# Layout determination of a Marine Fuel Terminal via Minimization of Risk to the General Public using Monte Carlo and Simulated Annealing Techniques

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## 1. INTRODUCTION

Given the current conjuncture of the Brazilian industrial development boosted by the discoveries of new reserves of oil and gas in the continental shelf, the implementation of new oil & gas enterprises have become frequent and essential to support the expansion of the infrastructure and diversification of the Brazilian energy matrix. In this category one may include new refineries, fuel and LPG distribution terminals, petrochemical and fertilizer plants, gas treatment units, among others, which were implanted recently in the country or are planned to be built soon.

Since these process facilities store substantial inventories of flammable and/or toxic fluid products, companies and environmental agencies are always concerned to avoid accidental releases (spillages) which may cause damages to the surrounding communities and the environment [1]. This is a global concern since the 70's due to the drastic repercussions of the accidents of Seveso, Italy (1976) and Bhopal, India (1984) [2]. In this context, the European Union issued Seveso I and II Directives, respectively in 1982 and 1996, for preventing accidents with dangerous inventories, as well as mitigating their consequences. Beside this, in addition to HSE issues, there is also the interest of avoiding accidents because they can result in severe financial losses, either due to operational discontinuity or damage to company image (a critical asset in nowadays globalized world) [1] [2] [3] [4].

In consonance with this scenario, this work developed a computational methodology, written in MATLAB R12 and based on the Monte Carlo (MC) method [5] [6] and the Simulated Annealing (SA) [7] [8] [9] techniques, to optimally locate tankage units in the plant area (layout) of a hypothetic Marine Fuel Terminal in order to minimize the potential damage to neighbor populations in the case of possible plant accidents. This is an example of the so-called Facility Layout Problem – FLP [10] [11] with focus on assess the minimization of risks to residential areas that already exist or would be located in their surroundings in the future.

An objective was constructed such that its numerical optimization corresponds to the minimization of the consequences – Hazard Ranges (HR) – to which the neighbour populations may be exposed in the eventuality of possible plant accidents. The numerical evaluation of the aforementioned HR objective is conducted with a MC algorithm, because it demands numerical estimation of several irregular, tortuous, non-convex, not necessarily contiguous, not necessarily disjoints or connected, areas. A variant SA strategy was developed and successfully used for numerical minimization of the HR objective.

## 2. OBJECTIVE

The main objective of this work consists in developing a computational methodology based on the use of the Monte Carlo (MC) method and a variant of the heuristic optimization method known as Simulated Annealing (SA) in order to:

1. Determine the optimal location of the tankage units inside the layout of the Marine Fuel Terminal being assessed in order to minimize the potential damage to neighbor populations due to accidents that may occur at this industrial facility which stores and manipulates large quantities of dangerous fluids;
2. Try to avoid future demands for additional risk mitigation measures, acting preventively at the first stages of the project design, specifically during the definition of the spatial arrangement of the plant;
3. Stimulate the concerning about the variable "Risk to General Public" (RGP) during the design of industrial plants.

The efficiency of this methodology has been shown through a case study of a given Marine Fuel Terminal presented in the next item.

## 3. METHODOLOGY

By definition, risk is basically evaluated considering three key factors: possible accidental events (e), the frequency (f) of each event (probability) and the consequences (c) which can arise from them. Specifically, the consequences refer to the potential of damage to people living next to the industrial installation resulting from these events, which mathematically are represented by (effect) distances associated with a given level of radiation, overpressure or toxic concentration, depending on the nature of the substance released [12] [13] [14].

Given the above, it is important to emphasize that this work focuses only on the reduction of the risk by minimizing the intersection of Population Polygon (PP) near to the Terminal with the so called Area of Interest (AI), i.e., the area covered by the accidental effect distances (consequences) related to each tankage unit which exceeds the limits of the industrial plant. This way, the reduction in frequency was not explored in this study.

In this context, firstly it will be presented the features of the hypothetic Marine Terminal being studied, following by the assumptions regarding the algorithm applied to minimize the risks to its neighbor population.

### *3.1 Marine Terminal*

The hypothetic Marine Terminal being investigated consists of six different tankage units, which respectively will store Crude Oil, Gasoline, Diesel Oil, Jet Fuel, Lubricants and Slop (that will be received from ships). Its location and area have been pre-established for logistics reasons and also due to its proximity to the consumer market, such that it is not possible to move the whole facility to another place (nevertheless, changing the location of each tankage unit inside its layout is not impeditive). Furthermore, its initial layout, which was pre-defined by designers and used as a starting point for the calculations, is presented in Figure 1.

Regarding the classification of the flammable substances which will be stored in the Terminal, according to the assumptions established by the Reference Manual BEVI Risk Assessments [15], products belonging to the categories 3 or 4 are not considered as flammable. It means that this kind of substances do not represent potential hazards to the general public living next to the Terminal and therefore must not be included in the analysis.

Thus, the consequences associated with “lubricants” and “slop” were assumed to be negligible, since these substances are classified as category 4. The classification of all the products stored in the Marine Terminal, as well as the features related to each tankage unit (such as operational conditions, inventory, number of tanks and area) are presented in the Tables 1 and 2, respectively.

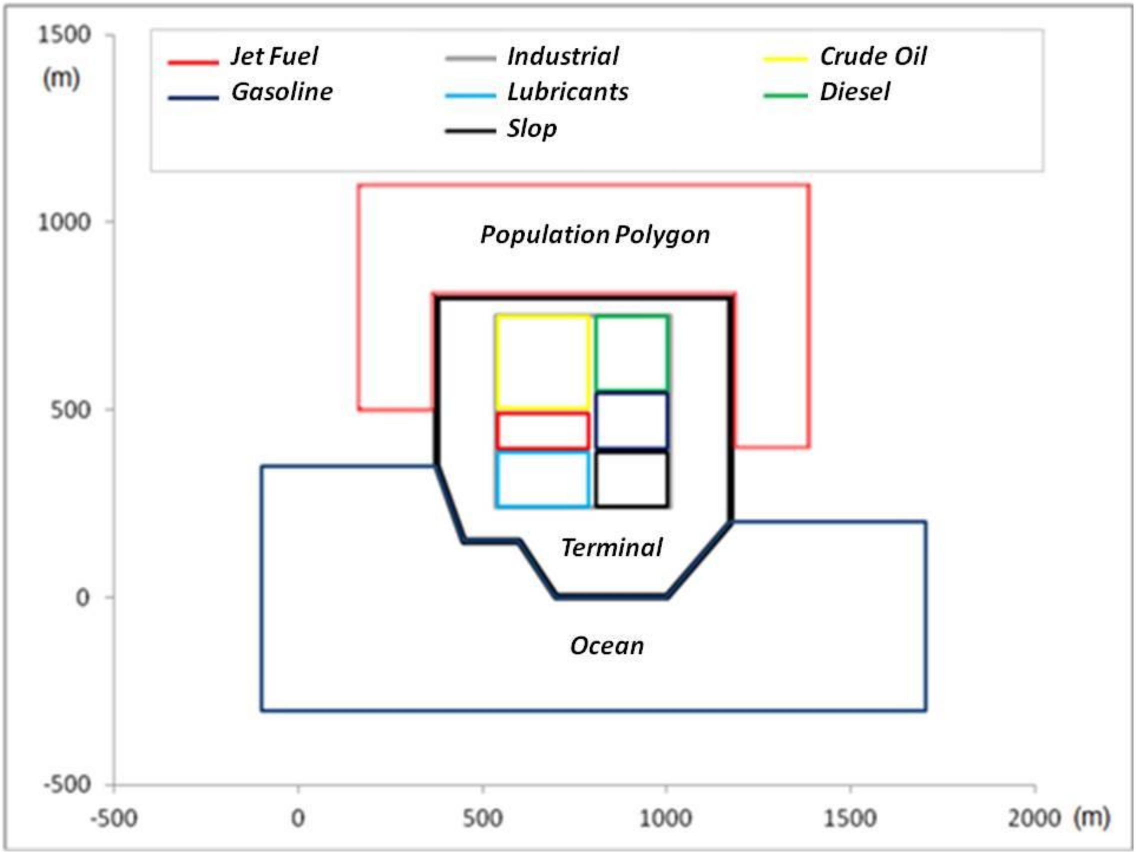


Figura 1 - Hypothetic Marine Terminal.

Table 1. Classification of the substances hypothetically stored in the Terminal.

| Product | Data | Classification |
|---|---|---|
| Crude Oil | Flash point = 7 ºC | Category 1 |
| Jet Fuel | Flash point = 40 ºC | Category 2 |
| Lubricants | Flash point > 150 ºC | Category 4 |
| Diesel Oil | Flash point = 38 ºC | Category 2 |
| Gasoline | Flash point = -43 ºC | Category 1 |
| Slop | - | Category 4 |

Table 2. Characteristics of the hypothetical storage units.

| Unit | Inventory per tank | Number of tanks | Operational conditions | Bund Area |
|---|---|---|---|---|
| Crude Oil | 65,000 $m^3$ | 6 | | 62,500 $m^2$ |
| Jet Fuel | 20,000 $m^3$ | 3 | | 25,000 $m^2$ |
| Lubricants | 20,000 $m^3$ | 6 | T = 25 ºC | 37,500 $m^2$ |
| Diesel Oil | 30,000 $m^3$ | 4 | P = 1 atm | 40,000 $m^2$ |
| Gasoline | 20,000 $m^3$ | 4 | | 30,000 $m^2$ |
| Slop | 10,000 $m^3$ | 6 | | 30,000 $m^2$ |

In order to perform the consequence calculations, it was used the software EFFECTS 9.0.13, developed by The Netherlands Organization [16]. By the adoption of the generic meteorological data suggested by CETESB [17] and presented in Table 3, the consequence results for each tankage unit showed in Table 4 were obtained. It is important to inform that only the hypothesis related to the catastrophic rupture of the tanks was considered, since it will result in the larger damage distances (worst case) [18]. Escalation was not taken into account. As a final point, in order to perform the layout optimization in MATLAB via the SA algorithm, only the largest values obtained for the storage units were respectively adopted as representative damage distances for each of them. These values are presented in bold in Table 4.

Table 3. Generic Meteorological Data published by CETESB.

| Parameter | Day period | Night period |
|---|---|---|
| Wind speed | 3.0 m/s | 2.0 m/s |
| Ambient relative humidity | 80% | 80% |
| Ambient temperature | 25 ºC | 20 ºC |
| Pasquill stability class | C | E |
| Soil temperature | 30 ºC | 20 ºC |
| Roughness of the terrain | 0.17 | 0.17 |

Table 4. Consequence results per typology of incidental events.

| Storage unit | Distances (day / night) | | | | | |
|---|---|---|---|---|---|---|
| | Pool Fire (9,83 $kW/m^2$)[1] | | Flashfire (LFL) | | Explosion (0,1 bar)[2] | |
| Crude Oil | **340 m** | 330 m | - | - | - | - |
| Diesel Oil | **300 m** | 293 m | - | - | - | - |
| Gasoline | **260 m** | 240 m | - | 208 m | - | 168 m |
| Jet Fuel | **240 m** | 238 m | - | - | - | - |
| Lubricants | - | - | - | - | - | - |
| Slop | - | - | - | - | - | - |

## 3.2 *Layout optimization*

The layout optimization is based on the minimization of the area defined by the damage distances which extrapolate the facility limits (so-called “Area of Interest” – AI) and potentially can reach the populations situated near to it (Population Polygons - PP) through the random movements of the storage units within the available industrial area.

Therefore, in order to calculate the Area of Interest (AI) and its intersection with the Population Polygon (PP), it was proposed an algorithm based on the MC method. Figures 2 and 3 illustrate a generic example of an industrial plant and the use of MC random sampling for estimating these areas numerically.

[1] It was adopted the Probit equation proposed by Purple Book (TNO) to estimate the damage due to thermal radiation [19] [20].

[2] Overpressure calculation was performed using the Multi-Energy method (curve 5) [16] [20].

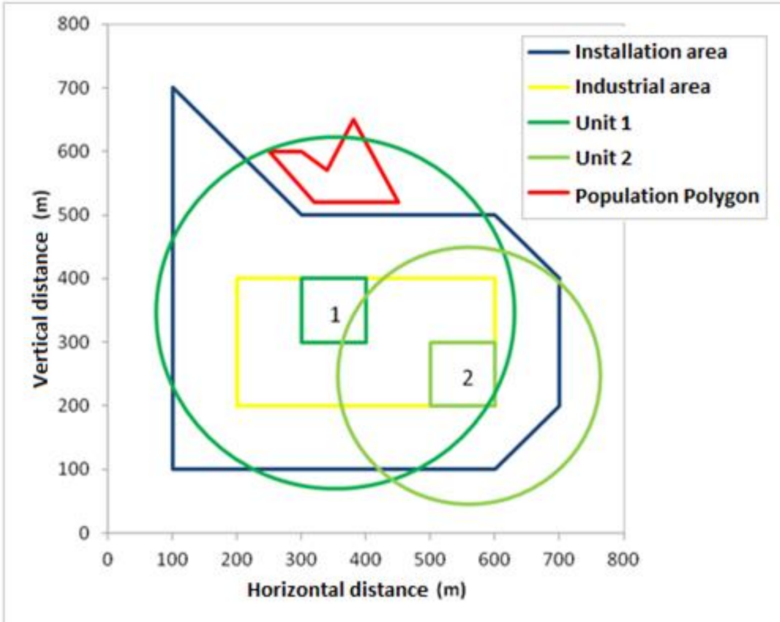


Figure 2. Generic Installation with its accidental effect distances - example.

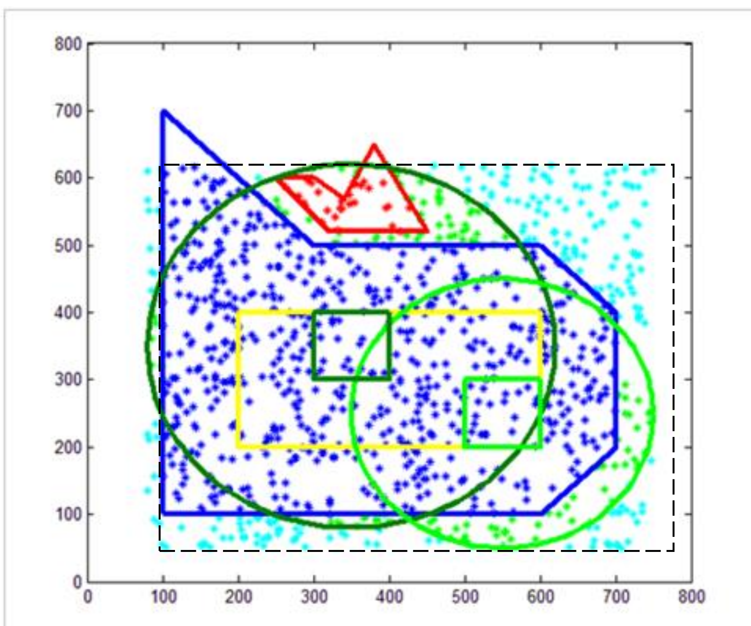


Figure 3. Application of MC procedure for calculating AI and its intersection with PP (red points).

Basically, the principle applied in Figure 3 is that the area of each relevant closed region of the map – no matter how tortuous its boundary can be – is proportional to the number of points randomly sampled by the MC routine which lie in its interior. In order to facilitate its visualization, the MC points belonging to each specific region are plotted with the same color. For example, the intersection area ($A_R$) between PP and AI is equal to the fraction of the total rectangular area of sampling ($A_{ret}$) given by the number of MC points painted in red ($n_R$) divided by the total number ($n_T$) of MC points, according to the Eq. (1):

$$A_R = \frac{n_R}{n_T} A_{ret} \tag{1}$$

The exposure of the general public to the consequences is modelled as a monotonously increasing function of the intersection area between AI and PP calculated as above. This function defines a HR objective to be minimized in order to achieve the best plant layout.

Additionally, it is important to mention that the area which belongs to the AI but does not belong to PP is also considered in the objective function (see Eq. (2)), since in the future this land can be occupied by population as well. However, it is weighted by a lower factor when compared to the already populated area. Regarding the ocean, as no permanent population is considered to exist on it, its factor was established as zero. In this context, the HR objective function (FOB) is defined as follows:

$$FOB = \left\{ \left[ \sum_{i=1}^{numpop} \left( factor_i . npop_i \right) + factor_{comp} . \left( narea_{\text{int}} - \sum_{i=1}^{npop} npop_i \right) \right] / \, ntotal \right\} . area\_ret$$

(2)

Where:

| | |
|---|---|
| *numpop* | Number of populated areas which exist near to the facility. |
| $factor_i$ | Weighting factor for each population polygon “i” (proportional to its population density). |
| $npop_i$ | Number of points situated inside each population polygon “i”. |
| $factor_{co}$ | Weighting factor for the part of the Area of Interest which is outside the population |
| $narea_{int}$ | Number of points situated inside the Area of Interest. |
| *ntotal* | Total number of points radomly generated using MC. |
| *area_re* | Retangular area where all the points were sampled (defined by the dotted lines in Figure |

As stated before, the minimization of the HR objective was accomplished by a sequence of random movements of the units throughout the available Industrial Area using a SA variant algorithm. During the search, either one unit is randomly chosen and moved per iteration, or two units are selected at the same time and their positions are changed between each other (unit 1 occupy the current unit 2 position, and vice versa).

As illustrated in Figure 4, two types of movements are allowed when only one unit is chosen per iteration: rotation and translation [21]. However, if a unit is moved to a position outside the pre-established Industrial Area, the algorithm automatically will move it back to the nearest position inside it (as shown in the same picture).

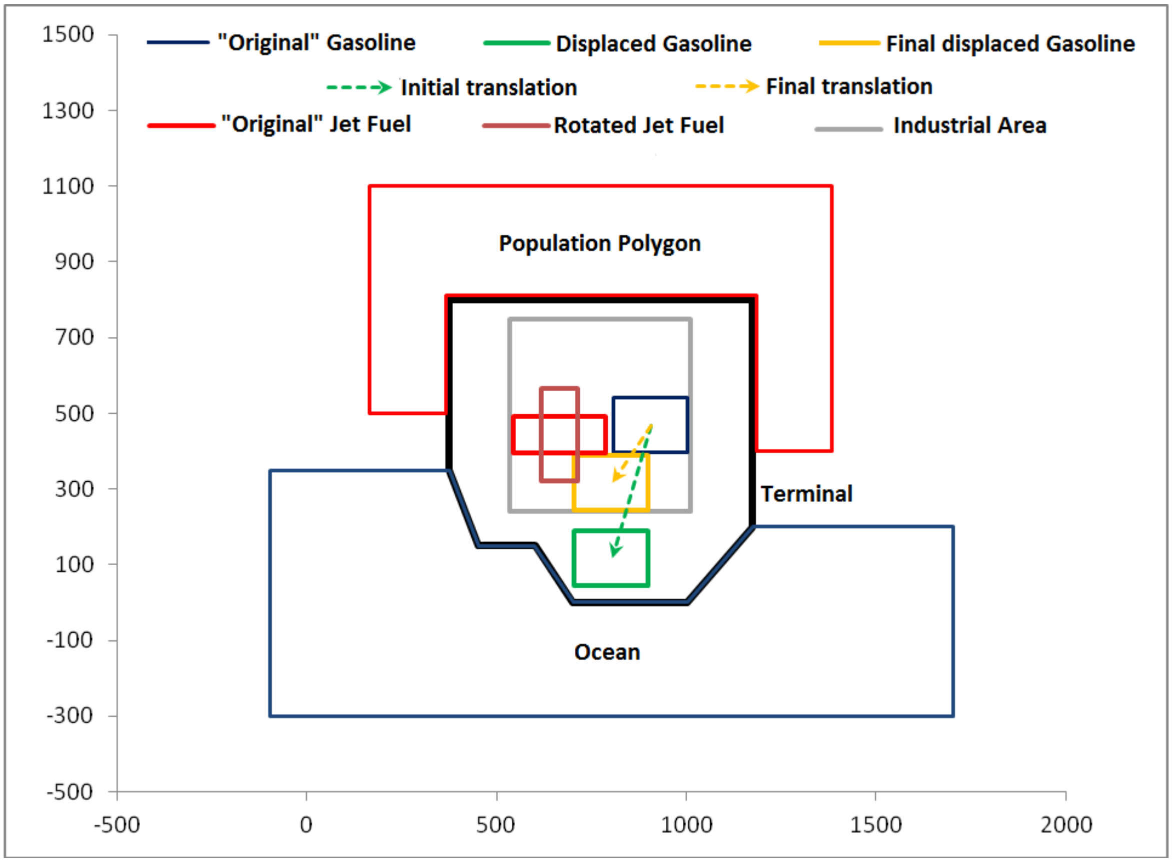

Figure 4. Examples of rotation (Jet Fuel) and translation (Gasoline) movements.

Furthermore, it is important to mention that there is the possibility of overlapping units during the movements cited before, since only one (or two) of them are moved per iteration. Even though this is acceptable during the optimization process (since the higher the entropy generated, the greater the chance that the global optimum is reached) [22], the final layout must not present superposed units, because it is physically impossible.

In this context, a new term was added to the HR objective FOB in order to penalize the overlapping units, according to Eq. (3). The weight factor used for this term is greater (one order of magnitude higher) than the empirical factors previously proposed in Eq. (2), since superposed units are unacceptable in the final layout.

$$FOB_{final} = FOB + factor_{ovl} \sum areas\_unids_{ovl} \tag{3}$$

Where:

| | |
|---|---|
| *FOB* | Objective function previously shown in equation 2. |
| $Factor_{ovl}$ | Weighting factor for the areas of the units which are overlapped. |
| $Areas\_unids_{ovl}$ | Areas of the units which are overlapped. |

By last, a SA algorithm was proposed to execute the minimization of the function defined by Eq. (3), such that the optimal layout (presented in the following section) corresponds to the configuration with the lower objective value.

## 4. RESULTS AND DISCUSSION

Figure 5 shows a representation in MATLAB of the initial layout of the Marine Terminal and its surrounding features (population polygon and ocean, as shown in Figure 1) which was used as the start point in the optimization process. The circles represent the accidental effect distances considered in this analysis, whose values are highlighted in Table 4.

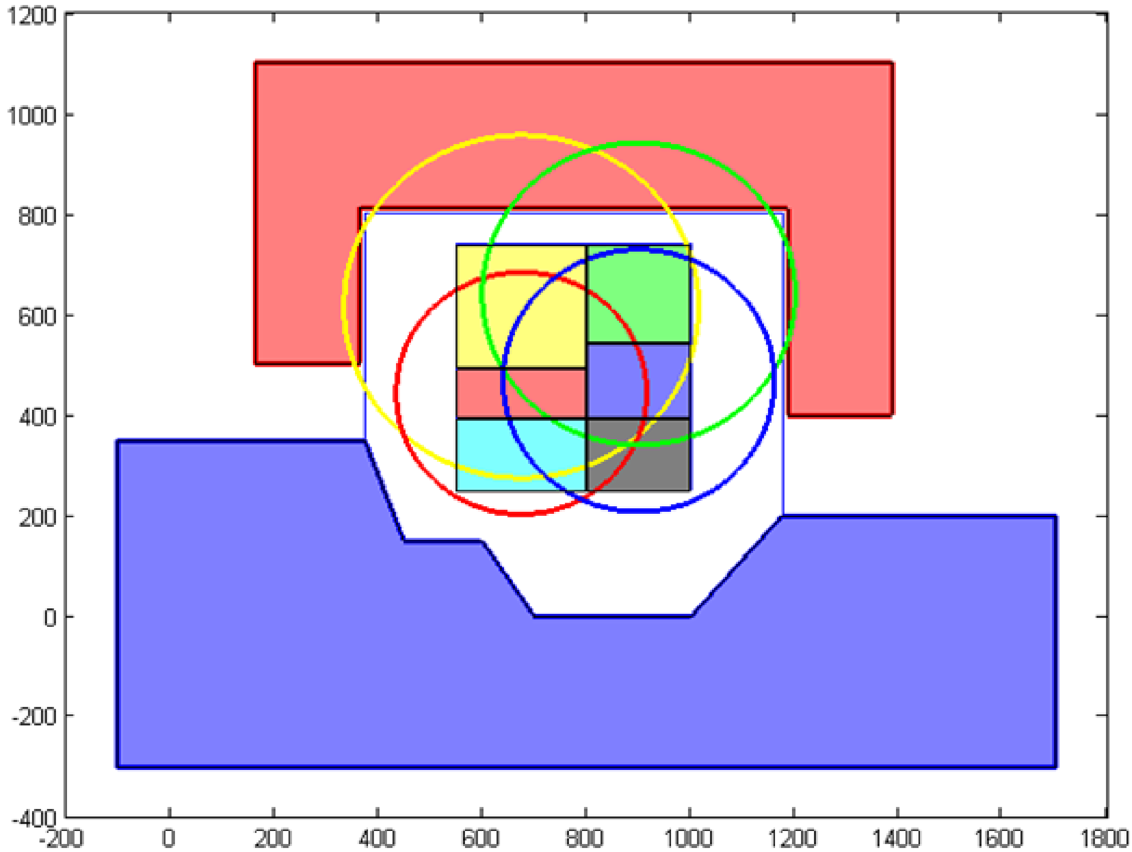


Figure 5. Representation of the initial layout of the Marine Terminal using MATLAB.

Through the application of SA algorithm as cited before, it was obtained the optimized layout presented in Figure 6. The coordinates of the centres of the units related to the initial and the final layouts are shown in Table 5.

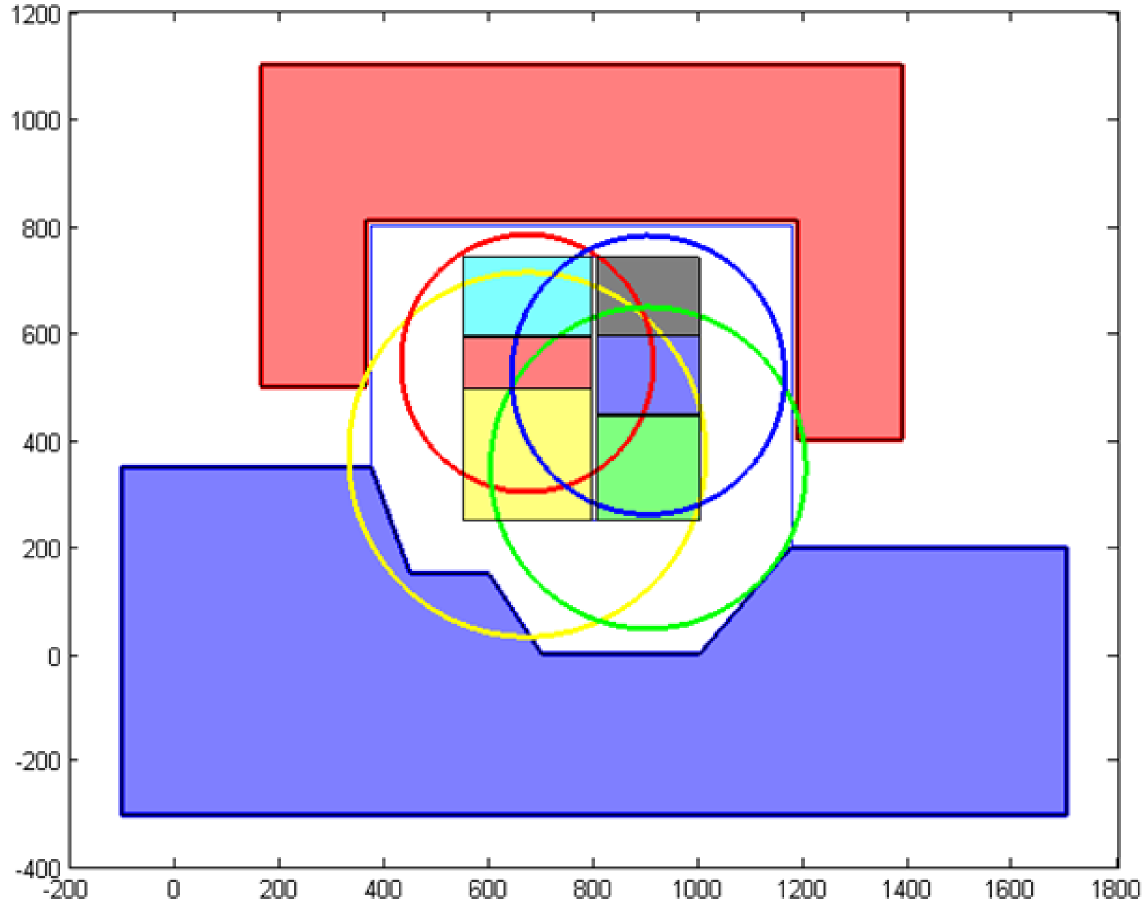


Figure 6. Optimized layout obtained after applying SA algorithm.

Table 5. Coordinates of the units for initial and optimized layouts.

| Storage unit | Colour | Coordinates of the centres | | | |
|---|---|---|---|---|---|
| | | Initial layout (x,y) | | Optimized layout (x,y) | |
| Crude Oil | | 675 | 615 | **648** | **373** |
| Diesel Oil | | 675 | 443 | **648** | **546** |
| Gasoline | | 675 | 320 | **648** | **668** |
| Jet Fuel | | 900 | 640 | **878** | **323** |
| Lubricants | | 900 | 468 | **878** | **497** |
| Slop | | 900 | 320 | **878** | **668** |

Regarding the minimization process, Figure 7 presents the distribution of iterations versus FOB values, which demonstrates the path coursed by the algorithm towards the optimal configuration shown in Figure 6. The total number of iterations reached, as well as the initial and the final FOB values are presented in Table 6.

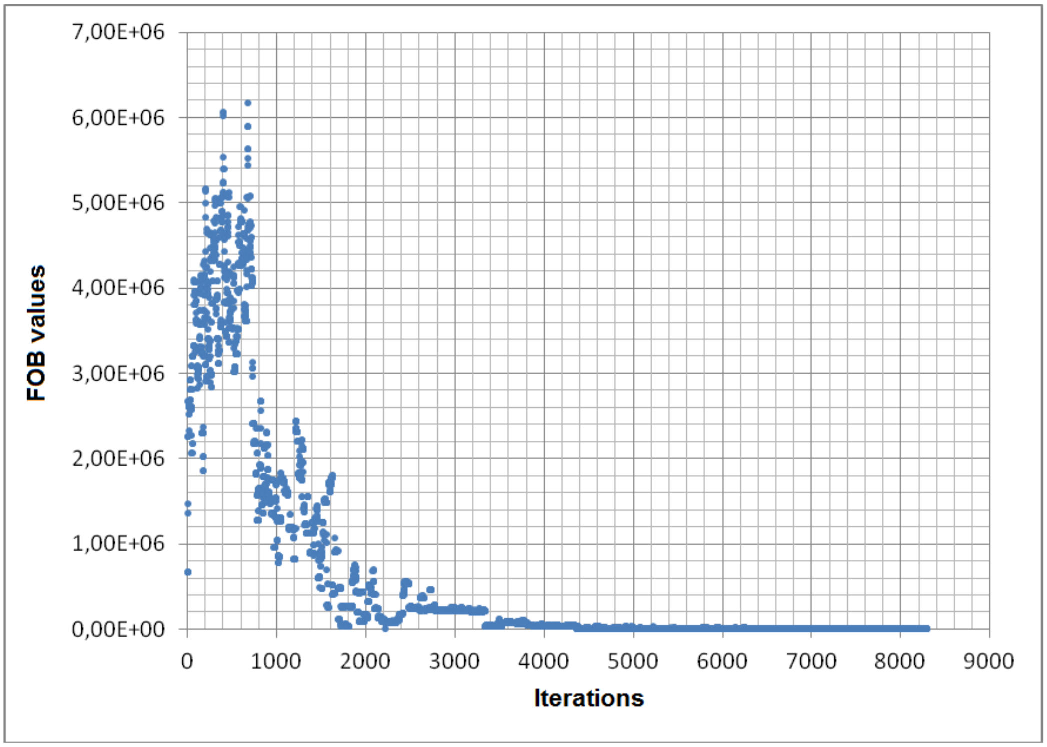


Figure 7. FOB values distribution during the optimization process.

Table 6. Optimization data obtained by applying SA algorithm.

| Parameter | Value |
|---|---|
| FOB for initial layout | 6.65E+05 |
| FOB for optimized layout | 1.31E+03 |
| Total number of iterations | 8290 |

Comparing Figures 5 and 6 one may notice a significant reduction in the area comprised by accidental damage distances that exceed the limits of the Terminal, especially regarding the portion that reaches the surrounding population. This visual result is confirmed by comparing the respective FOB values listed in Table 6, which reports a huge objective reduction by two orders of magnitude.

Analysing the changes performed by the SA algorithm, there is a clear tendency to move the units that have higher consequence results (Oil and Diesel Oil) away from the population living next to the Terminal, while, at the same time, allowing approximation of the units which stores non-flammable products (Lubricants and Slop) towards it. This behaviour is a reflection of the adopted weighting factors used in the HR objective function. Furthermore, it is also important to highlight that no overlapping units were obtained in the final layout, which therefore leads to a physically feasible solution.

Regarding the graph shown in Figure 7, its behaviour certainly can be considered as a typical curve obtained by the SA technique. In its initial stage, it is observed a large entropy (points without a clear pattern), while as the number of iterations increases the fluctuations become less pronounced, culminating in a configuration whose objective function value is minimal in the end of the minimization process.

Consequently, it is intuitive to conclude that the results imply the reduction of the HR regarding the operation of the Terminal, since the consequence distances were practically restricted to facility boundaries (Individual Risk reduction), including the minimization of the area which reaches the population polygon (Societal Risk reduction).

## 5. FINAL CONSIDERATIONS

This paper focused on the determination of the optimal location of tankage units inside the layout of a Marine Fuel Terminal in order to minimize the potential damage to neighbour populations due to accidents that may occur at this industrial facility. The proposed methodology based on the use of Monte Carlo method and the optimization technique known as Simulated Annealing was able to lead to were very efficient result, since the optimal layout obtained allowed the minimization of accidental effects to these communities.

Therefore, it can be concluded that the application of this methodology has contributed significantly to the reduction of Risk to General Public (RGP), given that the consequence distances were practically restricted to facility boundaries (Individual Risk reduction), including the minimization of the area which reaches the population polygon (Societal Risk reduction).

However, it is important to highlight that the proposed methodology is not able to prevent, for example, that new population developments grow towards the industrial facilities and thus start to be located inside the area defined by the accidental effect distances, which may imply the intolerability of risks in the future. In order to avoid this, an example of good practice is currently been applied in countries like Netherlands [23] and the United Kingdom [24] [25], which is known as Land Use Planning (a risk based approach). In the UK, for instance, when a new population development is planned in the vicinity of hazardous installations, Planning Authorities, Environmental Agencies and Companies are all involved in this process in order to mitigate the effects of major accidents on this population by following a consistent and systematic approach for planning permission around such sites.

## 6. ACKNOWLEDGMENT

DTS Alves acknowledges PETROBRAS S.A. for financial support. JL de Medeiros and OQF Araújo acknowledge PETROBRAS/CENPES., CNPq-Brazil and ANP-Brazil for financial support.

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