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Offshore wind farm design with the Coral Reefs Optimization algorithm

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ABSTRACT

This paper presents a novel algorithm for wind farm design and layout optimization: the Coral Reefs Optimization algorithm (CRO). The CRO is a novel bio-inspired approach, based on the simulation of reef formation and coral reproduction. The CRO is fully described and detailed in this paper, and then applied to the design of a real offshore wind farm in northern Europe. It is shown that the CRO outperforms the results of alternative algorithms in this problem, such as Evolutionary Approaches, Differential Evolution or Harmony Search algorithms.

1. Introduction

Wind power is one of the most promising renewable energy sources in the world [1,2], pushed by the crisis of fossil fuels and the environmental concerns that their excessive use produce. Wind power installed worldwide by the end of 2011 reaches a total of 238 GW, of which about 62 GW correspond to China, 47 GW to USA, 29 GW to Germany, 21 GW to Spain and 16 GW to India [3]. Wind power penetration is rising year by year in many countries, reaching a remarkable 26% in Denmark, 16% in Spain and Portugal, 12% in Ireland, and 9% in Germany [4]. Wind energy penetration in other developed countries is smaller (USA 3.3% [5], Italy 4.2% or France 2.8% [4]), though it is known that these figures will increase a lot in the next few years.

Wind energy is mainly produced in large production facilities called *wind farms*. In the past five years, new wind energy production facilities in the world have grown about 25% each year, and the forecast for 2013 is that the annual growth rate still remains a remarkable 15%. The majority of wind farms are located in land (onshore facilities), but wind farms located in the sea (offshore) seem to be more productive, and many companies are betting on this kind of facility when geographical conditions allow its installation. In fact, recent studies have reported a significant increment in the installation of offshore wind farms over 30% with respect of previous years [6]. In Europe, these facilities have been installed for more than 20 years ago, and nowadays represent a significant part of wind energy production in countries such as Denmark, Sweden or the Netherlands [7]. In addition, other studies have shown that the potential of offshore wind energy in important economies such as China [8] or Europe [9] is much larger than its onshore counterpart. Following recent studies [7], the main advantages of offshore wind farms are the availability of huge continuous areas for developing major projects, the higher wind speeds at the sea, less effects of turbulence or the elimination of visual impact and noise issues, among others. On the other hand, there are also several disadvantages with these facilities, such as more expensive installation and connection to the electrical network or limited access for maintenance operations, etc.

The increasing number of projects focussed on the installation of new wind energy facilities, has had an immediate effect in the research about wind farms' design. Moreover, automatic wind farm design based on optimization algorithms is nowadays a hot topic in wind energy, with dozens of articles and research works published recently. In fact, the pioneering work on automatic wind farm design is due to Mosetti et al. [10], back in the 1990's. In that paper, a genetic algorithm was proposed to tackle the problem of the optimal turbines layout in a wind farm. The model proposed in Ref. [10] has served as inspiration to many other articles, for example, the works by Grady et al. [11] or Emami et al. [12], that proposed different improvements in the objective function and genetic operators to obtain better search capabilities in the algorithms. Also

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dealing with evolutionary algorithms, the work by Mora et al. [13] describes a variable-length genetic algorithm with novel procedures of crossover, that are very effective to obtain optimal wind turbines layouts, including monetary cost as the objective optimization function. A similar approach using a hybrid evolutionary algorithm was previously presented in Martínez et al. [14]. This approach has been further studied recently in Refs. [15,16]. It is also significant the work by Sisbot et al. [17], that proposed a multi-objective evolutionary algorithm for a specific problem of wind farm design in Turkey, and the works by Wang et al. [18], where new improved wind and turbine models have been considered within a genetic algorithm. Another work that deserves special consideration is the one by Kusiak et al. [19], where a complete study of the problem including very different aspects and assumptions is considered. The authors solve the problem by applying an evolutionary programming approach. Other important works have been recently proposed based on evolutionary algorithms, such as the one by Wan et al. [20] where a real-coded genetic algorithm is proposed, the work by Huang [21] based on hybrid genetic algorithms, or the work by Saavedra et al. [22], where an evolutionary approach that considers wind farm shape and orography is proposed. There are also other bio-inspired approaches (alternative to evolutionary algorithms), that have been successfully applied to the wind farm design problem, for example the paper by Wan et al. on Particle Swarm Optimization [23] and the work by Eroglu et al. based on Ant Colony Optimization [24]. An excellent review of the most significant papers focus on onshore wind farm design has been recently published by Khan and Rehman [25].

There are also other works specifically focused on the optimal design of offshore wind farms using bio-inspired techniques. For instance the works by Elkinton et al. [26–28], where a novel model for the design of offshore wind farms is presented, and several approaches were compared in this problem. A greedy algorithm, a genetic algorithm, a pattern search approach and a simulated annealing techniques were tested in this problem. The work by Rivas et al. in Refs. [29], is also relevant. In that paper the authors proposed a simulated annealing algorithm to solve a problem of optimal turbine sitting in offshore wind farms. In the work by Zhao et al. [30] the authors presented a different approach for offshore wind farm design, focussed on minimizing the connections between wind turbines, considering a fixed layout of turbines. Finally, in a quite recent paper by Pérez et al. [31], the authors have proposed a specific approach to a problem of offshore wind farm design, based on mathematical programming techniques, specifically a combination of heuristic and gradient-based algorithms, that provides a good solution to the design of a real wind farm in northern Europe.

This paper is focussed on offshore wind farm design with a new optimization technique, the Coral Reef Optimization (CRO) algorithm. The CRO is a novel bio-inspired meta-heuristic for optimization problems, based on an artificial simulation of the coral reefs' formation and reproduction processes. The CRO algorithm emulates different phases of coral reproduction and fight for space in the reef, and finally produces an efficient algorithm for solving difficult optimization problems. The proposed CRO approach can be seen as a cellular-type evolutionary scheme, with superior exploration–exploitation properties thanks to the particularities of the emulated reef structure and coral reproduction. In this work we test the performance of the CRO in the design of an offshore wind farm in northern Europe, comparing its performance with that of alternative existing bio-inspired approaches. The results obtained show that the CRO is a competitive algorithm to be considered in optimization energy-related problems.

The rest of this article is structured as follows: the next section presents the CRO algorithm in detail, including an introduction to reefs and corals' structure and reproduction and an analysis of similarities and differences with other existing meta-heuristic algorithms. Section 3 shows the performance of the CRO algorithm in the design of an offshore wind farm. Finally, Section 4 ends the paper by giving some concluding remarks.

2. The Coral Reef Optimization algorithm (CRO)

This section describes some important properties of corals and coral reefs that will be simulated by the CRO approach. In order to introduce the algorithm, some characteristics of corals and reefs are provided. Details on the CRO implementation are provided at the end of the section.

2.1. Corals and reef formation

A coral is an invertebrate animal belonging to the group *phylum-cnidaria*, which also includes sea anemones, hydras or jellyfishes [32]. In fact, a more detailed classification includes corals in the *Anthozoa* class, together with sea anemones, sea pens or sea pansies. These animals are characterized by their ability to subsist either as individuals or in colonies of polyps, living attached to a substrate. There are more than 2500 different species of corals, living in shallow and deep waters, and each year new species are found and described.

An important subclass of corals are reef-building corals, also known as *hermatypic* or simply *hard corals*. Hard corals are usually shallow-water animals that produce a rigid skeleton of calcium carbonate, segregated from their base. A coral reef is formed by hundred of hard corals, cemented together by the calcium carbonate they produce. Periodically, the polyp lifts off its basal plate of calcium carbonate and secrete a new one, forming a tiny chamber that will contribute to the coral's skeleton. All polyps in the reef build and add these chambers to the reef, so the reef will grow upwards. Living corals grow on top of the skeletons of calcium carbonate of their dead predecessors. A coral reef is usually formed by corals living in colonies, or on its own. A colony is composed of a single specie of coral, but a reef's structure can comprise multiple types of species. In fact, a coral reef finally ends up as a true ecosystem, in which a diverse collection of animals and plants interact with each other, as well as with their environment. In addition to corals, many other animals and plants live in and from the reef, such as algae, sponges, sea anemones, bryozoans, sea stars, crustaceans (e.g. shrimps, crabs, lobsters), octopuses, squids, clams, snails and other mollusca. And, of course, a huge variety of fishes that find shelter and food in the reef.

In general, hard coral species require little space to settle and grow. Although a priori the implementation of this settlement procedure might be easy for a potential new member of the reef, in practice free space is an extremely limited resource in the reef environment [33]. As a result, species often compete with each other or exhibit aggressive behavior to secure or maintain a given plot of substrate [34]. Different strategies used by corals to compete for the space have been thoroughly described in the literature [34,35]. Among them, fast-growing is deemed as the most used and simple strategy since it grounds on the fact that there are corals that have evolved to yield a faster growth rate than others. When a fast-growing coral sets near a slow-growing one, the former attacks the latter by overtopping it. The underlying coral suffers from light deficiency, thus affecting its ability to conduct photosynthesis and to get into contact with food particles. As time evolves, overtopping by fast-growing species kills the slower-growing species underneath. Other aggressive strategies carried out by some species of corals include sweeper tentacles (i.e. detect and damage adjacent coral colonies), *mesenterial* filaments (namely, enabling external