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Application of Dijkstra Algorithm for The Multiobjective Optmization of Evacuation Routes In Toxic Cloud Scenario

Gisele Tatiane de Lima e Silva
Erika Oliveira da Silva
July Bias Macedo
Márcio José das Chagas Moura
Isis Didier Lins
Enrique Andrés López Droguett
Universidade Federal de Pernambuco – Centro de Estudos e Ensaios em Risco e Modelagem Ambiental

1. INTRODUCTION

In chemical industries, the presence of several hazardous products is usual. Under this scenario, the release of these materials could create catastrophic effects. Serious consequences arise from the occurrence of accidents. For example, disasters involving the generation of toxic cloud are considered the most lethal among other accidental typologies, such as fire and explosion. Accidents like the cyclohexane leaking in Flixborough (England - 1974), the release of dioxina TCDD (2,3,7,8-tetrachrlorodibenzo-p-dioxin) in Seveso (Italy - 1976) and the release of methyl isocyanate in the Disaster in Bhopal (India - 1984) are the main motivators of research on accidents with toxic clouds [1, 2].

Therefore, good process safety planning is required at these locations [3, 4]. A safety plan is a system that aims to prevent, prepare, mitigate and respond to accidents. Safety plan for chemical process requires different levels of protection barriers, acting as accident prevention measures and as mitigating measures [5 - 6].

The emergency response plan is the final layer of protection to consider and it is an essential part of the safety management of industries process. The objective in emergency planning is to reduce the consequences when an accident is out of control, where evacuation routes can be used [7,4]. Since Bhopal Disaster more significance was given for the study of risks and the development of safety plans in chemical plants [2, 8, 9].

In general, evacuations plans have fixed routes based on the shortest distances of travel and, sometimes, this approach may not be the best. Other aspects could be considered in evacuation planning, thus other aproaches such as of multi-objective optimization should be more apropiate [10 - 12].

2. GENERAL OBJECTIVE

Then, the focus of this paper is the analysis of accidents involving the release of toxic subtances at the atmosphere and an optimal evacuation route must be determined as a protective mitigation measure. To achieve this objective a multi-objective optimization of evacuation routes was developed based on modified Dijkstra's algorithm [13, 14, 15, 16]. The optimal route was obtained through minimization of the individual risk and time spent during evacuation. Some accidental hypotheses involving the formation of toxic clouds occuring in oil processing units will be considered in this paper.

6. METHODOLOGY

This paper uses the study presented in [17] and applies the algorithm developed to discover the optimal evacuation routes in scenario of a theoretical refinery. The optimization will be performed by minimizing two objective functions: the travel time between the point of origin and the end-point of the route, besides the individual risk in which the person is exposed during the accident. In this study, the optimal evacuation route was found, through a modified Dijkstra algorithm, in case of releases of toxic substances, considering a scenario of petroleum refining industry. The research can be divided into several stages: qualitative analysis, calculation of consequences, development of the set of evacuation routes, calculation of individual risk, calculation of evacuation time and development of multiobjective optimization.

6.1 Qualitative Risk Analysis

An oil refining industry is importance to the population due to the production of different and indispensable products for their daily consumption. Therefore, the choice of scenarios is made in the main processing units present within a refinery. The chosen unit is the Atmospheric Distillation Unit (ADU).

For the qualitative risk analysis the Preliminary Risk Analysis (PRA) was used. The choice of scenarios for the evaluation took into account two criteria: to have formation of toxic cloud and its consequence to be high risk category [18, 19].

6.2 Consequences Estimation

The quantitative risk analysis will be perfom through simulation on software ALOHA (Areal Locations of Hazardous Atmospheres) [20, 21], which was developed by the Environmental Protection Agency - US (EPA) and the National Oceanic and Atmospheric Administration (NOAA) and serves as a support in the planning of responses to chemical emergencies [22].

The input data of the program is information about the release of the chemical (flammability, toxicity, explosiveness, etc.), data relating to the equipament that is involved in the leakage of substances (dimensions, operating pressure and temperature, origin of the spill, etc.) and the weather conditions (wind speed, wind direction, air humidity, etc.), being very influential in the final result [22, 23].

The simulations performed in ALOHA are very importants for this paper, since it is from them that the toxic concentrations are calculated in each nodes (sites within the refining industry plant) within the network. These concentrations will be used in the next steps of the research methodology.

6.2.1 Accidental Scenario of Interest

Initially, it is necessary to identify some conditions that are considered for the development of the quantitative step of the risk analysis. In this phase the ALOHA software is used. The technical standard [25] establishes the characteristics of the building where the leak occurs and the atmospheric criteria used as input data.

The simulated scenario is located in the ADU, located at node 01 (Figure 1), and corresponds to a hydrogen sulfide release due to a pipe rupture. Therefore, it is considered a representative accidental scenario for the unit due to the possible volume of the substance that can be released. For the simulation in ALOHA the analyzed substance is the pure hydrogen sulfide (H_2S), which has been selected for the simulation because it is dissolved in the oil and, when discharged from the hydrocarbons, can form toxic clouds that are harmful to human health, IDLH (maximum concentration at which a worker can be exposed without harming health for 30 minutes) equals to 100 ppm. In addition, because it is a flammable gas, the formation of flame may occur in the presence of an ignition source. Therefore, H_2S can be considered a very representative toxic substance within the oil refining environment [24, 25].

Table 1 summarizes the data used as input in the ALOHA simulation. Thus, the response of the software is the concentration of the toxic product at each node. This information is important because these data will be used as input information in the modified Dijkstra algorithm.

Table 1 - ALOHA input data for scenario 1 - ADU

Diameter of pipe	Pipe length	Pipe connection	Pipe Roughness	Substance pressure	Substance temperature
5”	50 m	Connected with a tank	Smooth Pipe	2 atm	180 ºC

6.3 Development of the Evacuation Route Set

The set of possible evacuation routes was developed under the layout of a hypothetical oil refining industry. Twenty nodes were marked that correspond to strategic locations and units of a refinery. Two fixed points were considered: the beginning of the evacuation always occurs in node 1 and the safe endpoint is node 20. It was also used as a premise that the accident can occur in any location (node 1 to node 19), except the safe place (node 20).

A scale was used where each centimeter in the figure corresponds to one hundred meters of distance in the plant. Thus, the Euclidean distances between the nodes were calculated. Figure 1 illustrates the evacuation network that will be used for the development of this research.

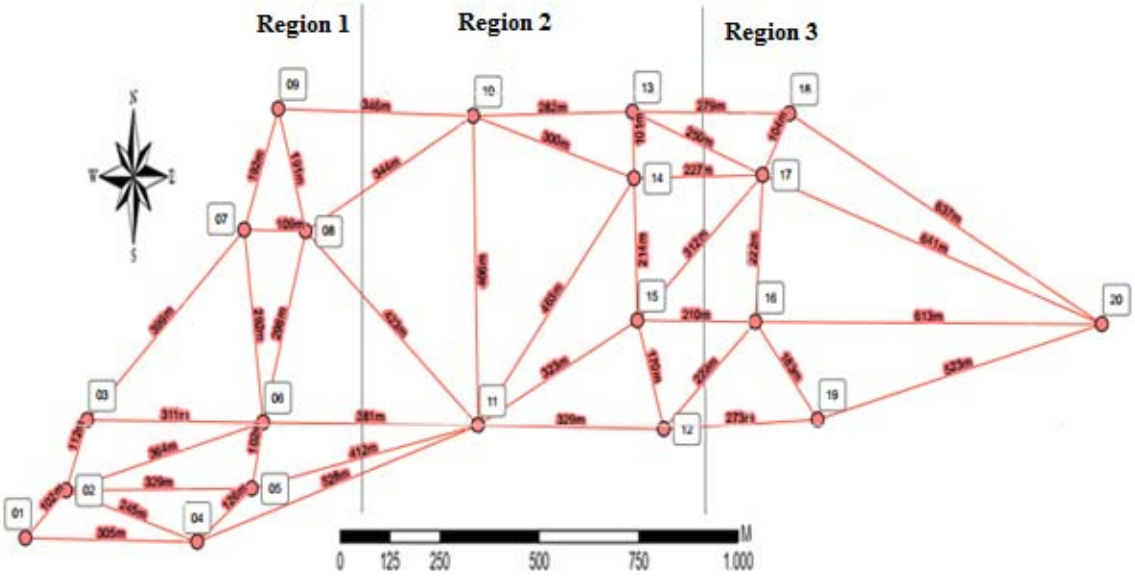

Figure 1 – Evacuation Node Set

6.4 Individual Risk Calculation

Toxicity can cause damage to people and to property of an organization. Therefore, it is necessary to calculate individual risk (IR) [26]. Equation (1)shows that from the probability of failure (*Pf*) and the probability of death in case of occurrence of this failure ($P_{d/f}$) it is possible to obtain the value of individual risk for the accidental typology *i* in the location *x,y* [17, 27].

$$RI_{x,y,i} = P_f \times P_{m/f} \quad (1)$$

In the calculation of the probability of death ($P_{d/f}$) shows the relationship between its value with the variable of Probit *X*. The Probit approach is widely used and there is a diferente way of determining for each accidental typology. Equation (2) provides the probability of death value from Probit and an error function (*erf*) [17, 27, 28].

$$P_{d/f} = 0{,}5\left[1 + erf\left(\frac{|X-5|}{\sqrt{2}}\right)\right] \quad (2)$$

For the calculation of the Probit Function it is necessary to combine the toxicity concentration of the released substance and the time of exposure to the hazard. Equation (3) shows the relationship between constant values *a* and *b* which depend on the type of chemical and the lethal dose, D. This dose is obtained from the relation of the toxic concentration, *C*, a constant that also depends on the type of material Chemical, *x*, and the duration of exposure time, t_e, shown in Equation (4) [17, 27].

$$X = a + b \ln D \quad (3)$$

$$D = C^x t_e \quad (4)$$

The individual lethal dose can be calculated by taking into account the path traveled during evacuation, being called the parameter D_{ij} (i and j, meaning the origin and end nodes, respectively). The value of D_{ij} is calculated from the amount of chemical concentration along the location of individual *x,y* and time *t* as shows in Equation (5) [17, 27].

$$D_{ij} = \int_{t_i}^{t_j} C^x(x,y,t)dt \quad (5)$$

For the complete evacuation route (R), the lethal dose can be calculated as shown in the system of equations below (Equations (6), (7), (8) and (9)).

$$D(R) = \sum_{i=1}^{n}\sum_{j=1}^{n} z_{ij}D_{ij} \quad (6)$$

Subject to

$$\sum_{j=1,j\neq i}^{n} z_{ij} - \sum_{j=1,j\neq i}^{n} z_{ji} = \begin{cases} 1, i = 1 \\ -1, i = n \\ 0, \ otherwise \end{cases} \quad (7)$$

$$\sum_{j=1,j\neq i}^{n} z_{ij} = \begin{cases} \leq 1, i \neq n \\ 0, i = n \end{cases} \quad (8)$$

$$z_{ij} = 0{,}1 \quad i,j \in \{1,2,\dots,n\} \quad (9)$$

Being z_{ij} is a decision variable, where its null value means that the arc $(\vartheta_i, \vartheta_j)$ will not be traveled and unitary value means the arc $(\vartheta_i, \vartheta_j)$ is traversed as shown in Equation (9). Equation (7) restricts the values of route R and Equation (8) avoids the formation of an internal cycle during the construction of route R.

6.5 Evacuation Time Estimation

Evacuation time estimation is important in complex industries such as refineries. Develop an emergency plan with this type of information is valuable and can save lives in case of acidentes [25].

In the occurrence of disasters, it is observed that the travel velocity in the arcs that form the route of evacuation tend to decrease with the passage of time and increase in the distance from the origin of the accident to the location of the individual. Thus, it is assumed that velocity is given by Equation (10) [17,29].

$$u_{ij}(t) = u_{ij}^0 . \alpha_{ij} . e^{-\beta_{ij}t} \quad (10)$$

Where u_{ij}^0 is the initial velocity in the arc $(\vartheta_i, \vartheta_j)$ and its under normal conditions, $u_{ij}(t)$ is the function that calculates the velocity during the movement between the nodes *i* e *j* under the disaster conditions, α_{ij} and β_{ij} are decay parameters of this velocity and they determine the magnitude of this reduction, affecting the travel time. The factor α represents the influence of the accident on the path and small values mean the disaster has a large influence on the evacuation. The value of β represents the effect of an occurrence in a time interval after its occurrence and the higher magnitude, the faster the displacement velocity decreases and the greater the extent of the accident [17]. These values of decrement can be estimated from the distance of the arc $(\vartheta_i, \vartheta_j)$ from the origin of the accident, the type of accidental scenario, path vulnerability and others [17, 29].

It is possible to obtain the traveling time through the recursive method shown in Equation (11), where t_{ij} is the travel time from node *i* to node *j*, presented by Equation (12), and, $l_{ij,}$ distance traveled in the arc $(\vartheta_i, \vartheta_j)$ [29; 30].

$$\int_{t_i}^{t_j} u_{ij}(t)dt = l_{ij}, 0 < i < j \leq n \quad (11)$$

$$t_{ij} = t_i - t_j \quad (12)$$

6.6 Development of Multiobjective Optimization

As a resolution to the problem introduced, the minimization of two objective functions will be analyzed: individual risk along the path traveled and evacuation time. In general, the methodology considers the probability of individual death from the chemical dose to which a single individual is subjected in situations of toxic cloud formation [17]. Therefore, it is necessary to choose RI as the main mode of measuring the present threat. In addition, the result of the optimal individual evacuation route can serve as a basis for the development of the emergency plan for a larger number of people.

The code, based on the Dijkstra algorithm and developed by [17], was implemented for this paper in C ++. The problem can be formulated as follows:

$$\min T(R) = \sum_{i=1}^{n} \sum_{j=1}^{n} z_{ij} t_{ij} \quad (13)$$

$$\min RI(R) \quad (14)$$

Subject to Equations (7), (8) and (9), where T(R) is the total time spent during the entire evacuation on route R and RI (R).

The approach used to solve the model shown is called a modified Dijkstra algorithm, being considered like this due to the use of the recursive method in calculations of parameters t_{ij} and D_{ij}. To obtain the optimal route R, a new factor λ_{ij} (Equation (15)), is considered as the weight of the path in the arc $(\vartheta_i, \vartheta_j)$ must be implemented and where the values ${R_T}^*$ e ${R_D}^*$ represents the short paths inrelation to time and lethal dose in the arc $(\vartheta_i, \vartheta_j)$, respectively, and τ and θ compose a weight vector (τ, θ ≥ 0, τ + θ = 1) [17, 42, 39].

$$\lambda_{ij} = \frac{\tau . t_{ij}}{T({R_T})^*} + \frac{\theta \, . \, D_{ij}}{D({R_D})^*} \quad (15)$$

The code was developed in three stages (algorithms I, II and III), the first one referring to the determination of the optimal routes from the choices of the nodes traveled and the calculations of t_{ij}, $D_{ij}$and λ_{ij}. It is in this phase that the set of non-dominated solutions is obtained. In the second stage ocurrs the verification of the solutions obtained in the previous phase for differents levels of risk tolerance. That is, the division of the solution of the previous algorithm happens in three subsets, removing solutions considered in the intolerable level of RI. In the last step an acceptable limit of risk (a predetermined value) is introduced that assists in obtaining the final solution of optimal route R *.

In the first step (Algorithm I), each passed cycle passes to the next node, which represents the distance traveled, t_{ij} and D_{ij} are modified and, consequently, λ_{ij} is changed. For each value of λ_{ij}, R(τ, θ) can be attributed as the shortest path in relation to this value, that is, the time values and the toxic dose are dynamic, changing according to the arc that is being traversed.

Assuming that N is a positive and very large number, P(i) e T(i) are the node markings i as set of nodes P (permanent) and nodes T (temporary), S_k are the sets of permanent nodes afther the Kth step of algorithm, σ(k) is the predecessor of the node k along the path R (from node i to node k) and w_{ij} is the intermediate weight of the arc (i, j), used for the calculation of optimal routes ${R_T}^*$ and ${R_D}^*$. From this, the modified Dijkstra algorithm (algorithm I) can be represented acording to Figure 2 [17, 29].

Step 1: Initiation (iterative step k = 0); Being P(i)=0, $S_0 = \{1\}$, p=1, $w_{ij} \geq 0$. Allowing T(k)=+∞ e σ(k) = N for whatever $k \neq 1$;

Step 2: If $n \in S_j$, can be obtained that P(n) is the shortest path, with weight, to node 1 from node n, being adopted as the best route and ends the algorithm. Otherwise, go to the next step;

Step 3: For each node i where $(p, i) \in E$ (set of arcs) e $i \notin S_j$, allowing $t_p = f_T(p)$, solving the equation $\int_{t_p}^{t_i} u_{pi}(t)dt = L_{pi}$ to obtain the t_i and with this, $t_{pi} = t_i - t_p$ and $D_{pi} = \int_{t_p}^{t_i} C^x(x, y, t)dt$ to find t_{pi} e D_{pi}.

Step 4: If $P(p) + w_{pi} \leq T(o)$, allowing $T(i) = P(p) + w_{pi}$ e $\sigma(i) = p$, go to the next step;

Step 5: Let $T(i,j) = \min\{T(i)\}, P(i,j) = T(i,j), S_{i+j} = S_j \cup \{i,j\}, p \leftarrow i, j \leftarrow j + 1$, go to step 2.

Figure 2 – Algorithm I (Source [17])

Thus, we obtain the best routes with respect to time and the lethal dose, $R_T{}^*$ and $R_D{}^*$, respectively, and then with the variation of τ in the interval [0,1], obtains the weight λ_{ij} of the arc on the evacuation and finally, the value of the best route in relation to the objectives functions (R (τ, 1-τ)) [17, 29]

In general, individual risk, calculated from Equation (1), can be divided into three groups according to risk tolerance, Q1 (IR > 1.10^{-5} $year^{-1}$), Q2 (1.10^{-5} $year^{-1} \leq$ IR $\leq 1.10^{-6}$ $year^{-1}$) and Q3 (IR < 1.10^{-6} $year^{-1}$).If the solutions are contained in Q1 group, they can not be accepted. In Q2 group, the risk is strategic in the decision making of the route choice, since in this way additional protection measures must be applied in order to reduce it. In Q3 group, the non-dominated solutions found are tolerable. The second algorithm (algorithm II) separates the solutions obtained in the previous algorithm into three subsets according to the acceptable level of susceptibility to the risk. The algorithm II shown in Figure 3 presents how to obtain the group of subsets of the non-dominated solutions [17].

The optimization of a single objective function obtains a unique result, differently what occurs in multiobjective optimization problems, where there is not a single global solution. Therefore, it may be necessary to adopt an artifice of an optimum value predetermined. Assuming l_{IR} represents an acceptable limit of risk provided by the decision maker or by a previous emergency plan, the concept of optimal solution as an output route R* ∈ Q, obtained from the model presented and if there is no other route R ∈ Q in such a way that IR(R) ≤ l_{IR}, and T(R) < T(R*) simultaneously [17, 39]. In order to obtain the optimum solution of the multiobjective model in scenarios of toxic cloud, the algorithm III is shown in Figure 4.

Step 1: Initialization (where the cycle counter, NC = 0). Let G = (V, E) (the evacuation network, where V is the set of nodes and E is the set of arcs that can be formed), Q1 = Ø, Q2 = Ø and Q3 = Ø, the set of values of the algorithm parameters including the maximum number of NCmax divisions is within the range of 0 to 1 and the individual risk limits l_1 and l_2 are 10^{-5} and 10^{-6}, respectively.

Step 2: τ=1, θ=1-τ, allowing the intermediate weight of arc (i,j), $w_{ij} = t_{ij}$, apply the Dijkstra algorithm (algorithm I) and obtain the value of $R_T{}^*$associated with weight and resulting on the optimal value, T($R_T{}^*$).

Step 3: τ=0, θ=1-τ, allowing the intermediate weight of arc (i,j), $w_{ij} = D_{ij}$, apply the Dijkstra algorithm (algorithm I) and obtain the value of $R_D{}^*$associated with weight and resulting on the optimal value, T($R_D{}^*$).

Step 4: If $NC \leq NC_{máx}$, $\tau \leftarrow NC/NC_{máx}$, with θ=1-τ, w_{ij}, use the o algorithm I to obtain the shortest path $R_{(\tau,\theta)}$ associated with weight w_{ij}, $f(\tau) = IR(R_{(\tau,\theta)})$. Otherwise, go to step 5;

4.1: If $f(\tau) < l_2, Q3 = Q3 \cup \{R_{(\tau,\theta)}\}, NC = NC + 1$, go to step 4.

4.2: If $l_2 \leq f(\tau) < l_1, Q2 = Q2 \cup \{R_{(\tau,\theta)}\}, NC = NC + 1$, go to step 4.

4.3: If $f(\tau) \geq l_1, Q1 = Q1 \cup \{R_{(\tau,\theta)}\}, NC = NC + 1$, go to step 4.

Step 5: The algorithm ends.

Figure 3 – Algorithm II (Source [17])

Step 1: Initialization (where the cycle counter, NC = 0). Let G = (V, E), $\tau_1 = 0$, $\tau_2 = 1$ (search values to τ), the optimal route weight vector (τ*, θ*) = (0,1), the set of values of the algorithm parameters including the maximum number of divisions NC_{max}, the limit of risk acceptable by the decision maker or predetermined in the emergency plan is l_{IR}, a growth rate of the weighting coeficiente, k, where $l_{IR} > 0$, $k \in (0,1)$ (in the present work it was adopted k = 0.5, similar to Gai *et al.*, 2017).

Step 2: τ=1, θ=1-τ, allowing the intermediate weight of arc (i,j), $w_{ij} = t_{ij}$, apply the Dijkstra algorithm (algorithm I) and obtain the value of $R_T{}^*$associated with weight, resulting on the optimum values, $T(R_T{}^*)$ e $D(R_T{}^*)$.

2.1: If $l_{IR} \leq D(R_T{}^*), R^* = R_T{}^*$, τ*=τ, θ*=1-τ* and the algorithm ends.

Step 3: τ=0, θ=1-τ, allowing the intermediate weight of arc (i,j), $w_{ij} = D_{ij}$, apply the Dijkstra algorithm (algorithm I) and obtain the value of $R_D{}^*$associated with weight, resulting on the optimum values, $D(R_D{}^*)$ e $T(R_D{}^*)$.

3.1: If $l_{IR} < D(R_D{}^*), R^*$ there is no optimal solution and the algorithm ends.

3.2: If $l_{IR} = D(R_D{}^*), R^* = R_D{}^*$, τ*=τ, θ*=1-τ* and the algorithm finishes.

Step 4: If $NC \leq NC_{max}$, $\tau \leftarrow \tau_1 + k.(\tau_2 - \tau_1)$, with the weight $w_{ij} = \lambda_{ij}$, use the modified Dijkstra algorithm (algorithm I) to obtain the shortest path $R_{(\tau,\theta)}$ related with weight w_{ij} and with the relative optimal to $D(R_{(\tau,\theta)})$. Otherwise, there is no optimal solution and the algorithm ends.

4.1: If $D(R_{(\tau,\theta)}) > l_{IR}, \tau_2 = \tau, NC = NC + 1$, go to step 4.

4.2: If $D(R_{(\tau,\theta)}) = l_{IR}, R^* = R_{(\tau,\theta)}$, τ*=τ, θ*=1-τ* and the algorithm ends.

4.3: If $\tau_1 = \tau, NC = NC + 1, R^* = R_{(\tau,\theta)}$, τ*=τ, θ*=1-τ*, go to step 4.

Figura 4 – Algoritm III (Source [17])

With the progress of all the steps shown in the methodology, it was possible to obtain the necessary results due to the ALOHA simulation (initial stages were the PRAs and QRA) and due to the simulation in the algorithm developed in C ++. With this, the final solutions to the problem could be obtained.

7. RESULTS AND DISCUSSION

7.1 ALOHA Results

Scenario 1 - ADU was simulated in ALOHA and the largest radius of dispersion reaches approximately 6.24 km in the downwind direction relative to the source node (node 1).

The highest concentrations for the network nodes during the entire simulated casting time are given in Table 2. These values are obtained in units of ppm in the application and converted to $mg.m^{-3}$ for use in the C ++ program. The leakage source node has a concentration considered infinite (during the escape this concentration at the site is very high) and, therefore, a big value is admitted in relation to the values of the other nodes. It can be observed that most points have no chemical concentration, which is due to the wind direction considered in the simulation.

Table 2 – Concentrations obtained at nodes in the network for scenario 1 - ADU

Node	Concentration ($mg.m^{-3}$)	Node	Concentration ($mg.m^{-3}$)	Node	Concentration ($mg.m^{-3}$)
2	0	9	0	16	0,122
3	0	10	0	17	0
4	456	11	1,21	18	0
5	8,66	12	5,94	19	7,47
6	0	13	0	20	1,03
7	0	14	0		
8	0	15	0,0186		

7.2 Results of Dijkstra Algorithm

The lengths between the nodes (i, j) can be obtained in Figure 1. The initial individual velocity adopted was 110 m/min (~ 1.83 m/s) as [31]. The pure hydrogen sulfide was used and with that, it is assumed that the parameters of Probit are a = -11.5, b = 1 and x = 1.9 [28]. The parameters of α and β are randomly obtained for each path that is traversed and within the intervals: α ε [0.8; 0.99999] and β ε [0.0001; 0.1]. From observation in the literature, as [30] and [17], the division of the values of α and β into these intervals could also be considered.

To use the Dijkstra algorithm, it is necessary to obtain the dispersion frequency of the chemical. Then, it is necessary to perform an Event Tree Analysis (ETA), presented in [25]. In scenario 1, the frequency of failure of leakage on pipe (initiator event) was obtained in the *Purple Book* [28] and its value is 3.10^{-7} m^{-1} $year^{-1}$. From this and the values of probability of immediate ignition, delayed ignition and explosion conditions, the final frequency of $6.75.10^{-6}$ $year^{-1}$ can be reached. This result must also be provided as input data to the Dijkstra algorithm.

In addition, the decision-maker should also indicate a value of the reasonableness limit for the individual risk (l_{IR}), that is, from what magnitude this parameter should be taken into account when choosing the route of evacuation. In the ADU scenario, the value adopted was of $6.6.10^{-6}$ $year^{-1}$, the number in which both objectives are considered (individual time and risk). In addition, it is also seen which is the optimal weight vector in which all objectives can be considered simultaneously and different from (1,0) and (0,1), where vector (1,0) only time is considered and vector (0,1) only the individual risk is taken into account for the optimal path choice.

Table 3 summarizes the main information resulting from this model simulation. In this table, the optimal values for time, individual risk (IR) and distance traveled (DT) are presented considering only one objective function at a time, i.e., minimizing the time ($R_T{}^*$) or minimizing individual risk ($R_D{}^*$). In addition, the optimum route (R*) for the problem is also shown, where the time and individual risk minimization were performed simultaneously.

Tabel 3 – Results of scenario 1 - ADU

	Route	Travel Time (min)	IR ($year^{-1}$)	DT (m)	Optimum weight vector (τ^*,θ^*)
$R_T{}^*$	1 – 4 – 5 – 11 – 15 – 16 – 20	27,9418	$6,6802.10^{-6}$ (acceptable)	1.989	-
$R_D{}^*$	1 – 2- 3 – 7 -8 – 10 – 13 – 17 – 20	35,5843	$5,9130.10^{-6}$ (acceptable)	2.239	-
R*	1 – 2 – 5 – 11 – 15 – 16 – 20	28,8879	$5,9130.10^{-6}$ (acceptable)	1.989	(0,9932;0,0068)

Figure 5 shows more clearly the optimal routes found. The blue color represents $R_T{}^*$, the yellow color corresponds to $R_D{}^*$ and the green color shows the optimal route obtained from the multiobjective minimization presented as R *.

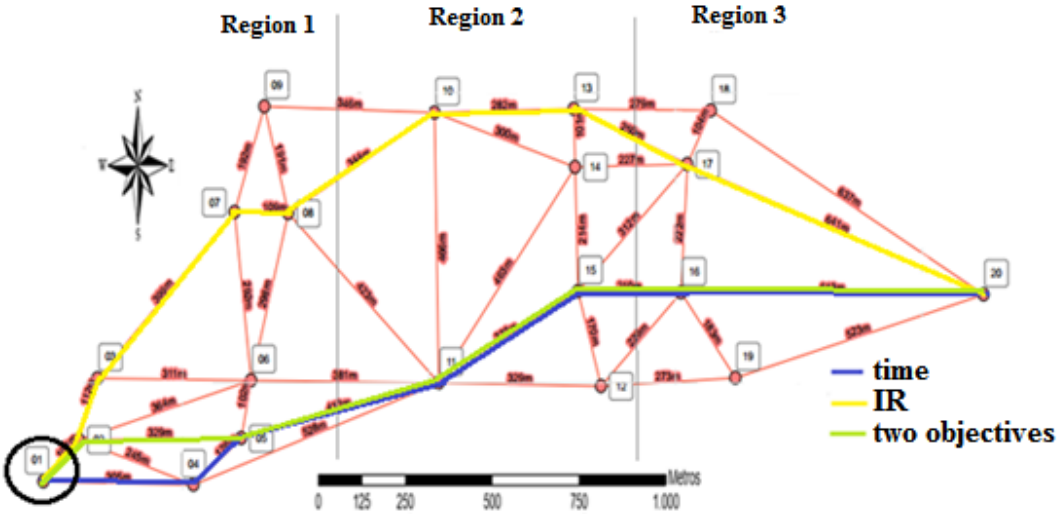

Figure 5 – Optimal Evacuation Routes in scenario 1 – ADU

In case of a situation of leakage of hydrogen sulphide in the ADU the optimum route to be traveled, relative IR and time, until the arrival of the safe location is by route R * (1 - 2 - 5 - 11 - 15 - 16 - 20) with a journey time of 29 minutes, distance of 1,989 meters and IR of $5.9130.10^{-6}$ $year^{-1}$, within the range considered acceptable according to [17, 25]. The IR of this route and $R_D{}^*$ are equal. This can be explained due to the fact that the concentrations in both paths are very similar.

Note in Figure 6 the node 4 is only traversed when the goal of minimum time is considered, Table 3 shows that the concentration of this node is the largest among the entire graph. Therefore, the only difference between the routes $R_T{}^*$ and R^* is the second node that compose these paths, where the optimal route, R^*, does not travel through node 4.

Furthermore, it is observed that the weight vector (τ^*, θ^*) equal to (0.9932; 0.0068) means that the individual risk has a rather small degree of importance in selecting the optimal route nodes. However, IR minimization should be considered in the final choice of route. The time has a high degree of relevance in the optimization process, that is, it has a high influence on the construction of the R* route. This is confirmed by the near equality in the component nodes of the routes $R_T{}^*$ and R^*, in the equal distances traveled and time spent.

8. CONCLUSION

The work was developed in several stages and, from them, the intrinsic danger to the petroleum refining processing unit could be understood. In addition, scenario of formation of toxic cloud were simulated, where the leakage of a substance very dangerous for people, H_2S.

The study problem sought through the minimization of two objectives, evacuation time and individual risk exposed during this route, to find the optimal routes in situation of release of the toxic cloud. To that end, the Dijkstra algorithm was used as a multiobjective optimization tool.

The optimal route (R *) could be found taking into account the two objectives studied (minimization of travel time and individual risk during evacuation); also presented the optimal paths when only one of the objectives was considered, $R_T{}^*$ for the route with the shortest evacuation time and $R_D{}^*$ for the route with the lowest individual risk calculated and also the respective evacuation times, distances traveled and individual risks.

These results can serve as basis for the development of industrial security planning of this profile whose objective is the protection of individuals against the consequences of an accident within the studied environment. With all this, it could be observed that the applied methodology is feasible, being able to apply in different scenarios.

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