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Methodology for integrated fuel lattice and fuel load optimization using population-based metaheuristics and decision trees

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ABSTRACT

A new methodology to deal in an integrated way with the fuel lattice design and fuel load optimization in a Boiling Water Reactor is proposed. The novel aspects are two. Firstly, the use of basic population based metaheuristics to deal with sets of potential fuel lattice design and sets of potential fuel reloads. Both populations evolve in a parallel and independent way between them. After some iterations the best current fuel lattice is fed to the fuel reload optimization process. Secondly, and in order to evaluate the quality of the lattice designs, the use of previously developed decision trees to speed up the calculations, thus avoiding the use of computationally expensive core reactor simulators. The computational experiments allowed to assess the benefits of our proposal. In one hand, the obtained solutions fulfilled the energy requirements and at the same time the core safety was guaranteed by thermal limits and cold shutdown margin. By the other hand, the use of decision trees allowed to speed up the process by a factor of 1200.

1. Introduction

The in-core fuel management in a BWR (Boiling Water Reactor) is a complex task because there is a need to solve several combinatorial problems, which are tightly coupled. Firstly, fuel lattice design requires the allocation of enriched uranium pin rods in a $N \, x \, N$ square grid, while some parameters are adjusted. Fuel reload design needs to allocate fuel assemblies in the core in a $M \, x \, M$ array of channels. It is clear that when M, N values grow up, the problem will be harder and the search space of solutions will be larger. Therefore, it will be more difficult to find an optimal solution.

Another aspect to consider in an optimization process is the required time to evaluate the solutions' performance using a reactor core simulator. For example, to evaluate an equilibrium cycle using two fresh fuel batches, each fuel batch formed by three different power axial zones, CASMO-4 (Rhodes and Edenius, 2004) spends around 300 min of CPU time (reported by the code) in a workstation at 3 Ghz to calculate fuel lattice parameters. SIMULATE-3 (Dean, 2005) spends around 39 min to run 5 operating cycles to reach equilibrium conditions in the same workstation. Therefore, 5.65 h are necessary to determine if a fuel lattice design would have good performance according to reactor core simulators. It is important to clarify, that only a single processor was used to do these calculations. Such computational cost is one of the main reasons that make researchers to deal with both problems in an isolated way.

As examples, we may cite the following ones. For fuel lattice design, Cuevas et al. (2002) used a modified linear programming method to optimize the enrichments distributions within light water reactor. A multi state recurrent neural network was applied by Ortiz et al. (2009) to minimize the Local Power Peak Factor (LPPF); additionally, a fuzzy logic system was implemented to diversify the search space. Gadolinia rods effects were analyzed versus LPPF minimization and with a greedy algorithm Ortiz et al. (2010) the fuel lattice design was optimized. Castillo et al. (2011) applied the path relinking technique to the fuel lattice design where the aims were to minimize the LPPF while the value of kinf (infinite multiplication factor) was kept into a reactivity interval. Finally, Montes et al. (2011) used an Ant Colony System to minimize both LPPF parameter and average uranium enrichment.

In fuel reload optimization there are several works. For example, Castillo Méndez et al. (2004) used a tabu search metaheuristic. Jiang et al. (2006) proposed the utilization of a distribution estimation algorithm of a research reactor. De Lima et al. (2008) used an Ant Colony System to optimize the PWR core fuel reload. Alvarenga de Moura et al. (2009) applied an algorithm based on particle swarm optimization for a

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PWR. Khoshahval et al. (2010) used a continuous version of particle swarm in a PWR. Also, Esquivel-Estrada et al. (2011) applied several variants of ant algorithms and compare them for a BWR reactor.

One way to speed up the evaluation of a given solution is to use a surrogated model (SM) which can be simply understood as a fast method to obtain an approximated assessment of the solution's quality. Some kinds of neural networks and Decision Trees (DT) are good examples of SM.

One of the first studied SM was developed by Kim et al. (1993a,b). They used a neural network and a fuzzy rule-based system to optimize fuel reloads in a PWR. Neural network was trained to predict hot excess reactivity at the beginning of the cycle and the power peaking factor. Fuel reload was optimized with the fuzzy rule-based system. Ortiz and Requena (2003) trained a neural network to predict thermal limits and energy produced in a BWR core. Then neural network was used with genetic algorithms (Ortiz and Requena, 2004a) and a recurrent neural network (Ortiz and Requena, 2004b) to optimize fuel reloads in a BWR.

Cadenas et al. (2016) show how DT can be built to predict core parameters from simple CASMO-4 results like LPPF, kinf at the beginning of the fuel lattice and uranium and gadolinia rods distribution. DT were used to predict thermal limits in a BWR core with relative errors lower than 5%.

In the context of optimization with metaheuristics, SM can play a key role because there is no need to obtain the "true" evaluation of a solution. Instead, the key problem is to determine if a solution is better or not that another one. In this sense, having a good approximated method could be enough to develop a successful approach.

So, considering that fuel lattice and fuel reloads in a BWR should not be managed independently, and given the unaffordable computational time required for evaluating solutions through reactor core simulators, our main aim is to propose a new methodology that allows to: a) solve the fuel lattice design and the fuel reload optimization problems in an integrated way, and b) perform the optimization in affordable time.

Two novel aspects should be highlighted. In first place, the use of basic population based on metaheuristics to deal with sets of potential fuel lattice design and sets of potential fuel reloads. In second place, and in order to evaluate the quality of the lattice designs, the use of previously developed decision trees to speed up the calculations, thus avoiding the use of computationally expensive software simulators.

The paper is structured as follows: in Section 2, fuel lattice design and fuel reload design problems are described. In Section 3, proposed methodology is presented and populations based on metaheuristics are explained. In Section 4, results of this methodology are shown. Finally, some conclusions are shown.

2. Description of the problems

In this section, we describe the fuel lattice and fuel reload design problems. In addition, some considerations regarding fuel assemblies and control rod patterns are outlined.

2.1. Fuel lattice design problem

In very simple terms, the problem can be stated as follows: given a $N\ x\ N$ grid, and an inventory of uranium enrichments and gadolinia concentration rods, find the allocation of rods in the grid that minimizes the LPPF while kinf is kept into a proposed interval, taking into account the beginning of the fuel lattice life; it is to say, at 0 GWD/T.

Fig. 1 shows a typical fuel lattice for a BWR. Uranium enrichments of the rods and gadolinia concentrations are not arbitrary values. Manufacturing processes produce uranium enrichments with established values. In our case, uranium enrichments range from 1.8% to 4.9% (in increments of 0.2% and 0.1% from 4.8% to 4.9%) while gadolinia's concentrations range from 2% to 7% (in increments of 1%). The allocation of rods in the grid must follow certain rules:

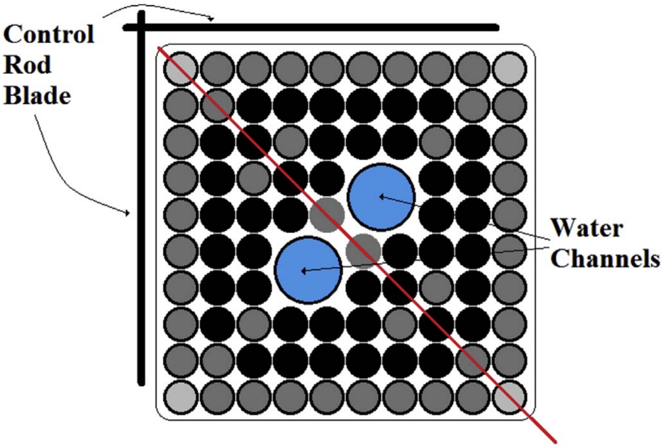

Fig. 1. Typical fuel lattice.

- The lowest uranium enrichments should be allocated in the fuel lattice corners and should not be allocated in central positions.
- Gadolinia rods cannot be allocated in peripheral positions
- In order to reduce the problem complexity, fuel lattice is designed with mirror symmetry along the diagonal (shown in Fig. 1)

Every possible allocation represents a solution to the problem. The quality of a solution is evaluated using a reactor code, which calculates the lattice parameters (LPPF and kinf) in 2D. For example, in previous studies (Cadenas et al., 2016) we employed CASMO-4 and SIMULATE-3 to evaluate a fuel lattice configuration (according to 3D calculus above mentioned) taking approximately 5.65 h in a workstation of 3 GHz of CPU speed.

2.2. Fuel reload design problem

The solution of the previous problem is a fuel lattice, which is then used to construct fuel assemblies. A fuel assembly is a vertical array formed by 25 nodes (or segments). One node in the bottom and two nodes in the top of the fuel assembly have natural uranium. In the other 22 nodes, optimized fuel lattices with enriched uranium are allocated.

The fuel reload design problem can be stated as follows: given a $M\ x\ M$ grid of channels representing a BWR core (Fig. 2), and a set of fuel assemblies, find the allocation of fuel assemblies to channels that maximizes the energy produced while satisfying the safety restrictions.

These safety restrictions are two: 1) thermal limits (including the fraction to linear power density (FLPD), minimum fraction to critical

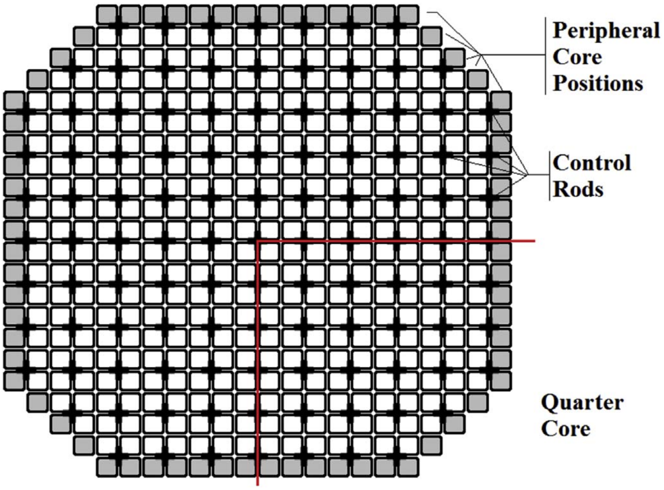

Fig. 2. Typical BWR core.