, such as SAMP-Jaya.

We see again that C-ITGO has a mean rank of 1.0, far less than IAPSO with 2.375, standing in second place. The plot for the mean rank is shown in Figure 12. The p-value (7E-06) for this case is also very small, rejecting the null hypothesis at critical

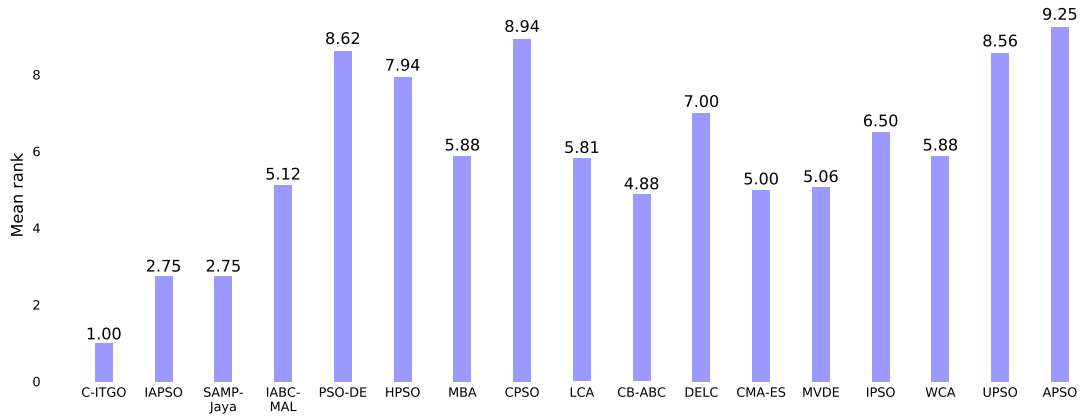


Figure 11: Mean rank plot for all methods that solve at least three problems.

level of $\alpha = 0.05$ or $\alpha = 0.01$.

We also present in Table 14 the results of applying the pairwise signed test, comparing C-ITGO against the same methods presented in Table 13 and considering the same performance metric. Here, a "+" represents that C-ITGO outperforms the corresponding method, a "=" represents a tie, and a "-" represents a loss (C-ITGO has worse performance than the corresponding method). If a method does not solve a certain problem, that entry is ignored (marked with "*"). The last row shows the final sum of the number of "+", "=", and "-" for all methods.

As we can see from Table 14, C-ITGO always has a better MNFEs than any method for all problems, so there are only "+" entries. Following the guidelines presented in Derrac et al. (2011), we can conclude that C-ITGO always achieves a p-value of at least

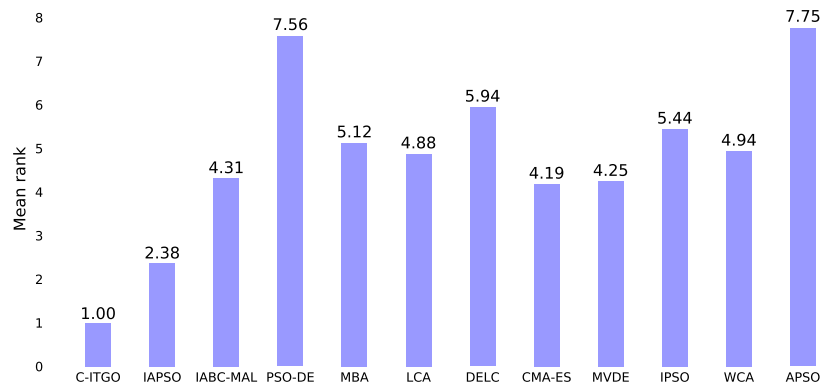


Figure 12: Mean rank plot for all methods that solve at least five problems.

Algorithms	Skillings-Mack ranks
C-ITGO	1.0
IAPSO	2.375
IABC-MAL	4.3125
PSO-DE	7.5625
MBA	5.125
LCA	4.875
DELC	5.9375
CMA-ES	4.1875
MVDE	4.25
IPSO	5.4375
WCA	4.9375
APSO	7.75
Skillings-Mack Statistic	44.23462786
p-value	7E-06
χ^2	19.67513757

Table 13: Skillings-Mack test for methods solving at least five problems.

0.05 when compared to the methods of Table 14.

To prove the superior convergence of C-ITGO, we present one more nonparametric statistical test, the Wilcoxon signed rank test, also described in Derrac et al. (2011). This is a more robust approach to a pairwise statistical comparison than the previous test, that aims to detect a significant difference between the means of two competing techniques.

The results shown in Table 15 were generated using the R package *wilcoxon.test*, considering C-ITGO against the other algorithms. Empty entries (problems not solved by some method) are treated by default.

Given that C-ITGO always had the best MNFEs when compared to all the other methods, as the Table 15 states, C-ITGO shows a improvement over IABC-MAL, MBA, LCA, CMA-ES, MVDE and APSO with a level of significance $\alpha = 0.01$, and over IAPSO with a level of significance $\alpha = 0.02$.

Eng. Prob.	C-ITGO	IAPSO	IABC-MAL	PSO-DE	MBA	LCA	DELIC	CMA-ES	MVDE	IPSO	WCA	APSO
WB	940.68	12,500 +	15,000 +	66,000 +	47,340 +	15,000 +	20,000 +	4,658 +	15,000 +	20,000 +	46,450 +	50,000 +
TC	535.08	2,000 +	15,000 +	24,950 +	7,650 +	15,000 +	20,000 +	19,445 +	10,000 +	20,000 +	11,750 +	120,000 +
TB	136.48	*	15,000 +	17,600 +	13,280 +	*	10,000 +	1,706 +	7,000 +	*	*	*
SRI	856.40	6,000 +	*	*	*	24,000 +	*	*	*	20,000 +	*	30,000 +
SRII	491.24	6,000 +	15,000 +	54,350 +	6,300 +	24,000 +	30,000 +	12,998 +	30,000 +	20,000 +	15,150 +	30,000 +
PV	1101.64	7,500 +	15,000 +	42,100 +	70,650 +	24,000 +	30,000 +	30,018 +	15,000 +	20,000 +	27,500 +	200,000 +
GT	773.0	800 +	*	*	1,120 +	*	*	*	*	*	*	8,000 +
MD	286.48	400 +	*	*	*	*	*	*	*	20,000 +	500 +	2,000 +
+/-		7/0/0	5/0/0	5/0/0	6/0/0	5/0/0	5/0/0	5/0/0	5/0/0	6/0/0	5/0/0	7/0/0

Table 14: The signed test comparing C-ITGO against the other methods that solved at least five problems. Empty entries are represented by *.

4. Conclusion

This work presents a modified iterative topographical global optimization algorithm, denominated C-ITGO, specialized in solving constrained optimization problems. The method developed in this paper uses a custom topographical heuristic, based on a stochastic application of the three steps criteria comparison, along with a space reduction procedure. In addition to being very simple conceptually, the C-ITGO algorithm is very generic in the sense that any local search procedure can be used to tackle a specific problem, be it continuous or discrete.

The C-ITGO method was compared against several algorithms found in literature, some presenting state-of-the-art results, in eight difficult constrained engineering optimization problems. In all tests performed, the C-ITGO outperforms any competing method regarding the mean number of function evaluations (MNFES) to converge to the best-known solution found, with performance gain in some problems being of an

	IAPSO	IABC-MAL	MBA	LCA	CMA-ES	MVDE	APSO
p-value	0.01606	0.001661	0.001207	0.002025	0.002155	0.002129	0.0007229

Table 15: Wilcoxon signed rank test comparing C-ITGO against other methods that solved at least five problems.

order of magnitude over the best performing methods compared.

We also presented several statistical tests comparing C-ITGO against the other methods used in this work. We have shown that C-ITGO outperforms the other competing methods, presenting a better performance that is significantly different at 0.05 level with respect to the MNFEs required to converge to optimal or near-optimal solutions for all the engineering design problems considered.

As future work, we suggest the following possibilities:

- use new, possibly even more complex optimization problems to test the performance of C-ITGO.
- compare C-ITGO against efficient deterministic global optimization methods.
- propose an adaptive method to auto adjust the parameters that can influence on C-ITGO performance.
- develop a parallel version aiming at faster execution time, even if this is not the main measure of performance.

Acknowledgments

This work is partially supported by the Brazilian Council for Scientific and Technological Development (CNPq): PIBIC/CNPq, process 163120/2017-8. The development of this research benefited from the UFT Institutional Productivity Research Program (PROPESQ / UFT). AJSN acknowledges the financial support provided by FAPERJ, CNPq and CAPES, research supporting agencies from Brazil. WFS gratefully acknowledges the financial support provided by CNPq.

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Appendix

GKLS class of functions

We used C-ITGO to optimize the 800 functions generated by the GKLS generator (Gaviano et al., 2003), considering the differentiable type (“D”). There are 100 functions for each setup, namely, with 2, 3, 4 and 5 variables, each consisting of “easy” and “hard” cases. The parameters used for each class of functions follows:

	N	M	Δ	r^*	ρ^*
Easy	2	10	10E-4	0.90	0.2
	3	10	10E-6	0.66	0.2
	4	10	10E-6	0.66	0.2
	5	10	10E-7	0.66	0.3
Hard	2	10	10E-4	0.90	0.1
	3	10	10E-6	0.9	0.2
	4	10	10E-6	0.9	0.2
	5	10	10E-7	0.66	0.2

Table 16: Parameters used in the GKLS generator.

Where:

- N - problem dimension;
- M - number of local optima;
- Δ - accuracy coefficient;
- ρ^* - radius of the attraction region of the global optimum;
- r^* - distance from the global optimum to the vertex of the paraboloid.

We compared the results achieved by C-ITGO against a number of deterministic global optimization methods. We used the approach described in Sergeyev et al. (2018) to compare meta-heuristics with deterministic algorithms. For each of the 100 problems of a given class, we ran C-ITGO 100 times, saving the mean number of function/gradient evaluations for that problem. We stopped when the best solution x' found in a run satisfies:

$$|x'(i) - x^*(i)| \leq \sqrt{\Delta}(b(i) - a(i)), \quad 1 \leq i \leq N, \quad (3)$$

where \mathbf{x}^* is the global optimal solution and \mathbf{a} and \mathbf{b} are respectively the lower and upper bound vectors defining the problem's domain. For all the GKLS problems, the fitness at the global optimum is $f(\mathbf{x}^*) = -1.0$ and the bounds are $a(i) = -1.0$, $i = 1, \dots, N$, and $b(i) = 1.0$, $i = 1, \dots, N$.

The deterministic methods used for comparison are DIRECT (Jones et al., 1993), DIRECT-L (Gablonsky & Kelley, 2001), the algorithm described in Sergeyev & Kvasov (2006), which we call DIRECT-KS, SGEO-QN (Fok et al., 2017) (using P_4) and ADC (Kvasov & Sergeyev, 2012).

The parameters used in C-ITGO are presented in Table 17. Because the GKLS classes of problems are unconstrained, the α parameter is omitted and the stochastic topographical heuristic is not used. The L-BFGS algorithm was used as the local search for unconstrained smooth optimization. A very small number of local search calls were necessary to reach convergence.

P_1	P_2	K_1	K_2	ϕ	Max_{LS}	LS_1	LS_2
50	2	3	1	0.5	5	10	20

Table 17: Parameters used in the C-ITGO algorithm.

Table 18 shows the results comparing the mean number of function/gradient evaluations necessary to achieve condition stated by equation 3. We use the same notation as in Sergeyev et al. (2018), where “>m(i)” states that i problems were not solved under 10^6 function evaluations.

Class	N	Deterministic Algorithms (100 runs for each algorithm and class)					Meta-heuristics (10,000 runs for each algorithm and class)			
		DIRECT	DIRECT-L	DIRECT-KS	SGEO-QN	ADC	GA	ABC	FA	C-ITGO
Easy	2	198.89	292.79	176.25	2161.00	97.22	>327452.5(2735)	2120.8	1190.3	151.36
	3	1117.70	1785.73	735.76	14430.00	491.28	>242231.7(1599)	10245.0	15269.2	734.50
	4	>47282.89(4)	18983.55	5014.13	102678.00	3675.84	>150597.5(1290)	>57669.5(19)	23166.7	4994.54
	5	>16057.46(1)	16758.44	5129.85	61064.00	3759.05	>237392.9(2208)	>38068.0(14)	>47203.1(16)	4628.62
Hard	2	1063.78	1267.07	675.74	5853.00	192.00	>370907.3(3149)	10366.2	>4299.6(3)	459.06
	3	>42322.65(4)	4858.93	2006.82	29937.00	618.32	>412037.8(2874)	26254.2	>21986.3(1)	1000.54
	4	>95708.25(7)	68754.02	16473.02	>186297.00(1)	5524.77	>247860.8(1900)	>150706.5(255)	40380.7	8233.73
	5	>217215.58(16)	>269064.35(4)	30471.83	>175124.00(1)	22189.47	>249965.6(2311)	>230192.9(879)	>79555.2(38)	32635.44

Table 18: Comparison of the mean number of function/gradient evaluations for each class of GKLS problems.

We see from the results presented in Table 18 that C-ITGO has promising results, having a smaller mean number of function/gradient evaluations than most methods in

most cases. It seems that the radius of the attraction region is the parameter which impacts most on the C-ITGO performance.

Table 19 shows some more statistics regarding the number of function evaluations executed by C-ITGO. The set of columns under ‘Statistics for all the 10,000 runs’ presents the minimum (**Min**), maximum (**Max**) and standard deviation (**STD**) of the NFEs calculated from the 10,000 runs for each of the eight classes of problems. The set of columns under ‘Statistics after averaging the 100 runs for each problem’ show the minimum (**Min**), maximum (**Max**) and standard deviation (**STD**) after averaging the NFEs required to solve all 100 problems of each class. As is possible to see in the Table 19, the worst run of the C-ITGO method required far less than 10^6 and 10^5 NFEs to reach convergence for any problem of the hard and easy classes respectively.

Class	N	Statistics for all the 10,000 runs			Statistics after averaging the 100 runs for each problem		
		Min	Max	STD	Min	Max	STD
Easy	2	1	994	102.03	111.25	237.54	28.31
	3	52	7074	677.07	399.46	1878.66	200.86
	4	60	59306	5137.66	1879.31	11716.62	1674.23
	5	60	78475	5000.32	2010.35	15779.96	1789.32
Hard	2	1	4719	392.52	268.91	867.78	116.33
	3	60	10233	932.80	549.00	2203.44	284.84
	4	63	122091	9047.97	3795.60	23451.30	3527.30
	5	68	270757	32558.35	11777.43	64622.82	10632.36

Table 19: Statistics for the number of function evaluations executed by C-ITGO on all the eight classes of problems.

Figures 13a and 13b show the *Operational Zones* for the C-ITGO algorithm, considering the easy and hard cases of the 5-dimensional class respectively. The 10,000 runs of the C-ITGO algorithm were used to generate the curves, as described in Sergeyev et al. (2018). Figures 14a and 14b show the comparison of the operational zones with the operational characteristics of some of the deterministic methods considered.

However, the ADC presents the best statistics in all the cases considered. Thus, we decided to execute a nonparametric statistical test, the Wilcoxon test (Derrac et al., 2011) (which is very useful to compare the performance of two algorithms when applied to a common set of problems), to check if there is any statistically significant difference of performance between C-ITGO and the ADC method.

Table 20 shows the results generated using the *wilcoxon.test* command of the R

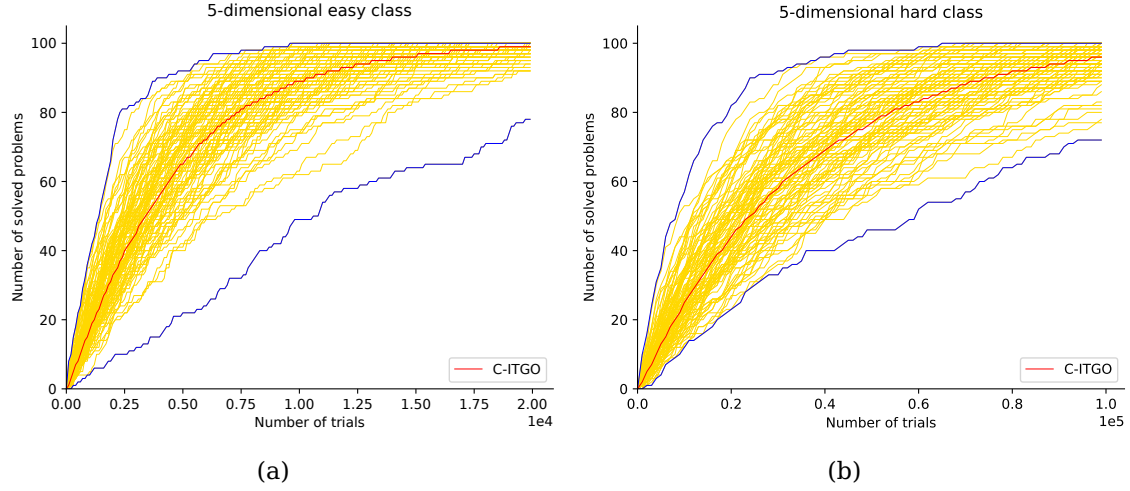


Figure 13: The operational zones built using the 10,000 runs performed by the C-ITGO algorithm for the five dimensional easy (a) and hard (b) cases. The lower and upper bounds are in blue, while the mean is in red.

software, considering ADC as reference/control against the other methods.

	DIRECT	DIRECT-L	DIRECT-KS	SGEO-QN	C-ITGO
p-value	0.0416	0.0781	0.2154	0.0037	0.2818

Table 20: Wilcoxon signed rank test comparing ADC against the other methods used to solve the GKLS class of problems.

The ADC method shows an improvement over DIRECT and SGEO-QN with a level of significance of $\alpha = 0.05$, and over DIRECT-L with a level of significance of $\alpha = 0.1$. When compared to DIRECT-KS and C-ITGO, the probability of presenting any significant statistical difference is bellow 80%, what is indicated by a p-value greater than 0.2.

When considering the eight different cases of the GKLS function generator, we can conclude that there is not any significant statistical difference between the C-ITGO and the ADC methods, showing that the performance of C-ITGO is equivalent to the ADC over the GKLS generated problems considered in this work.

We would like to explore further the effectiveness of C-ITGO for the unconstrained

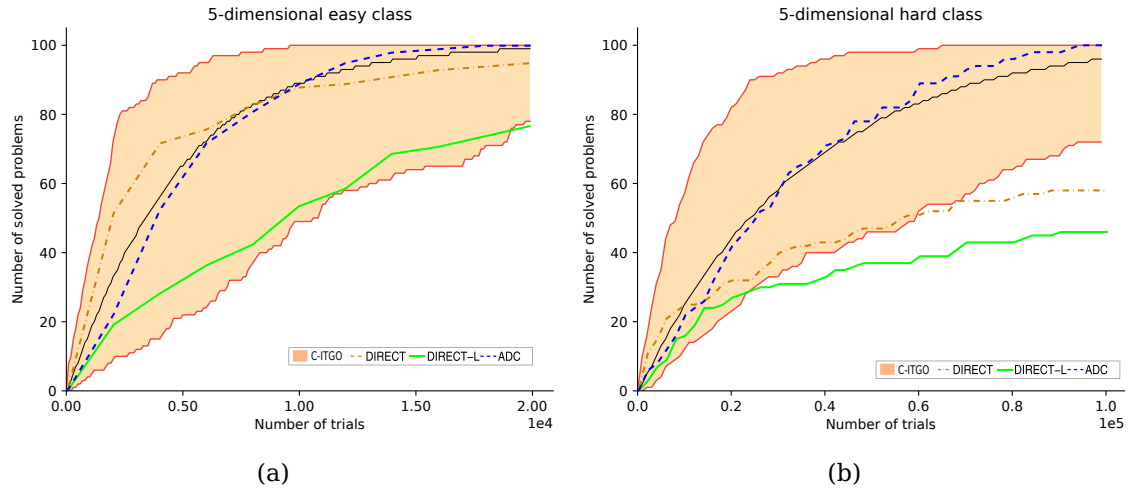


Figure 14: Operational zones built on the two 5-dimensional classes for the C-ITGO algorithm, and operational characteristics of the DIRECT, DIRECT-L and ADC methods.

case in a future work, possibly improving the current results.