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Review of the doctoral thesis of Wojciech Roman Kubiński, entitled "Optimization of the In-Core Fuel Management in a Nuclear Reactor Core Using Evolutionary algorithms"

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In this thesis, the PhD candidate Wojciech Roman Kubiński presents his research on evolutionary algorithms for the optimization of the first fuel core loading and the equilibrium cycle of a nuclear power reactor, and the irradiation scheme when producing radioisotopes in a nuclear reactor. The optimization of these problems is very important because it can lead to reactor core configurations that allow safer operations, more efficient utilization of nuclear fuel, and better irradiation strategies for radioisotope production.

The thesis is structured in 5 chapters and is well-written (although one can find several typos). The background of the different topics is introduced in a clear manner, the methods and the methodologies used in the work are explained in a satisfactory manner and investigated in relevant cases, and the results are analyzed and discussed in detail. The conclusions are rigorous and supported by the results.

In Chapter 1, the PhD candidate shows a good knowledge of the context of the work. In the first part, he describes the role of In-Core Fuel Management (ICFM) for safe and efficient operations of nuclear reactors and the strategy that may be followed for in-core fuel management. The importance of optimization of the ICFM is emphasized by providing an approximate estimation of the economic impact. In the second part, he discusses how radioisotopes can be produced and their crucial use in medical and industrial fields. Then, he provides basics of nuclear reactor physics and optimization algorithms that are needed for the understanding of the thesis.

In Chapter 2, the PhD candidate reviews past work carried out for in-core fuel management optimization and shows a good understanding about the previous research in the field. The review is very extensive and valuable, and it covers the optimization of single- and multi-cycle problems in nuclear power reactors, the optimization for radioisotopes productions in nuclear reactors, and the optimization of other problems related to nuclear engineering. In the last part of the chapter, the review is focused on the optimization studies performed for Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), research nuclear reactors, and Generation-IV reactors.

In Chapter 3, the PhD candidate studies the optimization of the initial fuel core loading in the case of a typical commercial Pressurized Water Reactor. For this purpose, the PhD candidate develops an adaptive genetic algorithm and applies it to extend the cycle length. Different constraints are considered while maximizing the cycle length, i.e., 1) the number of fuel assembly types is fixed, 2) the effective multiplication factor is kept within a specified range, 3) the fissile material mass is kept at a constant averaged level, 4) the number of fuel assemblies of a given type does not vary and no symmetry is imposed, 5) the power peaking factors are minimized. A new method based on the concept of genetic variance is proposed to describe the diversity of the individuals in the population processed by the genetic algorithm, and it is demonstrated to differentiate better between chromosomes with small variations and thus to improve the results. This part of the work is also interesting for two other aspects. First, the algorithm is tested for different values of its meta-parameters (i.e., the size of the population, the minimum number of generations, the mutation probability, and the crossover probability), so that the impact of the meta-parameters is evaluated, and the algorithm can be tuned properly. Second, the patterns of fuel assemblies obtained from the algorithm are discussed with respect to the characteristics of the fuel assemblies, giving meaningful insights into the behavior of the algorithm and into the physics of the optimized core configuration.

In Chapter 4, the PhD candidate explores the optimization of the equilibrium cycle, i.e., the general scheme for shuffling the fuel assemblies in a nuclear power reactor core after each cycle. For the problem, a realistic core that resembles the one of the European Pressurized Water Reactor (EPR) is taken. The Genetic Algorithm (GA) and the Parallel Simulated Annealing algorithm (PSA) are used to optimize the core shuffling scheme. In addition, the PhD candidate proposes an original hybrid algorithm that relies on the combination of GA and PSA, so that more efficient searches can be performed in high-dimensional spaces, and convergence issues due to local extreme can be avoided. In this part of the work, the PhD candidate introduces novel aspects, i.e., the use of a matrix formalism to represent the management of the fuel assemblies in the core along the different cycles and the use of the Shannon entropy to monitor the convergence of the algorithms. The three algorithms are applied with two different fitness functions (FF). The first FF is used to increase the fuel cycle length by maximizing the mean burn-up, while minimizing the hot channel enthalpy rise factor and keeping the maximum burn-up below a threshold. The second FF is an extension of the first one since it also considers the neutron leakage and a limit on the hot channel enthalpy rise factor. The tests are performed for 1/4 and 1/8 symmetry of the reactor core. The results are very valuable because they demonstrate, e.g., that: 1) the algorithms can find, from a random initial core configuration, improved fuel loading patterns with respect to the reference solution, 2) the performance of the three algorithms depends on the characteristics of the specific case, and 3) the type of symmetry may play a role in searching the optimal solution. As discussed in the thesis, the design of a real equilibrium cycle takes into account a larger number of reactor parameters in comparison with the current study. However, this research shows clearly the potential of the approach to support the development of optimal equilibrium cycles.

In Chapter 5, the PhD candidate investigates the optimization of the production of molybdenum-99 (a fundamental radioisotope for medical applications) from targets of uranium-235 placed in the Polish nuclear research reactor MARIA. A simplified model for the irradiation problem is derived and verified against the solution calculated with a well-established code. In addition, models for the most cost-effective number of irradiation cycles and length of an irradiation cycle are also constructed and discussed. Then, a convenient formalism is introduced to represent the irradiation scheme, and the optimization framework developed in the work is illustrated. The framework includes a genetic algorithm whose solutions are assessed via activation calculations that rely on both reaction rates measurements from the reactor and simulations. Irradiation scenarios with 10 samples for 1 to 4 cycles in the nuclear reactor MARIA, are analyzed. The results are relevant because they show that the GA-based procedure can be effectively applied to determine an optimal number of irradiation cycles with a reduction of costs. Also, useful indications for the optimization of the irradiation scheme can be retrieved, such as the fact that the number of times the samples are shuffled has a higher impact on the problem than how the samples are shuffled.

The PhD candidate Wojciech Roman Kubiński delivered an extensive thesis of excellent quality. He developed several original contributions that were used for 4 journal publications and 4 conference papers, which confirms the scientific significance of the work. This doctoral research provides methodologies and insights that have a clear potential for improving the optimization of important nuclear engineering problems such as fuel utilization and radioisotope production in nuclear reactors. Therefore, I strongly recommend that the PhD candidate Wojciech Roman Kubiński is admitted to a public defence, and that the doctoral thesis is distinguished.

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Paolo Vinai