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Optimal design of submarine pipeline routes by genetic algorithm with different constraint handling techniques

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ABSTRACT

This work deals with optimization methods for the selection of submarine pipeline routes, employed to carry the oil & gas from offshore platforms. The main motives are related to the assessment of constraint-handling techniques, an important issue in the application of genetic algorithms and other nature-inspired algorithms to such complex, real-world engineering problems.

Several methods associated to the modeling and solution of the optimization problem are addressed, including: the geometrical parameterization of candidate routes; their encoding in the context of the genetic algorithm; and, especially, the incorporation into the objective function of the several design criteria involved in the route evaluation. Initially, we propose grouping the design criteria as either "soft" or "hard", according to the practical consequences of their violation. Then, the latter criteria are associated to different constraint-handling techniques: the classical static penalty function method, and more advanced techniques such as the Adaptive Penalty Method, the ε-Constrained method, and the Ho-Shimizu technique.

Case studies are presented to compare the performance of these methods, applied to actual offshore scenarios. The results indicate the importance of clearly characterizing feasible and infeasible solutions, according to the classification of design criteria as "soft" or "hard" respectively. They also indicate that the static penalty approach is not adequate, while the other techniques performed better, especially the ε-Constrained and the Ho-Shimizu methods. Finally, it is seen that the optimization tool may reduce the design time to assess an optimal route, providing accurate results, and minimizing the costs of installation and operation of submarine pipelines.

1. Introduction

Real-world engineering optimization problems are complex by nature. Their modeling may be characterized by a very large number of design variables, being defined on high-dimensional spaces, with objectives and constraints that are generally non-linear functions of the variables [1,2]. For such problems, the application of classical optimization techniques requiring gradient information faces remarkable difficulties, such as being trapped in local optima. On the other hand, nature-inspired algorithms (NIAs) such as genetic algorithms (GAs) [3,4], particle swarm optimization (PSO) [5,6] and artificial immune systems (AIS) [7,8] have the distinct advantage of being able to solve multi-objective and multi-constraint problems that gradient-type optimizers have failed to meet. In fact, those and other heuristic and non-gradient methods have been successfully applied to many engineering problems [9–16].

However, the treatment of constraints is still an important issue in the application of NIAs to engineering optimization problems. Originally, GAs and other nature-inspired meta-heuristics were designed to deal with unconstrained search spaces [17,18]; the most common approach to treat constraints was to adopt penalty functions to transform a constrained optimization problem into an unconstrained one. Presently, the study of constraint-handling techniques associated to NIAs is an important line of research [2,19,20], to guide the search process of these algorithms to feasible regions.

This issue is even more important for the particular engineering application considered in this work, related to the development of

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offshore oil exploitation activities. This task involves the use of production systems comprised by fixed or floating platforms. The oil and gas produced by these platforms are transported using pipeline systems, as illustrated in Fig. 1. They may be considerably long, crossing rough seafloor that may present several obstacles such as subsea equipment, flowlines, and other pre-existent pipelines. Also, there may be environmental, commercial or even geopolitical issues that can determine specific regions that should be avoided: regions with corals; geotechnical hazards; or fields allotted to another oil company, as usual in the offshore fields along the Brazilian coast.

Traditionally, in the oil & gas industry, the selection of a route has been manually performed by the engineer by inspection of the seabed bathymetry and the available information regarding obstacles. However, this is an iterative and very complex process, highly dependent on the expertise of the engineer, and governed by several variables following design recommendations addressed by codes such as DNV-OS-F101 [21]. Therefore, it has already been recognized [22–24] that the selection of a submarine pipeline route with good performance and low cost must indeed be formally described and treated as a synthesis and optimization problem. In this context, a previous work [25] described the initial steps taken towards the development of a computational tool for the synthesis and optimization of submarine pipeline routes. That work described the geometrical representation of a route, and some of the terms of the objective function; the treatment of constraints considered only the classical static penalty method. Subsequently, a preliminary assessment of the Adaptive Penalty Method (APM) [26,27] has been presented in [28].

Now, this work presents the implementation of the optimization tool, with special focus on the study and assessment of different, more advanced constraint-handling techniques such as the Adaptive Penalty Method (APM), the ε-Constrained method [29], and the Stochastic Ranking/Ho-Shimizu technique [30,31]. The goal is to allow the development of more efficient optimization procedures that can be employed not only for this particular real-world application, but eventually can be generalized for other complex engineering problems in general. The constraint-handling techniques could be associated to different evolutionary optimization methods, such as PSO or AIS that have been implemented in an in-house tool for the optimization of risers and mooring lines of floating production systems [32,33], but here the focus will be on GAs that have been shown to be useful for the optimization of such offshore engineering problems [34–36].

Initially, Section 2 presents a brief overview of the main characteristics of the GA as implemented in the pipeline route optimization tool. Section 3 begins by addressing some aspects of the modeling of the optimization problem – specifically, the geometric parameterization of a given candidate route, and its encoding in the context of the GA. Next, alternative formulations for the objective function are defined, and the distinction between "soft" and "hard" design criteria is introduced, initially associated to the classical penalty technique. The more advanced constraint handling methodologies are then discussed in Section 4.

The modeling of the pipeline route optimization problem is concluded in Section 5 that describes the relevant design criteria and their incorporation in the context of the aforementioned constraint-handling techniques. Case studies are presented in Section 6 to illustrate the use of the optimization tool on actual offshore scenarios, and to compare the constraint handling methodologies. Lastly, final remarks and conclusions are presented in Section 7.

2. Genetic algorithm (GA)

Genetic algorithms may be considered one of the most well-known and successful bio-inspired evolutionary algorithms. GAs are inspired on Darwin's evolution theory, involving mechanisms of natural selection, genetic recombination and mutation: the fittest individuals have higher probability of surviving and reproducing, and their descendants keep the good genetic material in the species. A detailed description of GAs can be found in many references in the literature [3,4]. In summary, each candidate solution of the optimization problem is represented by a *chromosome*. The chromosome comprises a set of *genes*, encoding the M optimization variables or parameters of the problem, using an appropriate representation such as real number or a string of bits. A *population* of solutions is represented by a set of N individuals along with its chromosomes. In general, an initial population $P_0 = \{X_1^1, X_2^1, \ldots, X_j^1, \ldots, X_N^1\}$ is randomly created, where $X_i^r = \{x_{i,1}^r, x_{i,2}^r, \ldots, x_{i,j}^r, \ldots, x_{i,M}^r\}$ is the i-th individual in the r-th generation, and $x_{i,j}^r$ is the j-th parameter of X_i^r.

Individuals are evaluated via an *objective function* that characterizes the problem, taking into account a set of *constraints*. As a result of the evaluation, they are assigned a fitness value that assesses their relative quality as a solution for the problem. During the process of evolution, the fittest individuals have higher probability to be selected for the *mating* and *reproduction* operators. Selection operators generally follow probabilistic rules, the fitness-proportional *roulette wheel* method being one of the most popular. Mating is performed with *crossover*, combining genes from different parents to produce children and generate a new population. The children inherit features from each of the parents, and may be submitted to *mutation*, which confers innovative characteristics to the individual and provide a better exploration of the search space.

In *generational* GAs, the population is updated by replacing all parents by their offspring, which are made to compete with each other. GAs may also include *elitism*, which consists in directly injecting into the new population the fittest individuals from the previous population. The process ends when a pre-defined stopping criterion is reached, and the individual with the best fitness is then defined as the solution of the optimization problem.

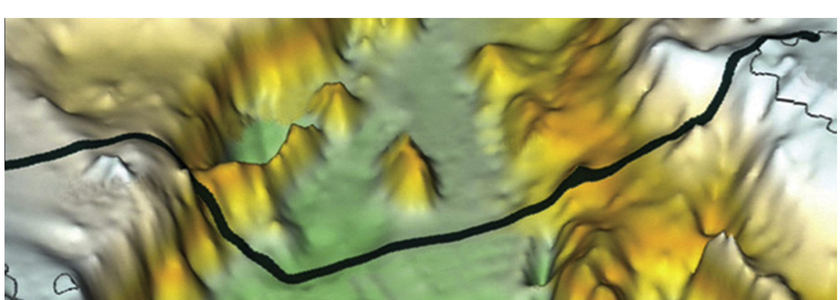

Fig. 1. Submarine pipeline.