Application of the Particle Swarm Optimization Method on the Optimization of Mooring Systems for Offshore Oil Exploitation

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Abstract
There are several methods inspired on nature for solving optimization problems. One of these methods is the Particle Swarm Optimization. This paper presents an application of this optimization tool in mooring systems for floating platforms used for offshore oil exploitation, following security criteria established by design rules. The objective is to find the minimum offsets for these platforms, taking the radius of the mooring system and the azimuth of the lines as project variables. Results of typical systems are presented, indicating that the method is effective. In order to facilitate the installation of mooring systems in a real case, the optimized radius of lines located at the same corner should be equal. For this purpose, the grouping of the mooring lines per corner is taken into account in the optimization process. This work also discusses the maximum velocity influence of the particles at the evolution and efficiency of the optimization algorithm.

Keywords: Optimization, PSO, Offshore, Mooring System.

1. Introduction
Oil demand has increased and oil exploration has advanced to deeper water. In this scenario, it is necessary to use anchored floating platforms. Then, the conditions of platform design and operation have become more and more complex and critic, time shorter and costs higher. This leads to search for optimization tools that provide safety and efficiency in offshore projects.

Traditionally, anchored offshore systems have a symmetric configuration of mooring lines. This paper aims at showing that the system can be more efficient in terms of vessel offset if both the radii and azimuth of the lines are variable.

The offset analysis can be computationally expensive, so the use of an optimization tool that results in a shorter time is highly indicated. The evolutionary algorithms have a high potential as a technique of computing to solve complex problems [1].

Through comparative studies [2], the PSO (Particle Swarm Optimization) was the one that presented the best results, being chosen to implement this system differently from the evolutionary algorithm used by [3] [4]. Once this is an initial phase of the project, static analysis was applied so as to verify the method’s effectiveness.

2. Anchorage System
The mooring lines connect the floating unit to the seabed so that it can remain fixed in the same location. To provide the necessary restoring force, the lines are arranged in catenary (conventional anchorage) or used as taut lines or tendons.

The anchoring system enables the floating unit to retain their position at sea, and therefore, it is of fundamental importance to safety and operation of the platform [5].

The radius of the traditional anchorage becomes impracticable and the offset too large as oil explorations advances to deep water. In this scenario, the anchorage radius and the platform offset should be reduced, but high level of security should be ensured throughout the system.

Several factors influence the anchoring system such as anchor type, materials that make up the lines, seafloor pattern, ship type and environmental conditions. The mooring lines can generally be composed of different materials with different physical and mechanical properties.

In this paper, the lengths of lines are grouped by corner and the azimuth between the lines and averaged line tension were considered as the variables to be optimized.

Unlike [3], the floating unit was kept fixed at the project site and anchoring variable to reach the optimal point to keep the vessel on the location with the smallest offset possible.

The mooring system is usually inexpensive compared to other systems components of a platform for offshore oil exploration. Regarding costs, therefore, the length of the lines is not representative, being directed mainly to the offset and vessel safety.
3. Particle Swarm Optimization

3.1. General Concepts
The Particle Swarm Optimization method was developed by Kennedy and Eberhart [6] from the mathematical model that implements a metaphor of the social behavior of a group of birds looking for food or a place to build the nest. This method is a stochastic computational technique based on the work of biologist Frank Heppner.

According to [7], each particle is treated as a point within the search space, which sets its own "flying" according to its own experience and the experience of other particles. The basic PSO algorithm consists of three steps: i) generation of positions and velocities particle; ii) update of velocity and iii) update of position.

First, the positions \(x_i^0\), and velocities \(v_i^0\), of the initial particle swarm, are randomly generated using the maximum and minimum limits of the variable values \(x_{\text{max}}\) and \(x_{\text{min}}\), as expressed in Eq.(1), Eq.(2). The positions and velocities are given in vector format with superscripts and subscripts denoting the \(i^{th}\) particle at time \(k\). In the Eq.(1), Eq.(2) \(\text{rand}\) is an random variable of uniform distribution, which may take any value between 0 and 1.

\[
x_i^0 = x_{\text{min}} + \text{rand}(x_{\text{max}} - x_{\text{min}}) \\
v_i^0 = \frac{x_{\text{min}} + \text{rand}(x_{\text{max}} - x_{\text{min}})}{\Delta t} = \frac{\text{position}}{\text{time}}
\]

The time interval \(\Delta t\) is substituted for iterations, receiving unitary value. It can be a scale value to increase the influence of the particle memory and swarm on the current movement.

The second step is to update the velocities of the particles in time \(k + 1\) using the fitness values that are functions of the positions of the particles in time \(k\). The current movement of the particles, the history of the particle and the swarm influence are the three values that affect the new search direction. As these values are incorporated by sum, shown in Eq.(3), with three weighing factors: inertia factor \(w\), which can be fixed, linear or variable [8], an individuality factor \(c_1\) and an identity group factor \(c_2\). The term \(p^i\) indicates the best particle position through time and \(p^g\) is the particle with the best global value of the current swarm.

\[
v_{i,k+1} = w v_{i,k} + c_1 \text{rand} \left( \frac{p^i - x_i^k}{\Delta t} \right) + c_2 \text{rand} \left( \frac{p_g^k - x_i^k}{\Delta t} \right)
\]

The last step in each iteration is update position. It is updated using its velocity vector as shown in Eq(4).

\[
x_i^{k+1} = x_i^k + v_{i,k+1} \Delta t
\]

The three steps, velocity update, positions update and fitness calculation, are repeated until the desired convergence criterion is reached.

In the classical PSO algorithm, the variable can assume any value, even outside its limits restriction. This phenomenon may lead to divergence. To avoid this problem in the present work, when the variables violate their minimum or maximum limits, they are artificially brought back to the limits by the cancellation of the current movement term.

\[
v_{i,k+1} = c_1 \text{rand} \left( \frac{p^i - x_i^k}{\Delta t} \right) + c_2 \text{rand} \left( \frac{p_g^k - x_i^k}{\Delta t} \right)
\]

3.2. Social Attraction
The Social Attraction [2] was developed to make space exploration more comprehensive, because through experiments it was found that there is a swarm tendency to migrate more quickly to the region's best point obtained so far.

This term is similar to the one coined by [9]; however, [9] uses a randomly chosen particle while the Social Attraction uses "mass center". Where each particle’s mass is represented by the function value in the point. Eq.(6) shows the term that represents the Social Attraction included in the code.

\[
c_3 \text{rand} \left( \frac{C - x_i^k}{\Delta t} \right)
\]

Where,

\[
C = \frac{\sum_{i=1}^{N} f_i x_i^k}{\sum_{i=1}^{N} f_i}
\]
4. Models Description and Methodology
Two models were used to test the algorithm. Both were modeled in SITUA/PROSIM software and were analyzed in terms of maximum mooring lines tension and minimum offset distance. This values were compared to safety standards. The objective was to seek a minimum platform offset maintained maximum mooring lines tension between safety limits. The anchorage radius and lines azimuths were used as design variables.

4.1. Free Variables
There are three free variables chosen to anchorage system optimization: anchorage radius, average mooring lines pretension and lines azimuth.

The anchorage radius had an allowed variation between 1500 m to 3000 m in model P1, while in model P2 this variation was between 200 m to 2000 m. The azimuth allowed variation for each corner was between $-10^\circ$ to $10^\circ$ in model P1 and $-5^\circ$ to $5^\circ$ in model P2; and the variation for mooring line pretension was between 1000 kN and 6000 kN for both models.

4.2. Objective Function
The objective function used is the vessel offset, which should be the minimal. The expression used for this purpose is shown below in Eq.(8).

$$f = e^{\frac{\text{offset}}{\text{depth}}}$$  \hspace{1cm} (8)

Where,

- offset is the largest vessel offset in meters, among the eight directions analyzed.
- depth is the depth in meters, in the location analyzed.
- $k$ is an adjustment factor, chosen to magnify the objective function variation range. After tests $k = 8$ was chosen.

Figure 1 show the graph of the objective function with variations of the factor $k$ and offset value. Offsets obtained in executions were between 0.1 and 0.3.

![Figure 1: Objective function with variation of the factor $k$](image)

4.3. Penalties
It was applied two penalties functions associated to line traction shown in Eq.(9) and Eq.(10).

$$\text{Pen03} = \begin{cases} \frac{\text{offset}}{\text{MBL}}, & \text{se } \frac{\text{TracMax}}{\text{MBL}} \leq 0.3 \\ 0, & \text{se } \frac{\text{TracMax}}{\text{MBL}} > 0.3 \end{cases}$$  \hspace{1cm} (9)

And
\[ Pen_{0.5} = \begin{cases} \frac{TracMax}{MBL}^{0.5}, & \text{se} \, \frac{TracMax}{MBL} \geq 0.5 \\ 0, & \text{se} \, \frac{TracMax}{MBL} < 0.5 \end{cases} \]  \tag{10} \]

Where, 

*TracMax* is the traction of the line most requested among all lines and all directions examined. 

*MBL* is the Maximum Breaking Load.

In this way, the penalized objective function is described as follows:

\[ f_{obj} = \frac{1}{f + Pen_{0.5} + Pen_{0.5}} \]  \tag{11} \]

Thus, the higher the objective function value, the smaller the platform offset.

4.4. Models Used

The models used for analysis were named P1 and P2.

Model P1 is simple, asymmetric and composed of eight mooring lines, with initial symmetrical arrangement. It has five risers with asymmetrical arrangement, all facing north. The deep water is 2400 m.

The model P2 is composed of 20 mooring lines arranged symmetrically and 19 risers. This model is more complex and real than P1. Its deep water is 1800 m.

4.5. Environmental Data

Environmental loads of wind and currents were applied to both models, that was made only static analysis. The current loads were applied to eight directions with recurrence periods of 100 years. As for wind load a recurrence of 10 years was used.

4.6. Analysis Program

Both models were modeled and analyzed with the program SITUA / Prosim [10].

The simple solution to reduce the vessel offset is to reduce the radius of anchoring and increase lines traction. However, [5] recommends that the line traction, does not exceed 50% of the rupture traction (MBL) when static analysis is used. Moreover, the traction should not be less than 30% of the rupture traction of the line (MBL), due to operational characteristics of the line. A program called PROGOTIM was developed and used, in conjunction with SITUA/PROSIM, to implement PSO and execute a number of experiments with the two models. The chosen stopping criterion, in the experiments, was the average of fitness value greater than or equal to 95% of the best individual for three consecutive generations.

4. Results Obtained

4.1. Model P1

Table 1 shows the variables of the original and optimized models.

<table>
<thead>
<tr>
<th>#</th>
<th>Original Model</th>
<th>Optimized Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>Radius (m)</td>
<td>Azim (°)</td>
</tr>
<tr>
<td>Line 1</td>
<td>3950.0</td>
<td>305.0</td>
</tr>
<tr>
<td>Line 2</td>
<td>3950.0</td>
<td>325.0</td>
</tr>
<tr>
<td>Line 3</td>
<td>3950.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Line 4</td>
<td>3950.0</td>
<td>55.0</td>
</tr>
<tr>
<td>Line 5</td>
<td>3950.0</td>
<td>125.0</td>
</tr>
<tr>
<td>Line 6</td>
<td>3950.0</td>
<td>145.0</td>
</tr>
<tr>
<td>Line 7</td>
<td>3950.0</td>
<td>215.0</td>
</tr>
<tr>
<td>Line 8</td>
<td>3950.0</td>
<td>235.0</td>
</tr>
</tbody>
</table>

Table 2 presents the degree of efficiency (maximum offset) between the original model and optimized.
Table 2: Maximum offset of the original model P1 and optimized

<table>
<thead>
<tr>
<th></th>
<th>Maximum Offset (m)</th>
<th>Maximum Offset (% water depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Optimized</td>
</tr>
<tr>
<td></td>
<td>319.0</td>
<td>226.0</td>
</tr>
</tbody>
</table>

Figure 2 shows the comparison of the offset diagrams of the original model P1 and optimized.

![Figure 2](image1)

(a) Original Model  
(b) Optimized Model

Figure 2 – Offset Diagrams of original model P1 and the optimized model.

Figure 3 presents the comparison between the overview of the original model P1 and optimized one. Green represents the mooring lines and blue represents the risers.

![Figure 3](image2)

(a) Original Model  
(b) Optimized Model

Figure 3 – Overview of original model P1 and optimized.

This optimized model presented the more pulled line with 49.7% of the line MBL. The stopping criterion was
reached in the 18\textsuperscript{th} generation and the total time analysis was 1 hour. A computer with a Pentium D 3GHz processor and 1GB RAM was used.

4.2. Model P2

Table 3 shows the free variables of the original and the optimized models.

Table 3: Comparison between original and optimized model P1

<table>
<thead>
<tr>
<th>#</th>
<th>Line</th>
<th>Original Model</th>
<th>Optimized Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Radius (m)</td>
<td>Azim (°)</td>
</tr>
<tr>
<td>1</td>
<td>Line 1</td>
<td>1413.7</td>
<td>32.5</td>
</tr>
<tr>
<td>2</td>
<td>Line 2</td>
<td>1413.7</td>
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<td>Line 12</td>
<td>1413.7</td>
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<td>Line 14</td>
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<td>Line 15</td>
<td>1413.7</td>
<td>232.7</td>
</tr>
<tr>
<td>16</td>
<td>Line 16</td>
<td>1413.7</td>
<td>308.2</td>
</tr>
<tr>
<td>17</td>
<td>Line 17</td>
<td>1413.7</td>
<td>313.1</td>
</tr>
<tr>
<td>18</td>
<td>Line 18</td>
<td>1413.7</td>
<td>318.1</td>
</tr>
<tr>
<td>19</td>
<td>Line 19</td>
<td>1413.7</td>
<td>323.1</td>
</tr>
<tr>
<td>20</td>
<td>Line 20</td>
<td>1413.7</td>
<td>328.1</td>
</tr>
</tbody>
</table>

Table 4 presents the degree of efficiency (maximum offset) between the original model and the optimized model.

Table 4: Maximum offset of the original model P2 and the optimized

<table>
<thead>
<tr>
<th>Maximum Offset (m)</th>
<th>Maximum Offset (% water depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>Optimized</td>
</tr>
<tr>
<td>239.0</td>
<td>95.0</td>
</tr>
<tr>
<td>13.3</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Figure 4 shows the comparison between offset diagrams of the original model P2 and the optimized.

![Figure 4 - Original Model vs. Optimized Model](image)

Figure 4 – Offset Diagrams of original model P2 and optimized.

Figure 5 presents the comparison overview of the original model P2 and the optimized model. Green represents the mooring lines and blue represents the risers.

![Figure 5 - Overview of Original Model vs. Optimized Model](image)

Figure 5 – Overview of original model P2 and optimized.

This optimized model presented the more pulled line with 50.0% of the line MBL. The stopping criterion was not reached and the execution stopped at the allowed maximum number of generations 30. The total time analysis was 2 hours. A computer with a Pentium D 3GHz processor and 1GB RAM was used.

5. Maximum Velocity Influence of the Particles

In this paper, a case study about the maximum velocity influence of the particles was made. Only the model P1 was used to this analysis. It was made 10 executions for each case and the Trelea type 1 [11] coefficients were used. The results can be seen in Table 5.
Table 5: Results of the maximum velocity influence of the particles

<table>
<thead>
<tr>
<th>Maximum Velocity (% range)</th>
<th>Average Generations</th>
<th>Average Fitness of the Best Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>11.0</td>
<td>0.80</td>
</tr>
<tr>
<td>20</td>
<td>8.2</td>
<td>0.81</td>
</tr>
<tr>
<td>50</td>
<td>10.6</td>
<td>0.83</td>
</tr>
<tr>
<td>100</td>
<td>9.7</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Note that using the Trelea type 1 coefficients there is no significant variation in both the average of the generations as the average of the best particle.

6. Conclusion

Based on the results, it seems that the application of optimization using evolutionary algorithms, especially the method of the Particle Swarm in offshore mooring systems, is effective and robust. It can also bring greater security to the designer in obtaining appropriate values for the vessel offset and the mooring lines tractions. It is known that more optimized and efficient anchorage projects can also collaborate in developing the system design of risers, which can be benefited by smaller offsets. However, it is known that to obtain a tool that can be applied to real projects, the variation of material type of segments lines as well as the dynamics analysis should be included in the optimization process. This can increase the computational cost and complicate the application of this method, requiring new developments to fulfill this aspect.

Another important aspect is that using the coefficients of Trelea type 1, the maximum velocities of the particles has little influence on the convergence as well as the fitness of the best particle.

References