How to Determine Individual Risk Due to Toxic, Fire, and Explosion Accidents in a Hydrocarbon Processing Area?

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Abstract: Accidents in the processing and storage of hydrocarbons can cause severe damage to people, not only within the facility but also in nearby places. In those cases, the occurrence of a major accident is considered. Moreover, there are many studies on how to determine the impact on people of these types of events. However, there is a real need to establish a methodology that integrates risk analysis techniques with other artificial intelligence ones and, in this way, to include the likelihood of the domino effect. For this reason, this research aims to determine the individual risk due to the domino effect of toxic, fire, and explosion accidents that can occur in a hydrocarbon processing area. For this purpose, a logical sequence of analysis of eight fundamental stages was made. In addition, the Bayesian and Petri networks are developed to determine the joint probability of the domino effect at different levels and the damages caused by toxicity, respectively. Finally, the individual risk is obtained, expressed using isorisk maps. As main results, these maps confirm that three deaths can occur up to 200 meters, while 250 will cause approximately four in just 10 years, values that decrease to 500 meters and are considered high according to specialized literature. Hence, this methodology is vital to quantify the possible damages of toxic accidents, fires, and explosions on people in the hydrocarbon processing industry.

Keywords: Accidents, Domino effect, Bayesian network, Individual risk, Fire, Explosion.

1. INTRODUCTION

Production, handling, and transport of dangerous goods in the hydrocarbon industry have been increased over the last few decades. For this reason, the consequences of accidents that happened in recent years have been devastating. These events affect the facilities, people, and environment [1-4]. Additionally, these serious accidents rarely begin and end with a single event. In fact, more often, they tend to produce the called domino effect [5]. This phenomenon occurs when a primary event triggers more events, and the consequences of all the accident sequences are worse than those of the single primary event. This incident is considered of high impact and has contributed to the development of catastrophic accidents, mainly in the process industries containing highly flammable hydrocarbons [6].

The hydrocarbon industry is one of the largest worldwide. Its importance is now indisputable considering the exploration, extraction, refining, and marketing of petroleum crude and its derivatives. Furthermore, these compounds, for their physical and chemical properties, specifically their flammability limits, constitute a danger for the development of toxic, fire, and explosion accidents, which can cause numerous deaths, environmental pollution, and economic losses [7-10]. Therefore, protection against such events has become increasingly essential in the safety management of oil deposits, for which various risk analysis techniques are used that allow forecasting the occurrence probability of accidents. Additionally, for predicting the domino effect due to the occurrence of a primary event, the Bayesian and Petri nets have been widely applied, which are precisely modern and reliable tools in the evaluation of industrial hazards [11].

Bayesian networks are graphical representations that explicitly reveal the probabilistic dependencies between variables and related information flows. The most relevant advantage of Bayesian networks is that they provide a useful tool to deal with uncertainties and information from different sources [11-14]. Moreover, Petri nets are a tool developed to model concurrent discrete systems [15]. They are graphs and formal mathematical models for specifying and analyzing the behavior of complex systems [13]. Also, both types of networks have been widely used in studies focused on the risk analysis of industrial facilities. Table **1** shows different applications of the Bayesian networks and Petri nets.

In order to evaluate the frequency of domino scenarios, Bayesian networks can be applied, taking

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Table 1: Applications of Bayesian Networks and Petri nets in Process Industries

Reference	Journal	Application
Dueñas Santana *et al*.,[3]	*Journal of Cleaner Production*	The Bayesian and Petri nets are used to quantify the individual impact of fire and explosion accidents in a hydrocarbon storage area.
Dueñas Santana *et al*.,[4]	*Engineering Failure Analysis*	Bayesian networks are used to quantify the synergistic effects within the determination of the probability of failure due to thermal radiation from fires.
Khakzad *et al*., [16]	*Reliability Engineering and System Safety*	They compare the applications of fault trees and Bayesian networks in safety and risk analysis in process industries.
Khakzad *et al*., [17]	*Risk Analysis*	They presented a new approach based on Bayesian networks for the estimation of probability and the determination of the propagation sequence of domino effects.
Khakzad [18]	*Reliability Engineering and System Safety*	A Bayesian methodology is developed to model both spatially and temporally the evolution of the cascading effects of a chain of accidents and the most probable sequence of accidents in a process plant.
Hu *et al*., [19]	*Process Safety and Environmental Protection*	They showed a dynamic method based on the Bayesian network for fault propagation studies in petrochemical process facilities.
Guo *et al*., [20]	*Journal of Natural Gas Science and Engineering*	A comprehensive risk assessment framework based on fuzzy Petri nets in combination with the analytical hierarchy process (AHP), the entropy method (EM), and the cloud model, has been proposed for oil and gas transportation pipelines of long-distance
Elusakin and Shafiee [21]	*Journal of Loss Prevention in the Process Industries.*	They applied an advanced analysis method using stochastic Petri nets (SPN) to estimate the reliability of subsea systems (BOP) subject to condition-based maintenance (CBM) with different failure modes.

advantage of their flexible graphic structure to show the sequential order of the scenarios and the probabilistic relationships among a large number of variables and, also, make a probabilistic inference with these variables [22-26]. Hence, the use of these networks leads to a more precise calculation of the escalation probabilities that is crucial for risk assessment and management of domino effects and also allows the interactions between units to be taken into account, which provides the sequence of most likely events during a scenario [11].

The risk of an accident is defined as the product of the frequency and magnitude of its consequences [27-28]. Isorisk maps are graphic representations that allow visualizing the distribution of certain disaster risks in a specific territory. These maps arise from the combination of hazard maps and vulnerability maps, which are already the result of specific indicators [3, 29-30].

Despite current research, it is necessary to group different existing risk analysis methodologies, with artificial intelligence techniques, in order to quantify the individual risk of toxic, fire, and explosion accidents. For this reason, the main aim of this study is to determine the individual risk due to accidents, considering the occurrence of the domino effect in a hydrocarbon processing area.

2. MATERIALS AND METHODS

This section presents the proposed methodology to assess individual risks due to toxic, fire, and explosion accidents and their cascading effect on the storage and processing of hydrocarbons. The proposed methodology consists of eight fundamental stages, as shown in figure **1**.

2.1. Step 1: Selection of the Process Unit

The first step of the methodology to be applied in this study is selecting the process units. For this purpose, the analyzed area is separated into subareas based on the potential of the equipment to cause damage to people if an accident occurs.

2.2. Step 2: Simulation of All Fire, Explosion, and Toxic Scenarios Using ALOHA Software

For the simulation of accident scenarios, the ALOHA software is used, recognized by the Ministry of Science, Technology, and Environment of Cuba (CITMA) as the most suitable simulator to express the behavior of toxic, fire, and explosion accidents, widely used and recommended for the evaluation of consequences in the risk analysis and with a huge international prestige. ALOHA was developed jointly by two international companies: The National Oceanic and Atmospheric

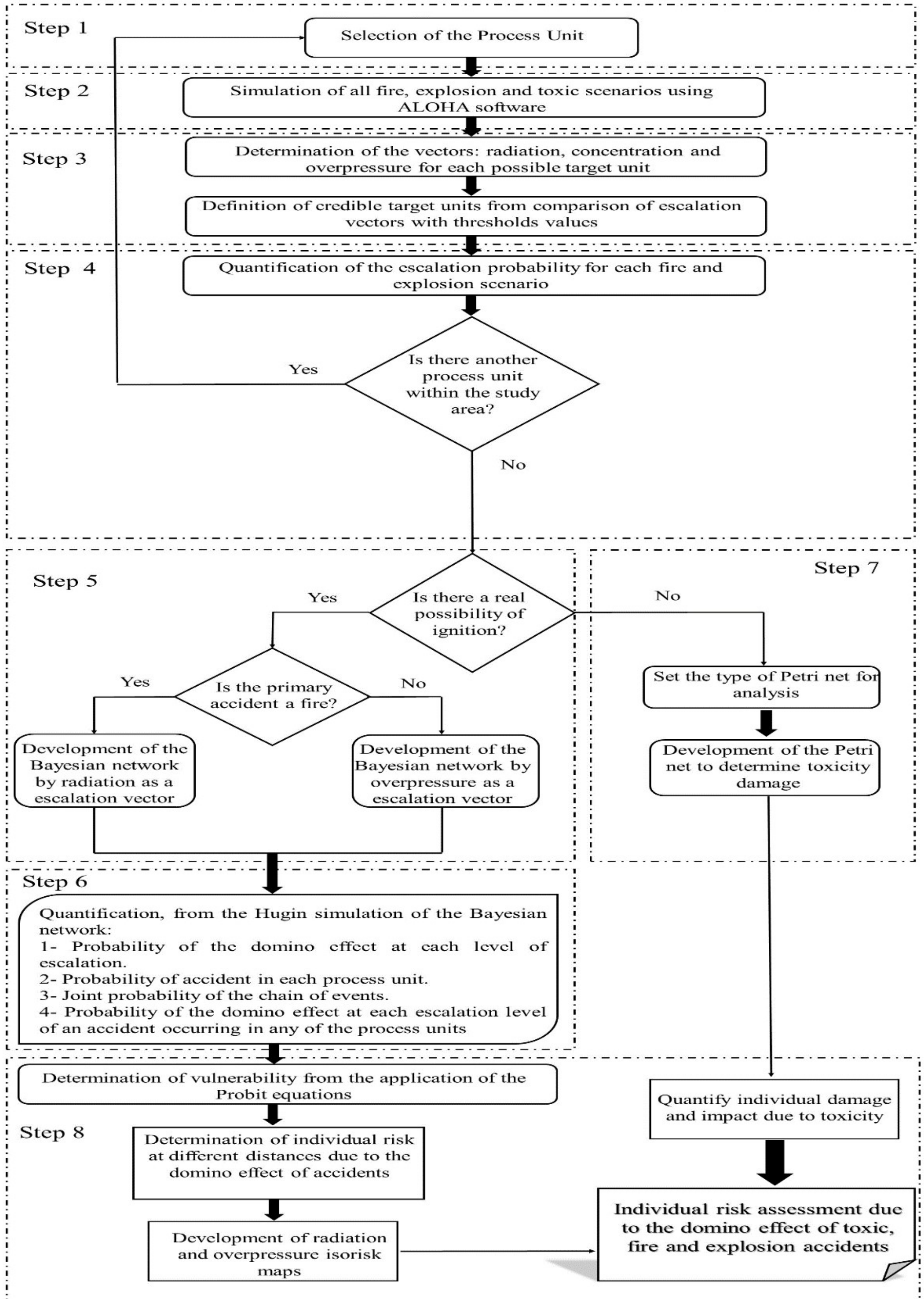

Figure 1: Proposed methodology in this research framework.

Administration (NOAA) and the Environmental Protection Agency (EPA) [3,4]. Additionally, ALOHA established the following Levels of Concern (LOC):

For thermal radiation, three LOC values are established:

- Red Threat Zone: 10 kW/m^2: potentially lethal within 60 seconds.
- Orange Threat Zone: 5 kW/m^2: second-degree burns within 60 seconds
- Yellow Threat Zone: 2 kW/m^2: pain within 60 seconds.

In the case of overpressure due to the explosion of a vapor cloud:

- Red Threat Zone: 8.0 psi: the destruction of buildings.
- Orange Threat Zone: 3.5 psi: serious injury likely.
- Yellow Threat Zone: 1.0 psi: shatters glass.

For the dispersion of a vapor cloud with toxic characteristics:

- AEGL-1: noticeable discomfort, irritation, or specific symptomatic effects. These effects are transitory, non-disabling, and reversible once the period of exposure ceases.
- AEGL-2: serious or irreversible long-lasting effects or your ability to escape impaired.
- AEGL-3: life-threatening effects or even death.

2.3. Step 3: Determination of the Vectors: Radiation, Concentration, and Overpressure for Each Possible Target Unit and Definition of Credible Target Units

Escalation vectors are obtained from the distances between the unit being analyzed concerning the rest of the units and depend to a great extent on their magnitude and dimension. Table **2** shows the threshold values established by Reniers and Cozzani [30] obtained from data from past accidents.

Thus, those process units which escalation vectors (using ALOHA simulation) present values greater than the established thresholds will be selected as possible secondary units, considering all the accident scenarios studied and the type of equipment that is analyzed (atmospheric or pressurized).

2.4. Step 4: Quantification of the Escalation Probability for Each Fire and Explosion Scenario

In order to determine the escalation probability, the first step is to obtain the thermal radiation and the overpressure values from ALOHA simulations for each possible scenario. Probit values are obtained from the equations described by Reniers and Cozzani [30] and Mukhim *et al*. [5], which are shown in tables **3** and **4**, respectively.

Moreover, a historical accident analysis is included in the methodology to be applied in this research to determine the occurrence frequency of these events in the study area, taking as a reference the last ten years of exploitation of the plant.

2.5. Step 5: Development of the Bayesian Networks

A Bayesian network is a statistical model that can operate with different distributions of time, used for reasoning under uncertainty [13,31,32]. For the Bayesian network development, the methodology proposed by Reniers and Cozzani [30] is followed. In order to simulate the Bayesian networks, Hugin software is used [33,34].

2.6. Step 6: Quantification of Probabilities from Bayesian Networks

After carrying out the Bayesian networks, the joint probability of the domino effect is determined for each primary unit studied, and in addition, the probabilities of occurrence of the domino effect are obtained for each level of propagation. For this purpose, the auxiliary nodes L_i express the probability of propagation of the primary accident to the possible i^{th} units, and the node $P(DL_i)$ indicates the probability of the domino effect of the i^{th} level must be introduced into the network. In

Table 2: Threshold Values for Escalation in Domino Effect Accidents

Accident Scenario	Escalation Vector	Target Equipment	Damage Threshold	Escalation Threshold
Fireball	Thermal radiation	Atmospheric	I> 100 kW/m^2	I> 100 kW/m^2
		Pressurized	Unlikely damage	Unlikely escalation
Pool fire	Thermal radiation	Atmospheric	I> 15 kW/m^2	I> 15 kW/m^2
		Pressurized	I> 45 kW/m^2	I> 45 kW/m^2
VCE	Overpressure	Atmospheric	P> 7kPa	P> 22kPa
		Pressurized	P> 20kPa	P> 20kPa

Source: Reniers and Cozzani, [30].

Table 3: Equations for Determining the Escalation Probability in Domino Effect Accidents

Primary Event	Target Equipment	Probability Models	Equation Number
Pool fire and BLEVE plus Fireball	Atmospheric	$\ln(ttf) = -1{,}13\ln(I) - 2{,}667 \cdot 10^{-5} V + 9{,}877$	(1)
		$Y = 9{,}25 - 1{,}847 \ln\left(ttf / 60 \right)$	(2)
	Pressurized	$\ln(ttf) = -1{,}29 \cdot \ln(I) + 10{,}97 \cdot V^{0{,}026}$	(3)
		$Y = 9{,}25 - 1{,}847 \ln\left(ttf / 60 \right)$	
VCE	Atmospheric	$Y = -18{,}96 + 2{,}44 \ln(Ps)$	(4)
	Pressurized	$Y = -42{,}44 + 4{,}33 \ln(Ps)$	(5)

ttf : time to failure (s); I : thermal radiation (kW/m^2); V : volume (m^3); Ps: overpressure (Pa)

Table 4: Equations for Determining the Escalation Probability for Specific Equipment

Primary Event	Target Equipment	Probability Models	Equation Number
VCE	Atmospheric vessels	$Y = -15{,}79 + 2{,}02 \ln(\Delta P)$	(6)
	Heat exchangers	$Y = -201{,}20 + 18{,}98 \ln(\Delta P)$	(7)
	Horizontal separator vessels	$Y = -88{,}88 + 8{,}79 \ln(\Delta P)$	(8)

ΔP : overpressure (Pa)

order to introduce these nodes, the probability tables proposed by Khakzad *et al*. [35] are used. The joint probability of the domino effect (P_{DE}) up to the last scaling level (n) is determined by equation 9.

$$P_{DE} = \sum_{i=1}^{n} DL_i \tag{9}$$

2.7. Step 7: Development of the Petri Net for Quantifying the Toxicity Damage

The main objective of applying Petri nets in this research is to determine the probabilities of harm to people due to the toxicity of the substances in the process based on multiple criteria such as those offered by ALOHA, [36]; HSE, [37] and Lees, [27]. These nets are developed according to the methodology proposed by Dueñas Santana *et al*., [3].

2.8. Step 8: Individual Risk Assessment Due to the Domino Effect of Toxic, Fire, and Explosion Accidents

The individual risk corresponding to each domino scenario is calculated from equation 10.

$$R_{i,de}^{(k,m)} = f_{de}^{(k,m)} \cdot V_{de}^{(k,m)} \tag{10}$$

Where:

$R_{i,de}^{(k,m)}$: Individual risk

$f_{de}^{(k,m)}$: Domino effect frequency.

$V_{de}^{(k,m)}$: Vulnerability.

Vulnerability is determined as the sum of the probability of death of all scenarios within the domino sequence and the toxic releases, with an upper limit of 1.

Probit Y equations exposed by Lees [27] are used to determine people's vulnerability. For calculating radiation effects, overpressure (including ruptured eardrums), and the concentration of toxic substances, specifically for hydrogen sulfide, the equations 11, 12, and 13 are used, respectively, which are listed in Table **5**.

Finally, the isorisk curves are developed to expose and quantify the number of deaths per year at different

Table 5: Equations for Quantifying People Vulnerability

Effect	Equation	Number	Terminology
Thermal radiation	$Y = -10,7 + 1,99 \cdot \ln\left(I^{4/3} \cdot t\right)$	11	I: Thermal radiation (kW/m2) t: exposure time (s)
Overpressure	$Y = 5,13 + 1,37 \cdot \ln(P)$	12	P : overpressure (bar)
Toxicity due to concentration	$Y = k_1 + k_2 \cdot \ln(C^n) \cdot t$	13	C : concentration (ppm) t: exposure time (min) k_1 =-31,42 k_2 =3,008 n =1,43

distances from where the accident occurs in the analyzed area.

3. RESULTS AND DISCUSSION

This section presents the results obtained after applying the proposed methodology in a real hydrocarbon processing area. This area is made up of six crude oil storage and processing tanks, four gas separator vessels, and four heat exchangers. Moreover, the results were revealed, thoroughly explained, and compared with scientific literature to validate the proposed methodology.

3.1. Results Related to the Definition of Process Units and Scenario Simulation (Steps 1-2)

For a better understanding and analysis, the study area was divided into two subareas, taking into account the closeness between the equipment. This plant division is shown in figure **2**.

The crude oil is pumped to the heat exchangers with the aim of increasing the temperature for viscosity and density reduction. After that, the crude oil is contained in tanks 6 (sub-area 1), 8, 15, and 16 (sub-area 2). Then, the crude oil is separated from the H_2S in the separator vessels. Finally, tanks 7 and 14 contain the crude oil after the gas separator processing, so the H_2S contained in these vessels are not significant regarding the crude oil volume. Once all the scenarios have been analyzed, it can be ensured that in the units studied, the behavior of the accidents is similar, being the most dangerous equipment, the tanks 6 and 15, and the gas separator vessel 2 because of the highest values of thermal radiation, overpressure, and concentration regarding the other process units. Moreover, the range of the escalation vectors in tank 15 is higher than those of the rest, which is because of its storage capacity. After analyzing the accident that will cause the maximum damage, a comparison is established between the three risk levels in this equipment, shown in table **6**.

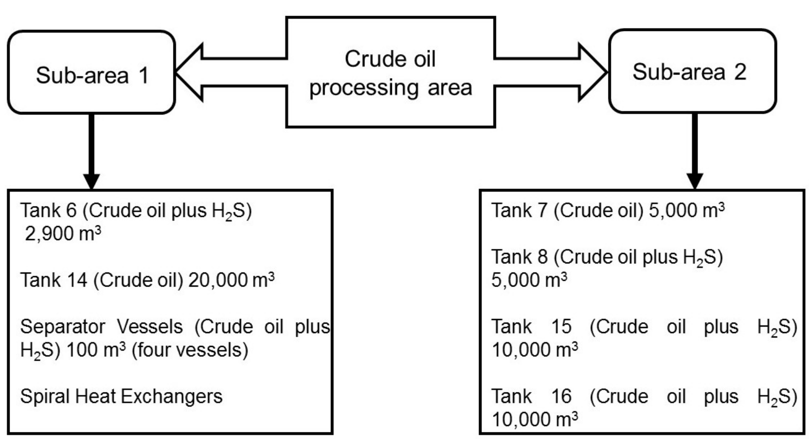

Figure 2: Sub-areas of the crude processing plant.

Table 6: Comparison of the Three LOCs in Each Scenario in Tank 15

Scenario	Distances (m)		
	Red Threat Zone	Orange Threat Zone	Yellow Threat Zone
Pool fire	95	130	196
Vapor Cloud Explosion	-	208	224
Fireball	1600	2300	3600
Toxic vapor cloud	1900	2400	10000

Hence, the fireball scenario, despite its short duration, constitutes one of the most terrible accidents that can occur in the industry since its scope is capable of exceeding the entire area of the plant and also affecting nearby areas. When this occurs, the accident is called a major one according to HSE [38], which coincides with the studies of Hemmatian *et al*., [39] and Kadri *et al*., [40]. Furthermore, the same situation happens with the toxic cloud scenario, constituting the accident that can cause the highest scope and effects within the company, since the radius of the areas of concern are so extensive that they can reach not only nearby towns, as is the case of the fireball, but to go further, as it affects neighboring cities.

3.2. Results Related to the Escalation Probability and Accident for Each Fire and Explosion Scenario (Stages 3-4)

The highest number of spills have occurred in tank 6 and gas separator vessel 2 since, in the last ten years, crude oil has been spilled five times in each of these units, for which a frequency of 0.5 is obtained respectively. It is followed by tanks 14 and 15 with 4, the remaining bullets and tank 8 with 3 and tank 7 with 2, while in tank 16 there has been only one spill. Next, tanks 14 and 15 have a frequency of 0.4; tank 8, 0.3; tnak 7, 0.2 and tank 16, 0.1. For hydrogen sulfide leaks, the highest values correspond to tank 6 as it contains a frequency of 0.2, indicating that this substance has been released into the atmosphere on two occasions. Thus, these values are considered high according to BEVI [41], Reniers and Cozzani [30], and Wells [42].

In figures **3** and **4**, the main results obtained after the simulation of the scenarios are shown. After analyzing the values of the escalation vectors, as well as the probability results and the distances at which the established thresholds are reached, it is concluded that units tank 6, gas separator vessel 2, and tank 15 are the possible equipment likely for developing primary

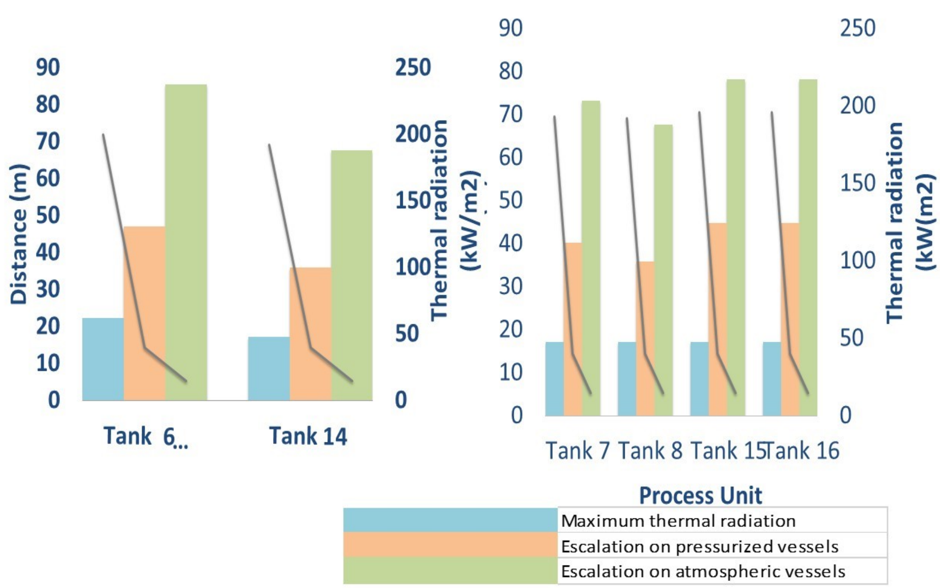

Figure 3: Results related to thermal radiation scope in the analyzed sub-areas.

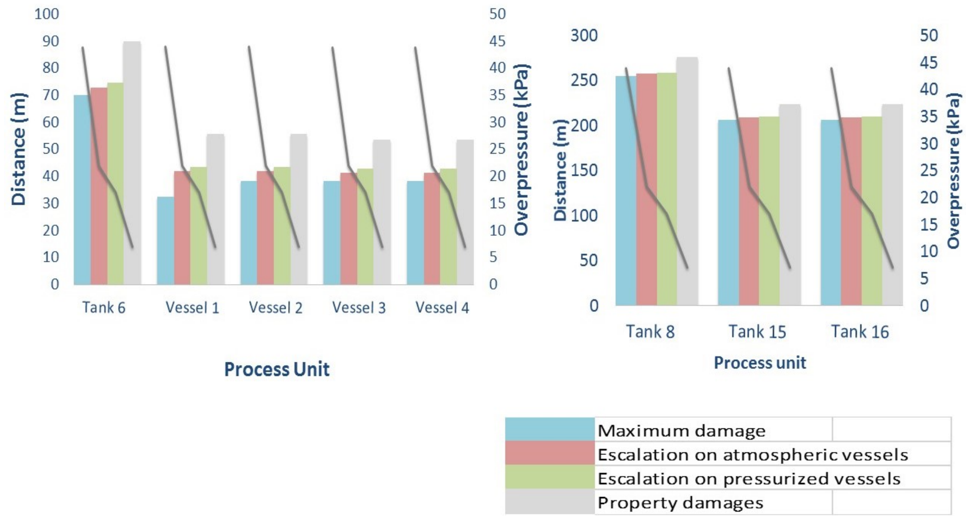

Figure 4: Results related to overpressure scope in the analyzed sub-areas.

accidents in both areas, as they are the most susceptible to escalation from the occurrence of a pool fire or a vapor cloud explosion.

3.3. Results and Analysis of the Bayesian Networks Developed (Steps 5-6)

Bayesian networks are one of the most useful, sustainable, and complete tools among several used for knowledge acquisition, representation, and application in the hydrocarbon industry [3-4]. They have been used for quantifying probabilities regarding domino effect occurrence. Bayesian networks are constructed in order to quantify the joint probability of the domino effect until the last level of escalation. They are carried out in the Hugin *software* from the chain of possible events of the potential primary units analyzed. The structure of all credible sequences can be exposed in ten Bayesian networks, as shown in table **7**.

Table 7: Structure of the Developed Bayesian Networks According to the Most Credible Domino Effect Sequences

Net	Primary Unit	Secondary Units	Tertiary Units	Quaternary Units	Escalation Vectors
1	Tk6	Tk8, Tk14, IC , B1, B2, B3, B4	Tk7, Tk15	Tk16	Thermal radiation:(Rest) Overpressure:(B1,B2,B3,B4)
2		Tk8, Tk14, IC, B1, B2, B3, B4	Tk7, Tk15, Tk16	-	Thermal radiation:(Tk6) Overpressure (Rest)
3		Tk8, Tk14, B1, B2	Tk7, Tk15, Tk16,B3, IC	B4	Overpressure (Rest) Thermal radiation (Tk7, Tk14)
4		Tk8, Tk14, B1, B2	Tk7,Tk15, B3	Tk16, B4	Overpressure (Tk6, B1,B2,B3,B4) Thermal radiation (Rest)
5	Tk15	Tk8, Tk14, Tk16	Tk6, Tk7	B1,B2, B3,B4, IC	Thermal radiation (Rest) Overpressure (B1,B2,B3,B4)
6		Tk8, Tk14, Tk16	Tk6,Tk7, IC, B1, B2	B3, B4	Thermal radiation (Tk15) Overpressure (Rest)
7		Tk6, Tk7, Tk8, Tk14, Tk16	IC, B1, B2	B3, B4	Overpressure (Rest) Thermal radiation (Tk7,Tk14)
8		Tk6, Tk7, Tk8, Tk14, Tk16	IC, B1, B2	B3, B4	Overpressure (Tk15, B1,B2,B3, B4) Thermal radiation (Rest)
9	B2	Tk6, Tk14, B1, B3, B4	Tk8	IC,Tk7,Tk15, Tk16	Thermal radiation (Tk7,Tk14) Overpressure (Rest)
10		Tk6, Tk14, B1, B3, B4	IC y Tk8	Tk7,Tk15, Tk16	Overpressure (B2) Thermal radiation (Rest)

Where: Tk; IC y B are tank, heat exchanger, and gas separator vessel, respectively.

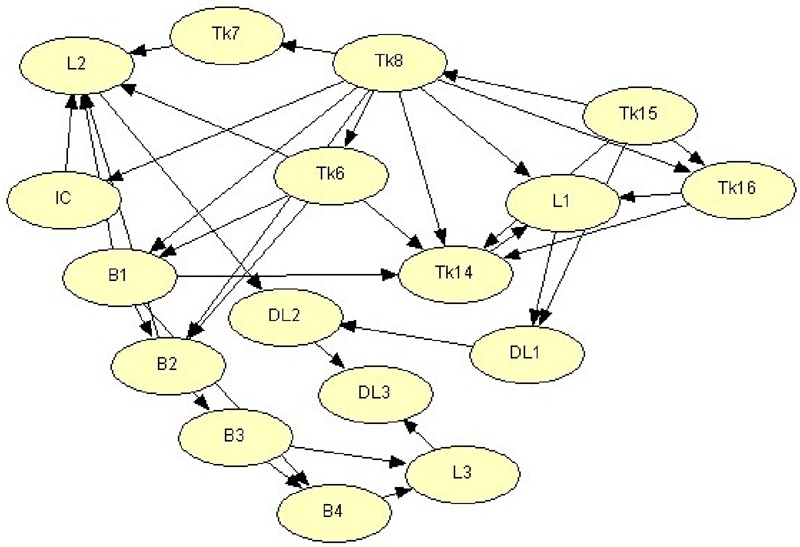

Figure 5: Structure adopted by the Bayesian network 6.

Figure **5** shows the structure adopted by the Bayesian network 6 because it is the one with the highest probability values of a domino effect of all those made.

In order to know the most dangerous potential primary unit within the industry, the graphs in figure **6** are developed. Figure **6** shows the probability of the domino effect at each level of escalation before and after a primary accident occurs.

Through the two graphs, it is observed that the unit that represents the highest dangerous potential within the entire plant is tank 15, since the probability of domino effect at the first level, both currently and that obtained from the development of an accident in the plant, considering a primary accident, is significantly higher than the rest. Moreover, in tank 6, the maximum results are 2.38 and 52.79% for each situation, while in gas separator vessel 2 they are 2.03 and 90.01%, respectively, which demonstrates that the possibility of producing the domino effect is high.

The joint probability is quantified as the sum of the probabilities of the domino effect up to the last existing level; in other words, it is the sum of the percentage values of the continuous character of the three levels obtained in tank 15. This probability turned out to be 9.81% in a year, a value that demonstrates the high dangerous potential that this equipment presents within the area according to Cai *et al.*,[43]; Kabir, Sadiq y Tesfamariam, [44]; Leoni *et al.*, [22] y Zerrouki y Smadi,

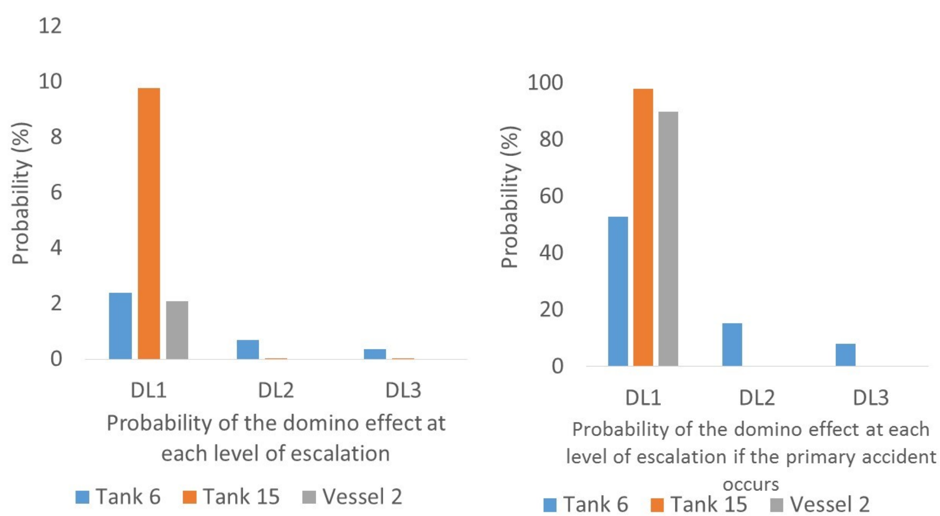

Figure 6: Probability of the domino effect at each level of escalation before and after a primary accident occurs.

[45]. Furthermore, as the sequence related to Bayesian network 6 referred to a pool fire accident in Tk15 and the occurrence of subsequent explosions in the rest of the process units, it is the one with the highest joint probability; and then, it is established as a pattern in the development of the corresponding Petri net.

3.4. Results and Analysis of the Petri net Developed (Step 7)

In this study, the Petri net is used to quantify the probability of harm to people due to the toxicity of hydrogen sulfide present in the process, taking into account the sequence of the domino effect and the synergism of accidents, starting from the chain of events exposed in the Bayesian network 6. In addition, all the equipment in the study area is taken into account except for tanks 7 and 14, which are precisely those that do not contain H_2S. The model obtained from the Petri net is shown in figure **7**.

Note: FT or FB represents the fault of the vessel, T or B the occurrence of an accident in the vessel. Transitions FT-T or FB-B, represent the occurrence of an accident in the vessel T or B; and T-FT or B-FB, the escalation vector of T or B that affects FT or FB, respectively.

Overall, a total of 15 places and 19 transitions are obtained with their corresponding certainty factors (radiation escalation probabilities, overpressure, and toxicity damage). It is appreciated that the highest probability values are those corresponding to the possible damage caused by toxicity, reaching 100% in all cases, based on the Probit equation proposed by Lees [27], which shows the level of risk that represents the presence of hydrogen sulfide for all the people who operate in the plant. These results are shown in Table **8**.

As main results, it is observed in the table that in all cases, the probabilities obtained are high according to Reniers and Cozzani, [30] and Zhou and Reniers, [46]. This indicates the possibility that exists of forming explosive and toxic vapor clouds as a consequence of the escalation of a pool fire that occurred in tank 15, as well as the danger of failure to which all the process units are subjected, due to the decrease in the mechanical resistance of the material that causes such an event. Furthermore, the maximum probability values are those obtained in tank 15, which is precisely the initiating unit of the domino event, and those reached by tank 16, which is fundamental because this is the closest equipment to the primary unit. Similar results

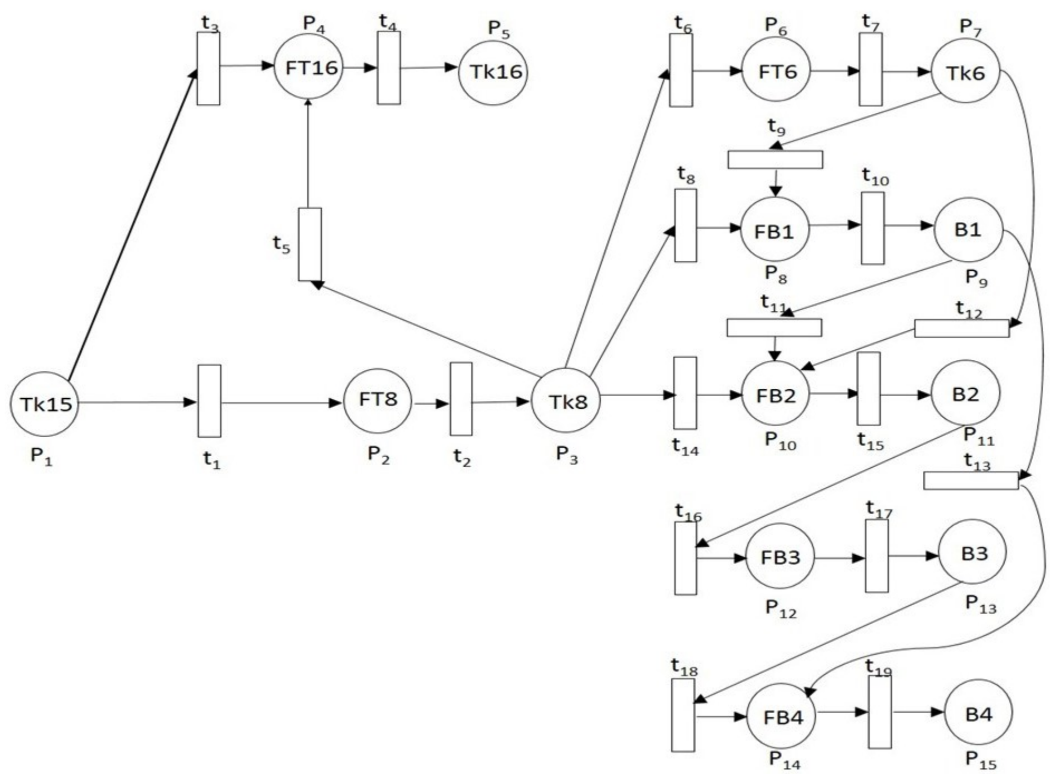

Figure 7: Petri net model developed to assess hydrogen sulfide toxicity damage.

Table 8: Results of the Probability of Accidents Resulting from the Petri Net Development

Probabilities	Equipment							
	Tk6	Tk8	Tk15	Tk16	B1	B2	B3	B4
Pool fire plus toxic vapour cloud	-	-	1,00E-01	-	-	-	-	-
Failure	1,61E-04	1,64E-04	-	9,80E-02	1,73E-04	1,81E-04	9,68E-05	1,44E-04
VCE plus toxic vapour cloud	1,61E-04	1,64E-04	-	9,80E-02	1,73E-04	1,81E-04	9,68E-05	1,44E-04

were obtained by Dueñas Santana *et al*., [3], Zhou and Reniers, [46] y Zhou and Reniers, [47].

In this way, it is possible to quantify the frequency of damage to people due to the synergistic effects of accidents and the formation of toxic clouds within the area. These values serve as a direct source of information in quantifying the individual impact due to toxic accidents.

3.5 Results Related to Individual Risk Assessment Due to the Toxic Accidents, Fires, and Explosions (Step 8)

Individual risk tends to be expressed through isorisk maps, allowing a clear vision of the magnitude and scope that the event may have. For this purpose, figure **8** shows the effects caused in people by thermal radiation, toxicity, overpressure, and their combined effect.

Figure **8** shows the high level of risk that exists in people when considering the continuous nature of a fire accident carried out in the plant since the effects of radiation at distances between 150 and 200 meters can cause up to 10 fatalities over a period of approximately 100 years. At the same time, worrying results are achieved because up to a radius of 400 meters, two deaths can cause the continuous nature of toxicological scenarios in just 10 years. These values generally decrease with increasing distance (except when the increase in the distance implies the development of

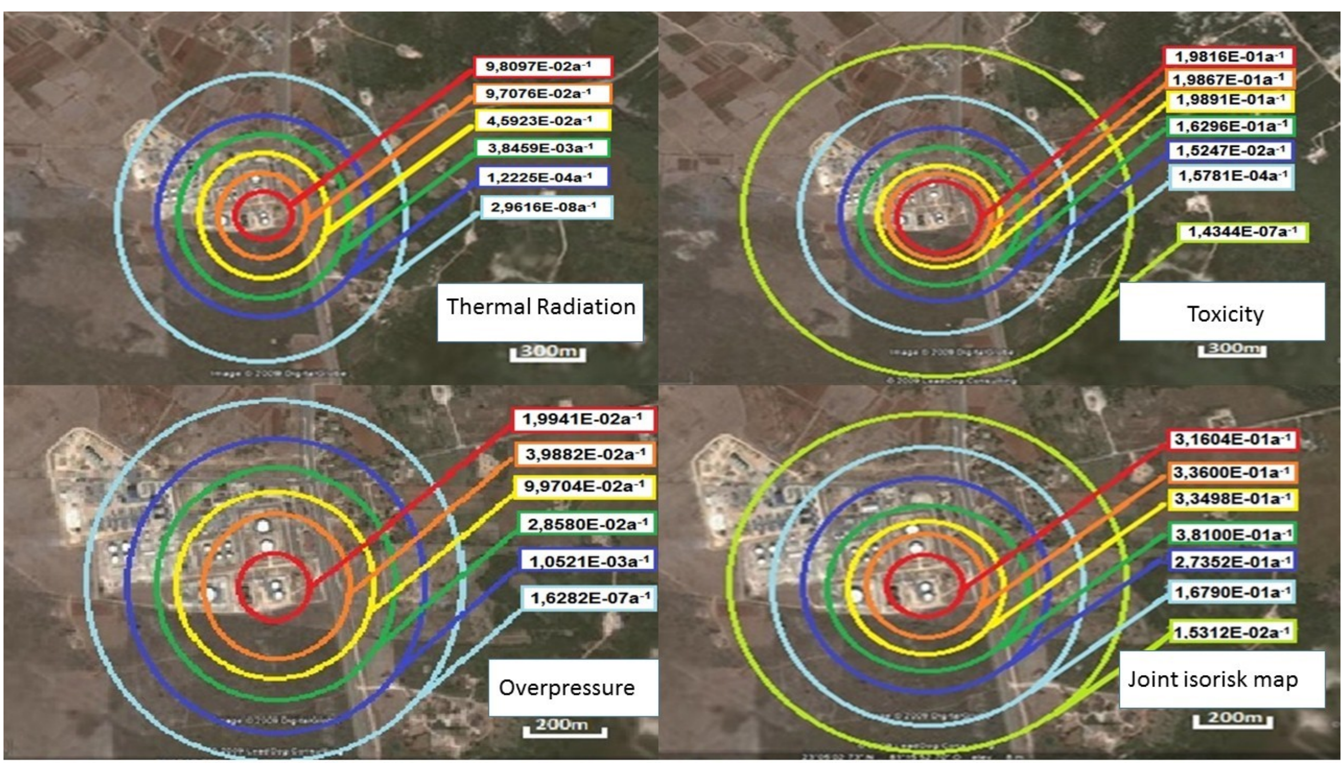

Figure 8: Isorisk maps due to the thermal radiation, toxicity, overpressure, and joint effects in the analyzed area.

new accidents within the chain of events) until reaching the maximum obtained of 700 and 1000 meters, respectively and also, they are considered high according to Reniers and Cozzani, [30] and Wells, [42].

Moreover, the domino effect of explosion accidents can cause two, four, and ten deaths to people exposed to distances of 100, 200, and 250 meters, respectively, in 100 years, which shows a contradiction in the behavior inversely proportional that exists between the level of risk and the length considered. This is because these radii of action increase the equipment whose escalation vector is significant in the vulnerability value, leading to an increase in this factor and, therefore, consequently to an increase in individual risk. However, at 300, 400, and 500 meters, the risk decreases since the contribution of new process units to the domino effect are not decisive. The same behavior is observed when considering the joint consequences of all accidents, since three deaths occur up to 200 meters, while 250 will cause approximately four in just 10 years, values that decrease until reaching 500 meters and are considered high according to Reniers and Cozzani, [30] and Wells, [42].

This study shows that accidents produced from tank 15 present a high level of risk to people within the plant and that the combined action of a fire in this unit and the explosion and formation of toxic clouds in the rest of the equipment process constitutes the most serious event that can occur in the analyzed area. Therefore, the development of a domino accident from tank 15 is very likely, and the need to reinforce industrial safety measures is imminent.

4. CONCLUSIONS

The successful combination of Bayesian networks with Petri nets, as well as their integration with risk analysis techniques such as the Past Event Analysis, the Event Tree and the Scenario Simulation, to quantify the frequency of the domino effect of accidents allowed the estimation damage to people due to the synergistic effects of fire, explosion, and toxic accidents. For the case study analyzed, the distances that each of the vectors reaches thermal radiation due to a pool fire, radiation due to a fireball, overpressure due to an explosion of a vapor cloud, and concentration due to the formation of a toxic cloud can reach up to 196 m, 224 m, 3.6 km and 10 km respectively, from an accident in tank 15, causing considerable damages to people. The Bayesian network with the highest probability is related to a pool of fire in tank 15 and consequent explosions in the rest of the process units with a value of 9.81% in a year; while the Petri net allows identifying this initial event, as well as the failure and development of new accidents in tank 16 with probabilities of 1.00E-01, 9.80E-02 and 9.80E-02, respectively. The synergistic effects of the accidents, shown in the isorisk maps, allow us to confirm that three deaths can occur up to 200 meters, while at 250 approximately four will be caused in just 10 years, values that decrease until reaching 500 meters and that are considered high according to specialized literature. Overall, this methodology can be applied in hydrocarbon storage and processing areas and demonstrates the need to integrate artificial intelligence techniques into risk analysis to ensure greater reliability of the obtained results.

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