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Metaheuristic optimization in shielding design for neutrons and gamma rays reducing dose equivalent as much as possible

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ABSTRACT

To obtain the optimum solution of the shielding design fast and accurate, 14 well known metaheuristic algorithms were studied in this study. Following the common practice, the algorithms were compared using several benchmark functions, and same number of function evaluations (NFE) was used in the comparison. An algorithm was tested by 30 independent runs in each function. Average of the NFE required to reach the global optimum and the success percentage were used to evaluate the performance of the various algorithms. The results showed that, the Genetic Algorithm (GA), the Differential Evolution algorithm (DE), the Shuffled Complex Evolution algorithm (SCE) and the Teaching-Learning-based Optimization algorithm (TLBO) have better performance than the others. Furthermore, the four algorithms were applied to optimize the shielding material, and 3 cases of shielding design were presented. As a typical case, the fission energy spectrum of ^{235}U was used in the shielding design. After 3 independent runs for each case, and comparing the mean best function values, it was found that the algorithm of SCE performs best. It implies that the algorithm of SCE is a better choice among the algorithms used in this study to optimize the shield. In addition, it was found that the composite multilayer is a better arrangement than the simple multilayer.

1. Introduction

The design of radiation shielding is significant in the developing of nuclear facilities, especially for the compact systems and mobile devices, such as compact pressurized water nuclear reactor (Tunes et al., 2017) and transportable neutron source (Hu et al., 2017). The shield always need to be compact, lightweight, and sometimes very specialized (Wielopolski et al., 2007), which make it difficult to obtain a satisfactory solution. Even for the most experienced shielding designers, they may do not know whether their design is optimal in any sense.

In general, the method of shield designing is a "brute force" trial-and-error procedure, which is tempered by experience (Schaeffer, 1973). However, optimization techniques (Hu et al., 2008; Leech and Rohach, 1972; Tunes et al., 2017) using genetic algorithms, sequential quadratic programming and transmission matrix methods have been gradually applied to improve it in recent years. These studies demonstrated that it is efficient to design the shield based on the optimization algorithms. The transport of radiation (neutrons and gamma rays are mainly considered) in these studies are almost performed by the Monte-Carlo methods (such as MCNP code and Geant4 toolkit) which always need time of seconds even minutes per count (Intel i7-4790 CPU, 8 threads). That is to say, it may need several days for an optimization even though a small material thickness and simple geometry were used.

To obtain the optimal solution of a realistic shielding example in a shorter time, there may have two ways. One is employing advanced variance reduction and multiprocessing techniques furthermore. Another is finding an optimization algorithm with better efficiency for this case. Objectively speaking, the former method largely depends on the computer performance, and the latter is of great significance to the general researchers.

Due to the optimization of shielding is almost as optimization over a black box, of which just has the objective function and constrain values, and the derivative information are impractical to obtain, the traditional techniques like steepest decent, linear programming, dynamic programming, etc. generally difficult to get the global optimal solution in an acceptable amount of time. The nature-inspired metaheuristic optimization algorithms are powerful tools for this case and the use of these types of algorithms is becoming more and more commonplace. D.D. DiJulio (DiJulio et al., 2016) has compared four metaheuristic algorithms in shielding design, but the algorithms researched are a little few and the shielding design is dealt simply. So, it is necessary to carry out a

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study on the metaheuristic algorithms in shielding design furthermore. This study exactly addresses this problem.

First, 14 well known metaheuristic algorithms are introduced, and a comparison of them are presented using several benchmark functions, then several algorithms with superior performance are selected preliminary (Section 2). Second, the shielding of neutrons and gamma rays are analyzed, and 3 cases of shielding design are presented, then the algorithms selected previous are applied to the 3 cases, an algorithm performances best for this purpose is found finally (Section 3).

In this study, calculations to design the optimal shielding are performed using the MCNP5 code and the ENDF/B-VI cross section set. The NCRP-38 (Rossi, 1971) neutron flux-to-dose rate conversion factors and the 1977 ANSI/ANS (Battat, 1977) photon flux-to-dose rate conversion factors are used. To improve the calculation of the scored quantities, variance reduction techniques such as weight windows are used. The calculation during optimization has a standard deviation less than 10%.

2. Algorithms and the comparison

2.1. Introduction of the algorithms

The nature-inspired metaheuristic optimization techniques have proved to be better than the traditional techniques in solving optimization problems that have many local optima and lack of derivative information (Rao et al., 2012). Today there exists a wide range of algorithms to choose from, some of the well-known metaheuristics developed during the last decades are: Genetic Algorithm (GA) (Holland, 1975) proposed by John Holland in 1975, which is based on the theory of natural selection and evolutionary biology; Simulated Annealing (SA) (Kirkpatrick et al., 1983) proposed by Kirkpatrick et al., in 1983, which is based on the physical process of annealing; Ant Colony Optimization (ACO) (Colorni et al., 1992) proposed by Marco Dorigo in 1991, which is based on the foraging behavior of real ants; Shuffled Complex Evolution (SCE) (Duan et al., 1993) proposed by Duan et al., in 1993, which combines the strengths of controlled random search algorithm, competitive evolution and complex shuffling; Cultural Algorithm (CA) (Reynolds, 1994) proposed by Reynolds in 1994, which is derived from cultural evolution process and can be seen as an extension to a conventional genetic algorithm; Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 2002) proposed by Kennedy and Eberhart in 1995, which is based on the social behavior of birds and fishes; Differential Evolution (DE) (Storn and Price, 1997) proposed by Rainer Storn and Kenneth Price in 1997, which is similar to GA with specialized crossover, mutation and selection method; Harmony Search (HS) (Zong et al., 2001) proposed by Z. W. Geem et al., in 2001, which is inspired by harmony improvisation process of musicians; Shuffled Frog Leaping Algorithm (SFLA) (Eusuff and Lansey, 2003) proposed by M. Eusuff and E. Lansey in 2003, which is based on the principle of communication among the frogs; Artificial Bee Colony (ABC) (Karaboga, 2005) proposed by Dervis Karaboga in 2005, which is based on the foraging behavior of honey bee swarm; Invasive Weed Optimization (IWO) (Mehrabian and Lucas, 2006) proposed by Alireza Mehrabian and Caro Lucas in 2006, which is inspired by spreading strategy of weeds; Imperialist Competitive Algorithm (ICA) (Atashpaz-Gargari and Lucas, 2007) proposed by E. A. Gargari and Caro Lucas in 2007, which is inspired by historical colonization process and competition among imperialists; Biogeography-Based Optimization (BBO) (Simon, 2008) proposed by Dan Simon in 2008, which is inspired by the biogeographic concepts: speciation (the evolution of new species), the migration of species between islands, and the extinction of species; Teaching-Learning-based Optimization (TLBO) (Rao et al., 2012) proposed by Rao et al., in 2011, which is based on the effect of the influence of a teacher on the output of learners in a class. A detailed description of the various algorithms can be found in the references.

In this study, standard or improved versions of the algorithms were used. The GA and PSO packages are come from the MATLAB Optimization Toolbox (MATLAB 2016a). The other algorithms are based on the freely downloadable codes from http://yarpiz.com/category/metaheuristics.

2.2. Comparison of the algorithms

Due to the long time needed in an optimization of the shielding design, often only one type of the algorithms could be used in practice. So, it is important to assert which one is better for this purpose in terms of computational efficiency and solution accuracy.

In the field of optimization, it is a common practice to compare different algorithms using benchmark problems (Rao et al., 2012). In this study, a suite of benchmark functions (Karaboga and Akay, 2009; Karaboga and Basturk, 2008) (Table 1) commonly used are considered. The Graphs of the functions in two dimensions are shown in Fig. 1. An algorithm can be believed to have good performance over most problems in real world if it can solve these functions accurately.

In general, proper selection of the parameters is essential for the searching of the optimum solution by these algorithms (Rao et al., 2012). After several trials and refer to the references, the parameters are selected as list in Table 2. Because the number of evaluations per iteration is varied with the kind of algorithms, the number of function evaluations (NFE) is used instead of the number of iterations to compare all the algorithms altogether in this study. It has proved that the algorithms are guaranteed to converge and reach the global optimum if they are run for a sufficient amount of time. But we can't afford to wait that long time in most cases. So, it is necessary to compare the algorithms using a reasonable NFE. In the following comparison, the NFE of the function f_1 to f_5 (dimensionality of 30) are set at 100×2000, and that of f_6 (dimensionality of 2) is set at 50×2000. In the ABC, SCE and TLBO optimizations, the numbers of iteration are set at 1000 instead of 2000 because twice evaluations are used per iteration. In the SFLA optimization, the iterations is set at 400 due to quintuple evaluations is used per iteration.

To evaluate the performance of the various algorithms visually and conveniently, average of the NFE required to reach the global optimum and the success percentage are employed. The mean NFE indicates the computational effort of the algorithm and the time needed in an optimization. The success percentage reflects the stability of the algorithm and the consistency of the algorithm to find the results in different runs. An algorithm was tested by 30 independent runs in each function. The success percentages and the mean NFE required are presented in Table 3. Because the function f_1 is very simple and f_6 is quite difficult, all the algorithms have found the global optimum in function f_1, while only few of them could solve the function f_6. Fig. 2 shows the convergence graphs for function f_2 and f_4. The function values considered is the average of function values for the 30 different independent runs.

To further assert which one is better among the algorithms, a rank was listed in Table 4 according to the success percentage and the mean NFE. The algorithms would have same rank if they have same values. In common practice, we always hope to solve a problem fast and accurate. That is to say, the computational efficiency and solution accuracy are equally important. So, the "R_T" would be a vital indicator during the selection of algorithms. In this way, the TLBO, SCE, GA and DE algorithms have shown superior performance than the others, and they are selected to further optimize the shielding materials in the following.