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Technical Note

Topographical global optimization applied to nuclear reactor core design: Some preliminary results

Wagner F. Sacco [a,*], Nélio Henderson [b], Ana Carolina Rios-Coelho [a]

[a] Instituto de Engenharia e Geociências, Universidade Federal do Oeste do Pará, Av. Vera Paz, s/n, Santarém, PA 68135-110, Brazil
[b] Depto. de Modelagem Computacional, Instituto Politécnico, Universidade do Estado do Rio de Janeiro, R. Bonfim, 25, Nova Friburgo, RJ 28625-570, Brazil

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ABSTRACT

The nuclear reactor core design optimization problem consists in adjusting several reactor cell parameters, such as dimensions, enrichment and materials, in order to minimize the average peak-factor in a three-enrichment-zone reactor, considering restrictions on the average thermal flux, criticality and sub-moderation. This problem is highly multimodal, requiring optimization techniques that overcome local optima. In order to do so, we use a clustering optimization technique based on the topographical information on the objective function called Topographical Global Optimization (TGO). This algorithm consists of three steps: a uniform random sampling of solutions in the search space, the construction of the topograph, and the application of a local optimization algorithm using the topograph minima as starting points. In this work, we use the Sobol quasi-random sequence to perform the first step and the Hooke–Jeeves direct search method (HJ), which is one of the less sophisticated algorithms of this type, for the third step. In spite of HJ's simplicity, the results are competitive in terms of fitness function values, being obtained at a computational cost one order of magnitude lower than the efforts required for achieving the best results so far. This fact suggests that better results can be obtained employing more modern and effective direct search methods. Nevertheless, as the problem attacked is quite challenging, the preliminary results show the potential of TGO to be applied to other nuclear science and engineering problems. For the best of our knowledge, this is the first time that TGO is applied to an engineering optimization problem.

1. Introduction

In the process of nuclear core design, configurations consisting of materials, enrichment and dimensions have to be analyzed with neutronic models. In practice, computational codes simulate the neutrons' behavior and interaction with the materials, given a reactor core geometry. Restrictions related to the average thermal flux, criticality and sub-moderation must be satisfied in order to obtain safe core configurations. Despite the complexity of the nuclear core design process, it is possible to formulate it as an optimization problem (Pereira et al., 1999). Thus, global optimization techniques may automatically perform the search for the best core configurations regarding safety and economic matters.

Some random optimization methods have been applied to solve this nuclear core design optimization problem, among them the genetic algorithm (GA, Holland, 1992) by Pereira et al. (1999), particle swarm optimization (PSO, Kennedy and Eberhart, 1995) by Domingos et al. (2006), and differential evolution (DE, Storn and Price, 1997) by Sacco et al. (2009) and Sacco et al. (2013). This problem is highly multimodal (Sacco et al., 2004), i.e. with many local minima, being, thus a great challenge for optimization algorithms.

Because of this multimodality, the search space should be thoroughly explored so that the optimization algorithm does not converge to a local optimum. To overcome this difficulty, many solutions have been proposed: a parallel genetic algorithm (Pereira and Lapa, 2003), a niching method (Mahfoud, 1995) applied to genetic algorithms (Sacco et al., 2004), and a hybrid algorithm that alternates exploration and exploitation of the search space (Sacco et al., 2008).

Between the early seventies and mid-nineties, a global optimization paradigm based on clustering was studied by some researchers, mainly in Europe. The seminal article by Becker and Lago (1970) was followed by, among others, Törn (1973, 1978), Timmer (1984), Törn and Viitanen (1992, 1994), and Ali and Storey (1994). Ali (1994), and Levi and Haas (2010) present fine reviews on the clustering-based methods. According to Törn and Žilinskas

* Corresponding author. Address: Instituto de Engenharia e Geociências, Universidade Federal do Oeste do Pará, Rua Vera Paz, s/n, Salé, Santarém, PA 68035-110, Brazil. Tel.: +55 93 8402 6503; fax: +55 93 2101 4902.

E-mail addresses: wagner.sacco@ufopa.edu.br, wagner.sacco@pq.cnpq.br (W.F. Sacco).

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(1989), the motivation for exploring clustering methods is based on the following:

(a) It is possible to obtain a sample of points in the search space consisting of concentration of points in the neighborhood of local minimizers of the objective function *f*.
(b) The points in the sample can be clustered giving clusters identifying the neighborhoods of local minimizers and thus permitting local optimization methods to be applied.

In this work, in order to overcome the nuclear reactor core design problem's multimodality, we propose the usage of a clustering optimization technique based on the topographical information on the objective function, which was introduced by Törn and Viitanen (1992), the so-called Topographical Global Optimization (TGO). These authors used the topographical heuristic which gives name to the algorithm to determine minima from a set of sampled points, so that they were initial solutions for a local optimization algorithm. For the best of our knowledge, this is the first time that TGO is applied to an engineering optimization problem.

The original TGO algorithm is non-iterative and based on the exploration of the search space (Ali and Storey, 1994). It consists of three steps (Törn and Viitanen, 1994):

1. A uniform random sampling of *N* points in the search space.
2. The construction of the topograph, which is a graph with directed arcs connecting the accepted sampled points on a *k* - nearest neighbors basis, where the direction of the arc is towards a point with a larger function value. The minima of the graph are the points better than their neighbors, i.e., the nodes with no incoming arcs.
3. The topograph minima are starting points for a local optimization algorithm. The best point obtained from all the executions using each minimum as the initial solution is the result of the algorithm.

The first step is performed using the Sobol quasi-random generator (Sobol, 1967), which, in spite of the name, is deterministic.

In the third step, we use one of the simplest direct search methods, the Hooke–Jeeves algorithm (Hooke and Jeeves, 1961). Direct search methods are local optimization techniques that do not make use of derivative information on the searching process. They had their golden age in the sixties, but fell in disuse because they lacked coherent mathematical analysis (Kolda et al., 2003). In more recent years, with the pragmatic use of metaheuristics, most of whom do not have proofs of convergence, there has been a revival of interest in direct search methods. This is because they are easy to program, solve nondifferentiable optimization problems like the one attacked here, and, last but not least, nowadays we do have affordable computers to run them. The papers by Wright (1996), Lewis et al. (2000), and Kolda et al. (2003) are landmarks of this trend.

The remainder of the paper is described as follows. The nuclear reactor core design is presented in Section 2. The description of the topographical global optimization method is presented in Section 3. The computational experiments and their discussions are in Section 4. Finally, the conclusions are made in Section 5.

2. The nuclear reactor core design problem

Let us describe the optimization problem (for a more detailed exposition, see Pereira et al., 1999): consider a cylindrical 3-enrichment-zone reference reactor , with a typical cell composed by moderator (light water), cladding and fuel. Fig. 1 illustrates such reactor. The design parameters that may be varied in the optimization process, as well as their variation ranges, are shown in Table 1. The materials are represented by discrete variables.

The objective of the optimization problem is to minimize the average flux or power peaking factor, f_p, of the proposed reactor, allowing the reactor to be sub-critical or super critical (k_{eff} = 1.0 ± 1%), for a given average flux ϕ_0. Let $\mathbf{X} = \{R_f, \Delta_c, \Delta_m, E_1, E_2, E_3, M_f, M_c\}$ be the vector of design variables. Then, the optimization problem may be written as

Minimize

$$f_p(\mathbf{X})$$

Subject to :

$$\phi(\mathbf{X}) = \phi_0; \quad (1)$$

$$0.99 \leqslant k_{eff}(\mathbf{X}) \leqslant 1.01; \quad (2)$$

$$\frac{dk_{eff}}{dV_m} > 0 \quad (3)$$

$$X_i^l \leqslant X_i \leqslant X_i^u, \quad i = 1, 2, \ldots, 6 \quad (4)$$

$$M_f = \{UO_2 \text{ or U-metal}\}; \quad (5)$$

$$M_c = \{\text{Zircaloy-2, Aluminium or Stainless Steel-304}\}, \quad (6)$$

Table 1
Range of parameters.

Parameter	Symbol	Range
Fuel radius (cm)	R_f	0.508–1.270
Cladding thickness (cm)	Δc	0.025–0.254
Moderator thickness (cm)	R_e	0.025–0.762
Enrichment of zone 1 (%)	E_1	2.0–5.0
Enrichment of zone 2 (%)	E_2	2.0–5.0
Enrichment of zone 3 (%)	E_3	2.0–5.0
Fuel material	M_f	{U-metal or UO_2}
Cladding material	M_c	{Zircaloy-2, aluminum or stainless steel-304}

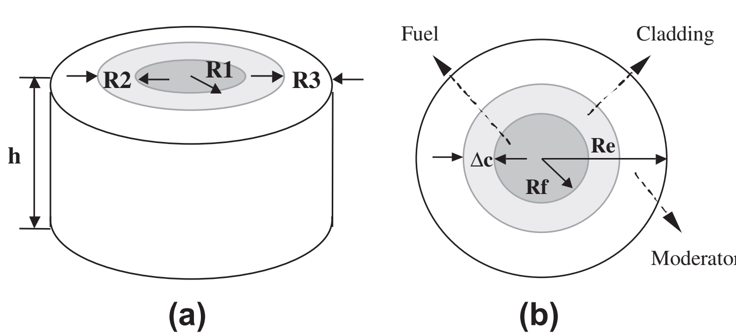

Fig. 1. (a) The nuclear reactor and (b) its typical cell.