Massive asynchronous master-worker EA for nuclear reactor optimization: a fitness landscape perspective

Mathieu Muniglia
CEA (french Commissariat à l'Energie Atomique)
Gif-Sur-Yvette, France

Sébastien Verel
Univ. du Littoral Côte d'Opale
Calais, France

Jean-Charles Le Pallec
CEA (french Commissariat à l'Energie Atomique)
Gif-Sur-Yvette, France

Jean-Michel Do
CEA (french Commissariat à l'Energie Atomique)
Gif-Sur-Yvette, France

ABSTRACT

In the global goal to increase the part of the intermittent renewable energies in the French energy mix, the production of nuclear energy has to be adapted to face the power variations. We propose to optimize the main variables of the control rods of a nuclear power plant to improve its management, and increase the safety margins in case of a more heckled load-following schedule due to intermittent renewable energies. Using a multi-physics simulator, the criteria of interest can be computed in few minutes of computation, and we are thus facing a black-box combinatorial optimization problem with expensive evaluation. Hence, we propose a parallel asynchronous master-worker Evolutionary Algorithm scaling up to thousand computing units. From a practical optimization point of view, one main difficulty is the tuning of algorithm parameters such as mutation rates. In this work, we perform a fitness landscape analysis on this expensive real-world problem, and show that it is possible to tune the mutation parameters according to the low-cost estimation of the fitness landscape structure.

CCS CONCEPTS

•**Theory of computation → Evolutionary algorithms;** •**Applied computing** → *Physics;* •**Computing methodologies** → *Massively parallel algorithms;*

KEYWORDS

Simulation Optimization, Parallelization, Combinatorial Optimization, Fitness Landscapes

ACM Reference format:
Mathieu Muniglia, Sébastien Verel, Jean-Charles Le Pallec, and Jean-Michel Do. 2017. Massive asynchronous master-worker EA for nuclear reactor optimization: a fitness landscape perspective .
In *Proceedings of GECCO '17 Companion, Berlin, Germany, July 15-19, 2017,* 2 pages.
DOI: http://dx.doi.org/10.1145/3067695.3076061

1 INTRODUCTION

In the actual context of energetic transition, the increase of the intermittent renewable energies contribution (as wind farms or solar energy) is a major issue. On the one hand, the French government aims at increasing their part up to 30% by 2030, against 6% today. On the other hand, their intermittent production may lead to an important imbalance between production and consumption. Consequently, the other ways of production must adapt to those variations, especially nuclear energy which is the most important in France. The power variations occur at different time scales (hour, day, or even week) and in order to counterbalance their effects on the electric grid, the nuclear power plants (NPP) are already able to adjust their production. NPPs which take part in the response of the power variations operate in the so-called load-following mode. In this operating mode, the power plant is mainly controlled using control rods (neutron absorber) that may introduce unacceptable spatial perturbations in the core, especially if the power variations are large and/or fast. The purpose of this work is to optimize the manageability of the power plants to cope with a large introduction of intermittent renewable energies.

The ability of Evolutionary Algorithm (EA) to find high quality solutions is likely to depend strongly on its parameters settings. In this work, we propose a parallel master-worker EA for large scale computing environment to solve the NROO problem. Despite the expensive cost, an analysis of the mutation parameters is then proposed. Such a study is not always possible for expensive optimization problems. Hence, we achieve a fitness landscape analysis of the NROO problem using low-cost features to argue that it helps to select the relevant parameters of the mutation operator.

2 PRELIMINARIES

Evolutionary optimization for nuclear energy problems. The use of Evolutionary Algorithms (EA) in order to optimize some variables of a nuclear power plant as regards performance or safety is not new. To our best knowledge, the only optimizations of the plant operation are made online. Na *et al.* [2] develop a fuzzy model predictive control (MPC) method to design an automatic controller for thermal power control in pressurized water reactors.

Parallel evolutionary algorithms. With the increasing number of computing units, parallel EA become more and more popular to solve complex optimization problems. Usually, two main classes of types of parallel EA can be distinguished : the coarse-grained model (island model) and the fine-grained model (cellular model). Besides, a Master-Worker (M/W) architecture with the fitness evaluation on workers have been extensively used and studied.

DOI: http://dx.doi.org/10.1145/3067695.3076061

Landscape aware parameter tuning. The performance of EA strongly depends on the value of their parameters (mutation rate, population size, etc.). Parameters setting is then one of the major issues in practice for EA. Following Rice's framework [3], one can use a fitness landscape aware methodology to first extract features from the given problem instance, then select the relevant parameters according to those fitness landscape features. Fitness landscapes are a powerful metaphor to describe the structure of the search space for a local search algorithm, and peaks, valley or plateaus for instance are used to depict the shape of the search space in this picture.

3 PROBLEM DEFINITION

The optimization process is based on the current load-following transient and this analysis focuses on a single Pressurized Water Reactor (PWR) type (1300 MW) of the French nuclear fleet. When an electrical power variation occurs (demand of the grid) a chain of feedback is setting up in the whole reactor, leading to a new steady state. It is usual to take advantage of this self-regulation in the case of small variations, but the regulated variables such as the temperature or the pressure in the primary or secondary circuits may reach unacceptable values in case of load-following, possibly leading to damages of the whole system. The control rods are then used in order to cope with this variation, and maintain the primary coolant temperature close to the target. In this work the 11 integer variables which defines the control of roads are optimized.

The value of interest is determined thanks to a model of the whole reactor described in [1], and developed within the APOLLO3®calculation code. The optimization aims at minimizing this value of interest, which represents a global operating criterion, based on the control diagram. This control diagram is used by the operator to manage the power plant and represents the evolution of the relative thermal power as a function of the power axial imbalance.

4 ASYNCHRONOUS PARALLEL EA

On the one hand, the fitness evaluation duration is about 40 minutes on average with a large variance. On the other hand, a large number of computing units ($w = 3072$) are available to run the optimization algorithm, but they are only free for few hours (around 15 hours per experiment). Hence, we propose a master-worker (M/W) framework for the EA. The model of the M/W has been made asynchronous: the workers are updated on the fly without a synchronization barrier, and each worker only computes the fitness value using the multi-physic simulator. We propose then an asynchronous $(1 + \lambda)$-EA with mutation operator dedicated to integer vector tuned by the mutation per variable rate and mutation range of each variable.

5 EXPERIMENTAL ANALYSIS

First, the performance of the algorithm with a baseline parameters setting is studied with 3072 computing units during 24 hours. Then, the mutation parameters are deeply analyzed with the algorithm launched on 3072 computing units during 5 hours. At last, a fitness landscape analysis is conducted using random walks.

The Fig. 1 shows the average normalized best fitness found for each parameters setting. The best sets as regards this criterion

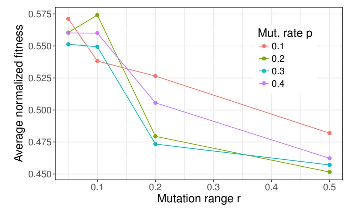

Figure 1: Average normalized best fitness as a function of the mutation parameters.

are then the ones for which the mutation range r is maximal. Inversely, the worse are the one for which the mutation range is minimal. Besides, this parameters setting found an optimal solution which reduces almost 65% of the reference fitness of current management, with only the quarter of the computation cost of the baseline settings. The Fig. 2 shows the correlation between the performance of the EA in terms of average normalized best fitness found and the feature values of the fitness landscape. The result of the real-world NROO problem with costly fitness function is in accordance with fundamental works in EA such as on the well-known NK-landscapes : the problem difficulty and the performances are correlated to the ruggedness of the fitness landscapes. In contrast to the classical result obtained on the previous fundamental works however, the more rugged the landscape, the better the performance of the parallel EA.

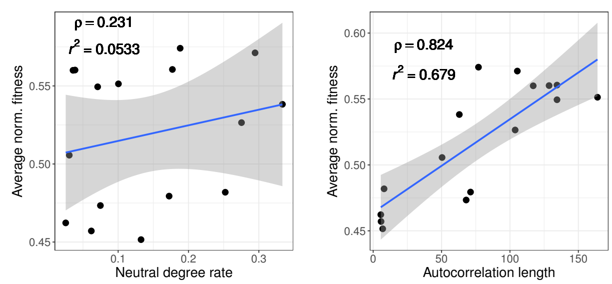

Figure 2: Scatter plots and linear regressions between the average best normalized fitness and the features of fitness landscapes.

6 CONCLUSION

In this paper, a real-world black-box combinatorial optimization problem with expensive evaluation has been studied, and to solve it, an asynchronous master-worker $(1 + \lambda)$-EA running on a massively parallel architecture was used. It has then been possible to improve of almost 65% the considered criterion, meaning that on a given load-following transient, the operation of the core keep the axial power offset almost constant. Moreover, our first result shows that a fitness landscape approach could be used to tunes the parameters.

REFERENCES

[1] M. Muniglia, J.-M. Do, J.-C. Le Pallec, H. Grard, S. V. Verel, and S. David. A multi-physics PWR model for the load following. *ICAPP*, 2016, San Francisco.
[2] M. G. Na, I. J. Hwang, and L. Y. Joon. Design of a fuzzy model predictive power controller for pressurized water reactors. *IEEE on Nuclear Science, Vol. 53 (3)*, 2006.
[3] J. R. Rice. The algorithm selection problem. *Advances in Computers*, 15:65–118, 1976.