



Research article

Contribution of Bayesian networks as a robust tool in risk assessment under sustainability considerations, a case study of Bandarabbas refinery

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ABSTRACT

Background and purpose: Refineries are among the industrial centers that supply the energy and raw materials to downstream industries. To achieve sustainable development goals, creating appropriate balance between economical and environmental goals has always been the focus of managers and policy makers in the societies. Bayesian Network model has become a robust tool in the field of risk assessment and uncertainty management in refineries. The focus of this research is to prioritizing different units from the point of view of social and ecological aspects for facilitating the decision making process in the context of waste material treatment in Bandarabbas refinery in line with the sustainable development goals.

Materials and methods: The methodology of this research is based on risk assessment with the aid of Bayesian Networks. To this end, first material flow analysis of the processes procured risk identification, subsequently influence diagram and Bayesian Network structure were designed. After completing conditional probability tables, finally risk factors were prioritized. What is more, sensitivity analysis of the model performed by applying three approaches namely predictive, diagnostic, and considering only one risk.

Conclusion: According to the risk assessment results, Amine treatment and Fuel units were classified as the most significant risk factors, whereas Pipelines and Plant air & instrument air system were identified as the most environmental friendly units. In addition, sensitivity analysis of the model provided appropriate framework to shed some light on the circumstances of determining dominant risk factors whether only one or concurrently all of the endpoints are evaluated.

1. Introduction

According to the International Energy Agency (2018), there is anticipated to be 25% rise in demand for energy consumption by 2040. Currently, a major part of the demand for energy is supplied through fossil fuels, especially oil and gas. The production of oil and gas industries in the vicinity of the sea has a share of 30% of the energy produced in the whole world [1]. A refinery produces large amount of solid, liquid, and gaseous wastes including volatile organic compounds, catalytic residues, heavy metals, oily sludge, and complex structured wastes including PAHs, oil and grease, TDSs, sulfides, ammonia, and nitrates [2]. Furthermore, to overcome global

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Abbreviations

IEA	International energy agency
LPA	Layer of protection analysis
VOC	Volatile organic compounds
BN	Bayesian networks
PAH	Polycyclic aromatic hydrocarbons
DM	Demineralized
TDS	Total desolved salts
ID	Influence diagram
USEPA	United states environmental protection agency
CPT	Conditional probability table
ERA	Environmental risk assessment
CPD	Conditional probability distribution
AHP	Analytic hierarchy process
DAG	Directed acyclic graph
FCA	Fuzzy comprehensive assessment
AOP	Advanced oxidation processes
GRA	Grey relational analysis
MEA	Monoethanoamine
NN	Neural network
COD	Chemical oxigen demand
ETA	Event tree analysis
WFGD	Wet flue gas desulphurisation
PN	Petri net
SCR	Selective catalytic reduction
BBN	Bayesian belief networks
SNCR	Selective non-catalytic reduction
LPG	Liquified petroleum gas
CCS	Carbon capture and storage
HAZOP	Hazard and operability
CCU	Carbon capture and use

warming implications, it is necessary for different economic sectors in the world to reduce greenhouse gas emissions [3]. Hence, one of the main bottlenecks in oil and gas industry is managing large amounts of waste materials that are produced in various processes.

According to the general framework provided by the US Environmental Protection Agency, environmental risk assessment is defined as a process that evaluates the adverse ecological effects on ecosystems that are exposed to drivers [4]. According to another definition, environmental risk assessment includes the process of identifying and evaluating potential negative impacts on organisms, humans and societies, which are mainly caused by the release of industrial waste materials and the exposure of organisms and humans to these substances [1]. Risk is defined as the product of the probability of the hazard occurrence and the consequence of the impacts. The main goal of ERA is to analyze the casual relationships between the risk factors and the adverse effects on the ecosystem [5]. In the field of risk assessment, heterogeneous kinds of quantitative and qualitative methods have been developed. Classical risk assessment includes methods vis. Analytical hierarchy process (AHP), Fuzzy comprehensive assessment (FCA), and Grey systematic theory. While the AHP method is based on a combination of quantitative and qualitative judgments to support domain knowledge, the FCA method processes the ambiguous data in risk assessment and expresses its result quantitatively. On the other hand, Grey's methodology uses Grey relational analysis (GRA) in risk modeling when accessibility to required data is restricted. Classical methods mainly rely on expert judgments, and one of the dominant cons of these methods is the impossibility of considering non-linear relationships between risk factors. Although the mentioned limitation in classical risk assessment can be eliminated by the neural networks (NN), cloud modeling, event tree analysis (ETA), and Petri nets (PN), there have been still limitations in uncertainty modeling and data integration. Bayesian Networks have removed these limitations. They also cover systems that operate based on continuous learning, and procure the ability of processing both qualitative and quantitative data simultaneously [6], and updating data [5], while remove the limitation of considering non-linear relationships in classical risk assessment. BNs are among robust models for making probabilistic conclusions, and the application of these networks is widespread in a wide range of fields such as academic research and development, biological studies, computer games, transportation, urban traffic and vehicle control studies, data processing, medicine, linguistics, psychology, reliability analysis, planning, and meteorological forecasting [7]. In general, BN model is a robust tool due to the very low prediction error and high accuracy, its suitable graphical form, and the ability of combining different types of data sources [8]. Jimenez-oyola et al. [9] have estimated human health risks using BN in a mercury mining district. Lan et al. [10] have considered industrial equipment as the end point and evaluated the industrial risks due to exposure to land slide, using BN model. Cui et al. [11] studied pipeline risk assessment using BN model and game theory in order to identify the pipeline failure mechanism. Malekmohammadi and

Tayebzadeh Moghadam [5] used BN in the field of environmental risk assessment in a dam. Mkrtchyan et al. [12] addressed insurability risk assessment using Bayesian Belief Networks in order to identify refineries that are at the risk of fire and explosion and estimated the associated risk levels. Perez et al. [13] studied environmental health risk assessment using BN in order to identify the correlation between air pollution and pathologies in an industrial area. According to the sustainable development objectives, industrial processes should be designed in such a way that the environmental impacts of the processes through the efficient waste treatment systems are solved effectively. Sustainable waste management ensures optimal resource usage while producing the least amount of waste possible [14]. Due to the existence of resource limitations in the field of waste management, it is not possible to eliminate the environmental impacts in a refinery concurrently. Dividing a production system into different sub-systems and prioritizing them from the viewpoint of social and ecological adverse effects enables managers and policy makers to make appropriate balance between economic and environmental targets in the planning phase of the manufacturing so that achieving cleaner production and sustainable development objectives facilitated. This research provides a suitable framework for prioritizing different units in line with the sustainable development goals and green manufacturing. Moreover, it is among the few studies in the field of risk assessment with BN, which provides the capability of considering social-ecological aspects as well as water, soil, air, and sound pollution simultaneously or separately. On the other hand, heterogeneous kinds of pollutants which have the potential of releasing into the water, soil, and air environments have been comprehensively considered, thus making it stand out.

2. Methodology

2.1. Study area

This refinery is the first refinery designed based on gas condensate feed stock with a capacity of 360,000 barrels per day, and accounts for process units such as Gas condensate distillation, Liquefied gas purification, Continuous catalytic regeneration, Naphtha purification, Isomerization, Kerosene and gas oil purification, and Utility, additionally includes non-process units such as the Flare line and Storage tanks. The main products of this refinery include petrol, diesel, liquefied gas, hydrogen and sulfur. This refinery is located in the southern of Hormozgan province in Iran in the geographical coordinates of $56^{\circ} 2' - 56^{\circ} 4' E$ and $27^{\circ} 9' - 27^{\circ} 11' N$ (Fig. 1) and plays a significant role in the supply of country's fuel.

2.2. Material flow

In this section, with the aid of process documents of the refinery, the material flow analysis has been performed in order to identify waste materials and potential risks. These documents include information regarding the complete description of the processes in units and equipments, the complete description of physical interactions and chemical reactions in each equipment, along with the temperature and pressure conditions of the reactions, and the amount of input materials and output products of the units and equipment. The investigated units consist of Sulfur recycling & solidification unit, Amine treatment unit, Sour water stripper unit, Steam and electricity unit (DM water system), Water system, Fuel unit, Plant air & Instrument air system, and Pipelines.

2.2.1. Sulfur recycling and solidification unit

In order to remove sulfur gases such as $H_2S(g)$, $SO_2(g)$, $COS(g)$, and $CS_2(g)$ in the Sulfur recycling and solidification unit, the waste gas treatment plant has been designed. The waste materials coming out of this plant include $H_2S(g)$ and $CO_2(g)$. The H_2S gas of the waste gas treatment plant is transferred to the furnace of the Sulfur recycling and solidification unit where it is burned at a very high

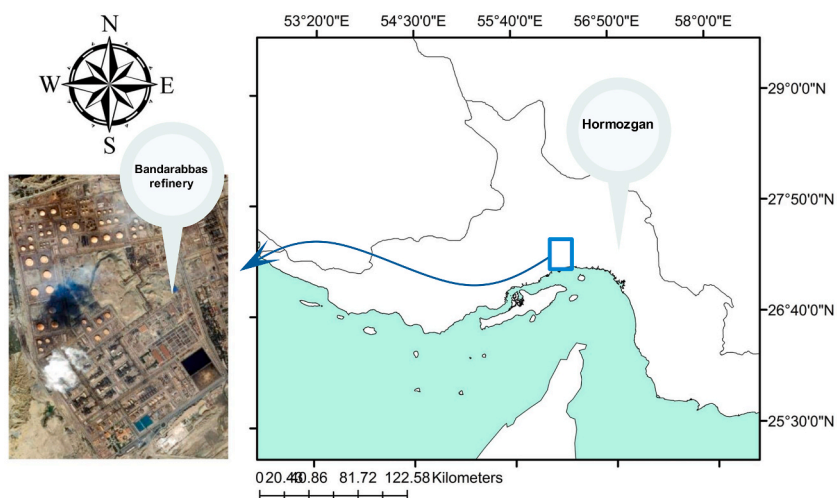


Fig. 1. Map of the study area.

temperature (650° Celsius) until complete combustion takes place and $\text{SO}_2(\text{g})$ is produced. Also, the ammonia gas entering from the Sour water stripper unit is burned in this furnace at a very high temperature to completely decompose $\text{NO}_x(\text{g})$. Therefore, $\text{SO}_2(\text{g})$, $\text{NO}_2(\text{g})$, and $\text{CO}_2(\text{g})$ are released into the atmosphere.

2.2.2. Amine treatment unit

This unit includes two separate units namely Amine absorption and Amine reduction. In refineries, alkanolamines are used to separate acid gases such as $\text{H}_2\text{S}(\text{g})$ and $\text{CO}_2(\text{g})$ from sour gas, among which diethanolamine (DEA) is often preferred due to its greater stability. In the Amine absorption unit, the sour gas released from the processes carried out in the Naphtha purification, Kerosene hydrotreating, and Diesel refinement units is collected in a tank. The liquid phase of this gas containing H_2S and hydrocarbon is transferred into a hydrocarbon drainage chamber. Sour gas is transferred from the tank to the Amine absorption tower, after that $\text{H}_2\text{S}(\text{g})$ is dissolved in the reduced amine solution and sent to the amine reduction unit. The sweet gas of the amine absorption tower is transferred to a separator tower to separate the remaining amine in the sweet gas, thereafter the sweet gas is directed to the Fuel system of the refinery while the remaining amine is transferred to the amine drainage chamber. The remaining liquid hydrocarbons in the amine absorption tower are also sent to the hydrocarbon drainage chamber whose outlet is connected to the Flare line. The Amine reduction unit is intended to regenerate amine containing $\text{H}_2\text{S}(\text{g})$ output from Naphtha purification, Kerosene hydrotreating, and Diesel refinement units along with amine containing H_2S gas output from the Amine absorption unit. In this unit, first the amine containing $\text{H}_2\text{S}(\text{g})$ (rich amine) is transferred to the tank of the Amine reduction unit. In order to prevent the release of H_2S gas, the tank pressure is controlled by nitrogen gas and some of the H_2S vapors are absorbed by a reduced amine solution. The liquid hydrocarbons in the tank located in the Amine reduction unit are transferred to the hydrocarbons drainage chamber, whereas the rich amine is directed to the amine reduction tower. The H_2S gas separated from the rich amine is sent to the Sulfur recycling and solidification unit. Furthermore, in case of existing high pressures in the tower, some of the H_2S is directed to the Flare line. The DEA solution is produced in a drainage chamber, by mixing the reduced amine from the Amine reduction unit with DM water. Its waste material which contains nitrogen-containing hydrocarbons is sent to the Flare line. The waste material flow in the Amine treatment unit has been depicted in Fig. 2.

2.2.3. Sour water stripper unit

The sour water originated from the processes carried out in Naphtha purification, Kerosene hydrotreating, Condensate distillation, Diesel refinement, Sulfur recycling and solidification, and Amine treating units contains ammonia and hydrogen sulfide. The sour water output from the mentioned units is first transferred to the counteractive chamber. Afterwards in order to prevent the interruption of sour water from different processes, the sour water is transferred to a tank. The pressure of the counteractive chamber and the tank is controlled by nitrogen gas. In case of existing high pressures inside the counteractive chamber and the tank, these gases are burned in the furnace of the Sulfur recycling and solidification unit for hindering the emission of ammonia and hydrogen sulfide gases. The sour water is transferred to the separator tower. Subsequently, the ammonia and hydrogen sulfide dissolved in the water are converted to gas. Ammonia and hydrogen sulfide gases from the separator tower are transferred to the sulfur recycling unit, while the sour water

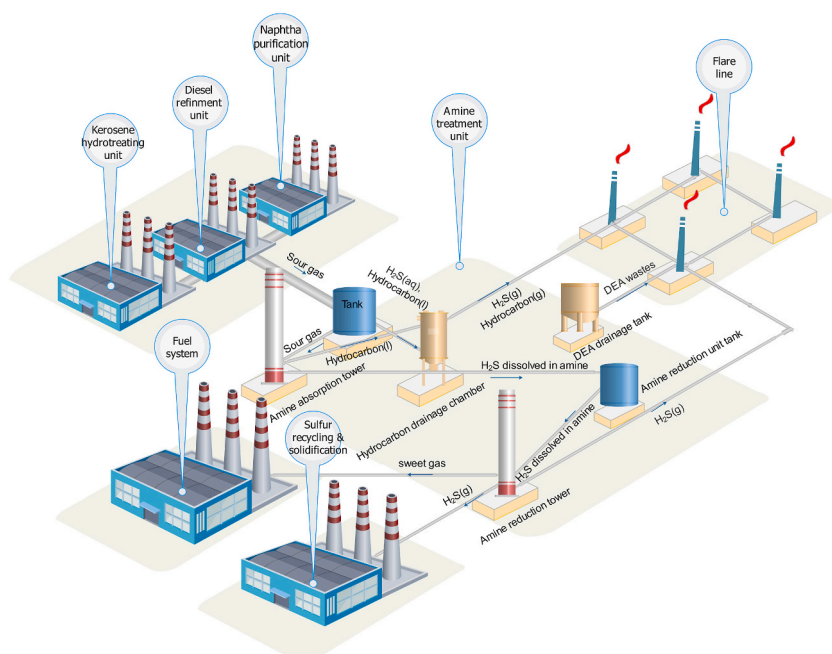


Fig. 2. Waste material flow in Amine treatment unit.

residue is transferred to the drainage chamber and next to a tank for purification, and the residue water in the tank is transferred to the residue water pond. The pressure of the separator tower is controlled by nitrogen gas. In case of existing high pressures in the tower, these gases are transferred to the Flare line. Also, the acid gases in the drainage chamber are fed to the furnace. Fig. 3 demonstrates waste material flow in Sour water stripper unit.

2.2.4. Steam and electricity unit, DM water system

Water without mineral salts is exploited for dilution, injection, washing, and storage for generating electricity and steam. In order to prepare DM water, water contaminated with Ca^{2+} , Mg^{2+} , Na^+ , SO_4^{2-} , HCO_3^- , Cl^- , and HSiO_3 are neutralized by polystyrene resins in a tank. When the concentration of silica and the conductivity of the produced DM water exceed the permissible limits, the resin regeneration operation is carried out. Cation-contaminated resins are regenerated by sulfuric acid solution and anion-contaminated resins are regenerated by caustic solution. Spent caustic water and sulfate salts are transferred to the wastewater pond in this unit.

The produced wastewater is neutralized by sulfuric acid solution and caustic solution with the aid of injected air flow and later is directed to the residue water pond to be transferred to the sea. Wastewater containing spent caustic contains sulfur and also has relatively high alkalinity and salinity [15]. For this reason, it encompasses a very high COD. Oily sludge is an emulsified solid waste material that appears in the water system of refineries due to the presence of organic substances and leaves implications on the surrounding environment. Hence, it needs to be processed in order to reduce its toxicity [16].

2.2.5. Water system

The incoming water from the sea is first desalinated and later is used in different parts of the refinery vis. DM water system, the water needed for producing caustic solution, equipment cooling, fire fighting, emergency showers, washing, and drinking. The water required for cooling the equipments is stored in a tank. In order to prevent air from entering the water, the water pressure is controlled by nitrogen. The output water from the various processes of the refinery, which contains oil and petroleum by-products, first enters the water residue ponds in this unit, and after separating these materials, it enters the ponds outlet and next is transferred to the sea. The output water from the processes with a temperature of 50° Celsius is transferred by the pump to the plate heat exchangers thus the temperature of the water is reduced to 40° Celsius, while the temperature of the fluid (sea water) escalates from 35 to 45° Celsius.

2.2.6. Fuel unit

The gas turbines need for fuel is supplied normally through the natural gas, while the diesel is used as backup fuel. The fuel consumed by furnaces and boilers is sweetened gas, and natural gas is used as backup fuel. If the pressure of natural gas in the gas storage tank of the refinery is low, gas turbines need for fuel is supplied through the diesel, while LPG gas is utilized as fuel for furnaces and boilers. In an emergency, the residue from the distillation tower is consumed as fuel for furnaces and boilers. Methane and nitrogen constitute 86 and 9% of the natural gas consumed by the refinery, respectively. 71% of the LPG gas consumed by the refinery is butane and 26% is propane. Normally, when natural gas and sweetened gases are applied as refinery fuel, NO_x , CO , and CO_2 gases resulting from combustion are released into the atmosphere.

2.2.7. Plant air & instrument air system

This unit is responsible for supplying air for the applications of precision instruments, the Merax unit and catalytic regeneration,

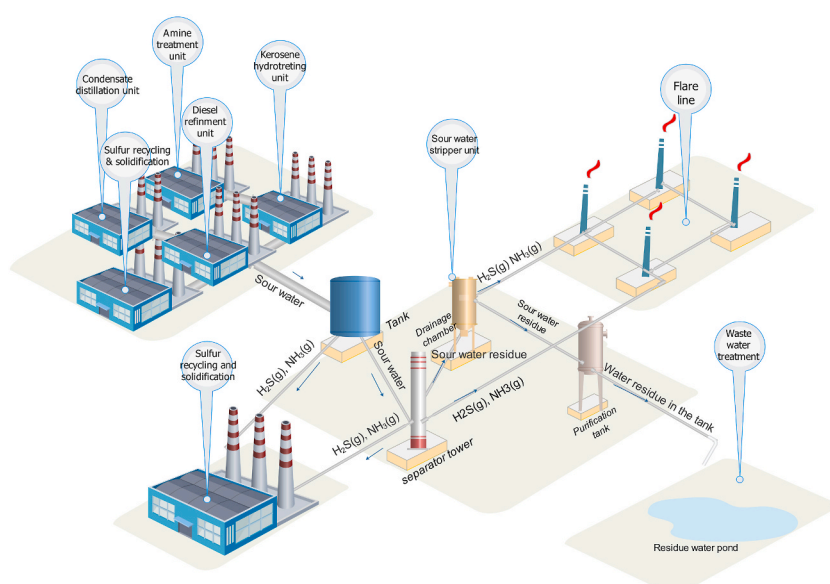


Fig. 3. Waste material flow in Sour water stripper unit.

and various parts of the Utility unit. It contains ambient air compressors. Compressors are equipments whose performance is accompanied by extraordinary noise.

2.2.8. Pipelines

Pipelines are considered as an interface between equipment and different units of the refinery. The leakage is the main implication of the Pipeline. The damage and leakage factors include natural phenomena, human factors, erosion and corrosion of materials, and the method of transmission. Hydrocarbons leak out of tanks for various reasons, including temperature fluctuations and volatile properties (VOCs). Also, improper adjustment of pressure control valves leads to leakage of gases and liquids.

2.3. BN design for risk assessment

BN modeling consists of variable definition and node selection, design of network structure, determination of utility function and conditional probability tables, data processing, and probabilistic inference [17]. The required data in this research were collected through the combination of refinery process documents, data sets, and domain knowledge. For this purpose, each unit in the refinery was considered as a subsystem and the required data was collected through pre-designed questionnaires. The average of the aggregated statistical data was considered as the input for the BN model. This research was performed in three phases. In the first phase, relying on experts' opinions, potential risks were identified, afterwards in the second phase of the research, the influence diagram was designed based on the required conditions for BN modeling. In the continuation of the second phase, by determining the conditional probability tables and utility function values, environmental risk assessment modeling was performed by the Netica software, and finally the BN network model related to the risk assessment presented. At the end of the second phase, the risks were prioritized, additionally using sensitivity analysis some useful inferences were presented. In the third phase, some solutions were procured to reduce the risk levels. Also, in the sensitivity analysis stage, three approaches namely predictive, diagnostic, and considering only one risk factor were presented.

BN is a kind of graphical model where the nodes specify variables and the relationship between variables is specified by arcs. Nodes with output arcs are entitled parent nodes and nodes with input arcs are called child nodes. These conditional distributions are determined by experimental data, statistical models, simulation, and previous studies. The arcs connected between nodes represent dependencies, and the intensity of causal relationships is expressed by conditional probabilities. For each child node, conditional probability distributions are assigned to the different permutations of the parent nodes' states. It is not possible to create loops in these models, therefore they are considered as models with direct acyclic graphs (DAGs). Due to the ease of calculations, the state of the nodes is usually considered discrete (binary or multiple), although in some cases it is necessary to use continuous states as well [8, 17]. BN models have the capability of forward conclusion, which means that the parent nodes are initialized later changes in the child nodes' states is investigated. Another feature of these models is the possibility of drawing conclusions in such a way that the parent node is fixed to the desirable value, thereafter the value of the different states of the child nodes is computed based on Bayes' law. Consequently, BNs have capabilities such as specifying the most important variables that cause a specific value of the parent node, and vice versa determining the sensitivity of the parent node to the variables pertaining to the child nodes in the network.

First, variables of the model were defined, and subsequently influence diagram were designed by means of domain knowledge. The design of influence diagram is based on some basic variables namely Air, Soil, Water, and Noise pollution which represent physico-chemical environment and make direct relation between the risk factors and social-biological environments; whereas Human health, Plants and wild life, and Habitats represent social and biological environments. However, the risk numbers has been defined based on

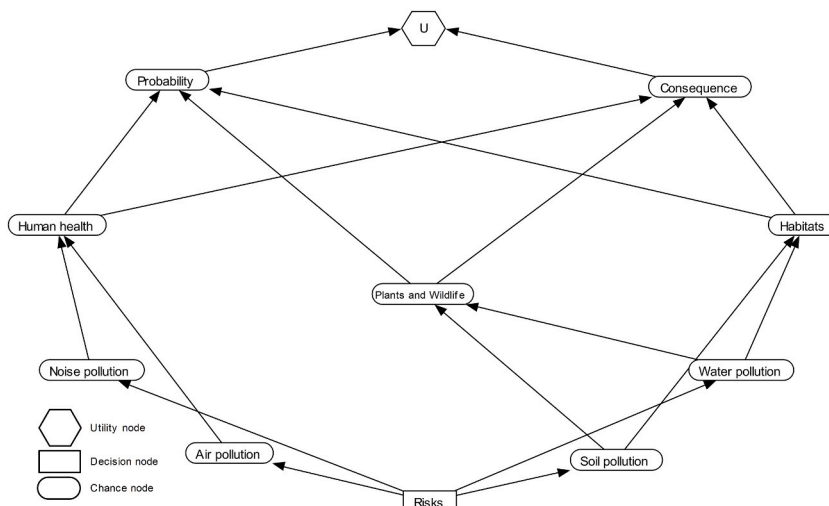


Fig. 4. Influence diagram.

product of probability and consequence nodes that located upside of the hierarchical structure (see Fig. 4).

For designing BN structure, Water pollution, Soil pollution, Air pollution, Noise pollution, Consequence, and Probability nodes have been defined as chance nodes with high and low states. Nodes Habitats, Plants and wild life, and Human health also have been considered as chance nodes, but with satisfactory and poor states. After identifying the risks, different states related to the decision node were also defined in the BN structure. Table 1 shows the characteristics of different nodes in the BN structure.

The values of the utility function were determined according to the all possible permutations of the risk descriptors namely the probability of occurrence and the severity of the effect. If the permutation of probability and consequence nodes is high and high, respectively, the utility function take the value of 1; in the case of low and low, the value of the utility function is 0.1; in the case of high and low, the value has been considered 0.6, and finally, if it is in the form of low and high The value of the function has been defined 0.7.

Determination of conditional probability distributions was performed by means of designing some questionnaires. Table 2 shows the content of two questionnaires designed for determining conditional probability distributions of the Sound. Questionnaires related to Noise pollution node were completed by ten Hygiene, Safety and Environment experts in different units identified as risk factors in the refinery. In these questionnaires, they were asked to answer the question “During an 8-h shift, how long are you exposed to unpleasant noise due to the specific unit processes?”. Next, the collected data was converted into the percentage scale and the values of the high state corresponding to the CPD of noise pollution node were obtained. Data related to CPD of Air pollution node were obtained with the aid of recorded data in HSE air monitoring systems. The data pertaining to ten days from the time period of February to March 2021 were selected as sample. These data represent the time period in which the HSE air monitoring systems were in alert mode in a minute time scale and the air pollution condition exceeds the occupational standard limits (Table 2). Similar to the Noise pollution node, the obtained data were converted into percentage scale, subsequently high state values corresponding to the CPD of Air pollution node obtained. Thereafter all data averaged and procured the input data for the conditional probability tables in the model. CPDs of Water and Soil pollution nodes also went through the same procedures as Sound and Air pollution nodes.

2.4. Sensitivity analysis method

BN models provide forward and backward inference. The predictive approach or forward inference is that first the parent nodes are initialized, thereafter the result is checked in the child node. The diagnostic approach or backward inference is that a state of the child node is determined, next the changes in the probability distribution of the parent variables would be checked based on Bayes’ law. Therefore, BNs have capabilities such as specifying the most important parent variables that cause a specific value of the child node through the backward inference, and on the contrary, they have the ability to determine the sensitivity of the child node to the parent variables in the network through the forward inference [18]. In the predictive approach, the probability value of one or more nodes for the parent node is considered 100% and the changes in the probability distribution of the child nodes are examined [5]. On the other hand, in the diagnostic approach, the probability of one or more offspring nodes is considered to be 100%, and changes in the probability distribution of the parent node are investigated. Also, in the third approach, only one of the risk factors of the model is considered, subsequently the probability distribution of other nodes is investigated and the role of the risk factor in the occurrence of various consequences is investigated and the most important ones are determined. The results of these approaches are presented in the results section.

Table 1
Characteristics of nodes in the BN structure for risk assessment.

Node	Node type in ID	Node states	Node type in hierarchical structure
Utility	Utility node	–	Goal
Consequence	Chance node	Low-high	Criteria
Probability	Chance node	Low-high	Criteria
Effect on habitats	Chance node	Poor-Satisfactory	Subcriteria-Level 1
Effect on plants and wild-life	Chance node	Poor-Satisfactory	Subcriteria-Level 1
Water pollution	Chance node	Low-high	Subcriteria-Level 2
Soil pollution	Chance node	Low-high	Subcriteria-Level 2
Air pollution	Chance node	Low-high	Subcriteria-Level 2
Noise pollution	Chance node	Low-high	Subcriteria-Level 2
Risk factors	Decision node	Steam and electricity unit <ul style="list-style-type: none"> • Plant air & Instrument air system • Water system • sulfur recycling and solidification unit • Sour water stripper unit • Pipelines • Fuel system • Amine treatment unit 	Alternatives

Table 2
Aggregated data for determining conditional probability distributions of the Noise and Air pollution nodes.

	Questionnaire/Sample number																			
	1		2		3		4		5		6		7		8		9		10	
	noise	air	noise	air	noise	air	noise	air	noise	air	noise	air	noise	air	noise	air	noise	air	Noise	air
Steam and electricity	48	72	10	202	48	115.2	5	288	5	288	19	144	29	129.6	10	72	29	100.8	38	28.8
Amine treatment	48	892.8	15	576	34	720	14	504	14	504	24	864	38	864	10	1008	14	950.4	29	1036.8
Plant air & instrument air system	120	201.6	168	29	216	43.2	154	57.6	154	57.6	173	57.6	197	100.8	178	28.8	250	43.2	312	100.8
Water system	10	144	19	72	38	288	48	360	34	144	53	201.6	19	288	14	432	5	172.8	0	57.6
Sulfur recycling & solidification	39	345.6	10	245	48	374.4	10	72	10	72	5	316.8	19	360	29	259.2	29	460.8	43	374.4
Sour water stripper	48	518.4	29	360	19	144	14	216	14	216	5	374.4	29	432	43	216	14	172.8	24	230.4
Pipeline	9.6	14.4	48	159	14	43.2	19	72	19	72	10	144	19	28.8	34	43.2	19	86.4	48	57.6
Fuel	58	648	5	720	24	676.8	29	864	29	864	10	936	48	849.6	19	619.2	14	748.8	5	993.6

Table 3

Risk factors, equipments, environmental endpoints, and potential impacts.

Amine treatment unit	Pipelines	Sour water stripper unit	Sulfur recycling and solidification unit	Plant air & Instrument air system	Fuel system	Water system	Steam & electricity unit	Risk factors
<ul style="list-style-type: none"> Hydrocarbon drainage chamber Amine reduction tower Amine reduction tank Drainage tank in amine regeneration unit 	<ul style="list-style-type: none"> Pipe Tank Control valve 	<ul style="list-style-type: none"> Separator tower Tank Drainage chamber Purification tank 	Furnace	Compressor	<ul style="list-style-type: none"> Furnace Gas turbine Boiler 	Residue water pond	DM water system	Equipment
Human Air	Human Air Soil	Human Air Water	Human Air	Human	Human Air	Water Air	Water	Endpoints
<ul style="list-style-type: none"> Burning hydrocarbon(l) and H₂S(aq) from drainage chamber in the flare line, which causes the release of CO(g), CO₂(g) and SO₂(g) into the atmosphere H₂S(g) direct emission into the atmosphere if the pressure of the tank and amine reduction tower rises CO₂(g), CO(g), and NO₂(g) emission into the atmosphere due to the burning of waste materials from DEA production in the drainage tank in amine regeneration unit 	<ul style="list-style-type: none"> Hydrocarbon transfer to the soil and release of VOC into the atmosphere 	<ul style="list-style-type: none"> NH₃ and H₂S emissions into the atmosphere by the counteractive chamber and tank for the sour water stripper unit Burning NH₃(g) and H₂S(g) caused by the separator tower and the drainage chamber in the flare line, which causes the release of NO₂(g) and SO₂(g) into the atmosphere Release of sour water from the purification tank containing NH₃(aq), H₂S(aq), and hydrocarbon(l) into the sea 	<ul style="list-style-type: none"> Air pollution with SO₂, NO₂, and CO₂ gases released from furnace 	<ul style="list-style-type: none"> Noise pollution 	<ul style="list-style-type: none"> NO, CO, and CO₂ emissions into the atmosphere by furnaces, boilers, and turbines 	<ul style="list-style-type: none"> Water pollution by oil by-products Release of VOC into the atmosphere 	<ul style="list-style-type: none"> Release of water contaminated with caustic, polystyrene resins and sludge into the sea 	Potential impacts

3. Results

3.1. Identified risks

In this section, the potential risks of each unit are presented.

3.1.1. Sulfur recycling and solidification unit

Release of SO₂(g), NO₂(g), and CO₂(g) from the furnace of the Sulfur recycling and solidification unit is the main consequence of this unit.

3.1.2. Amine treatment unit

Incineration of liquid hydrocarbons and H₂S(aq) originated from the hydrocarbon drainage chamber in the Flair line trigger the release of CO₂(g), CO(g), and SO₂(g) in the atmosphere; Incineration of H₂S(g) from the amine reduction tower in the Flair line leads to release of SO₂(g) into the atmosphere; Produced H₂S(g) is odorous and is considered as one of the toxic air pollutants, thereby direct release of H₂S(g) into the atmosphere in case of existing high pressures in the amine reduction tower and amine reduction tank is considered as another side effect; finally CO₂(g), CO(g), and NO₂(g) emissions due to the burning DEA-waste materials from the drainage tank, constitute the dominant impacts of this unit.

3.1.3. Sour water stripper unit

Possibility of releasing NH₃(g) and H₂S(g) into the atmosphere by the Sour water stripper unit tank; Incineration of NH₃(g) and H₂S(g) generated in the tank (incineration takes place in the furnace in the sulfur recycling and solidification unit); Incineration of NH₃(g) and H₂S(g) generated in the separator tower and drainage chamber leads to the release of NO₂(g) and SO₂(g); and the discharge of sour water residues containing NH₃(aq), H₂S(aq) and hydrocarbons(l) from the purification tank into the sea, are among the adverse effects of this unit.

3.1.4. Steam and electricity unit, DM water system

The possibility of releasing water contaminated with spent caustic, polystyrene resins, and sludge into the sea are the most significant implications of this unit.

3.1.5. Water system

The possibility of seawater contamination with oil by-products from the residue water pond, and the emission of VOCs in the

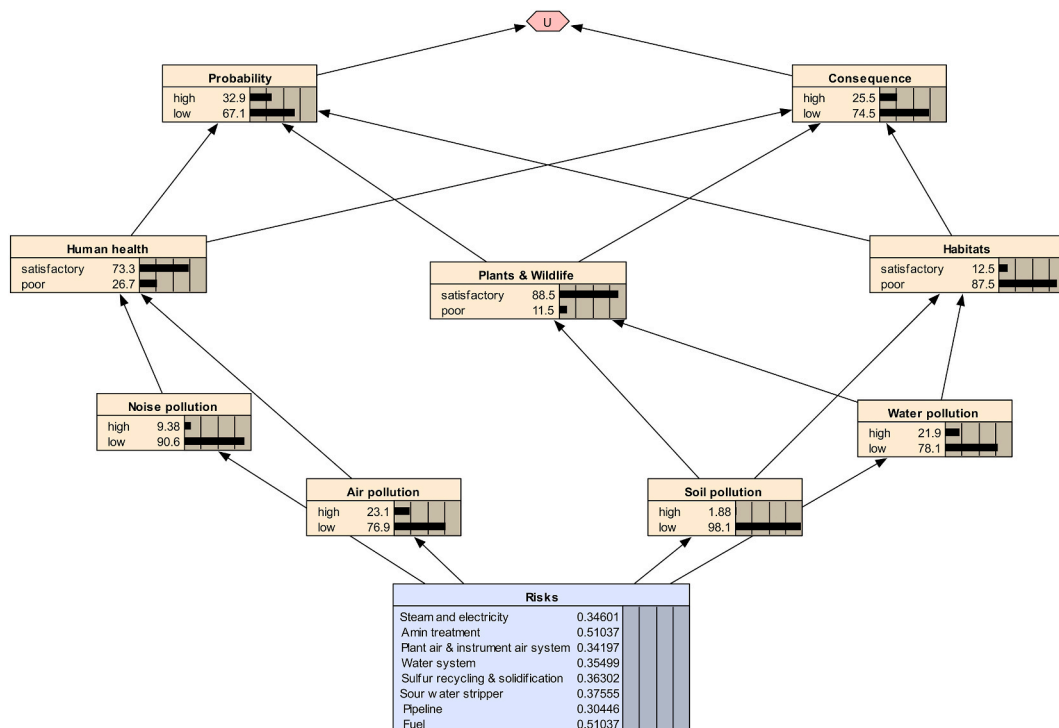


Fig. 5. BN for environmental risk assessment.

atmosphere comprise the negative side-effects of this unit.

3.1.6. Fuel unit

The NO_x(g), CO(g), and CO₂(g) emissions to the atmosphere by furnaces, boilers, and turbines have been considered as the most important potential impacts of this unit.

3.1.7. Plant air & instrument air system

Noise pollution by the compressor is the main implication of this unit. People who are exposed to sound more than 85 dB on a daily basis are at the risk of hearing loss [19]. Also, unusual noise stimulate disturbances in heart rate, cholesterol level, uric acid level, metabolism, and weight [20].

3.1.8. Pipelines

Leakage from pipelines, tanks and pressure control valves is considered as the negative effect of the pipelines. The identified risks have been listed in Table 3. In the first column of this table, the risk factors, and in the second column the equipments generating potential risks in each unit have been shown. Also, human, water, soil, and air environments are considered as end points in the third column of table. Finally, the fourth column of this table contains a description of potential risks related to the equipments located in each unit.

3.2. Prioritizing risks

By entering conditional probability values in CPTs, BN was created (Fig. 5). Based on the results obtained from the decision node, which includes the expected value of the risk factors mentioned in the decision node of the BN, the risk factors were prioritized. The utility variable expresses the negative effect of different risks, so that higher values indicate more negative impacts and have a higher rank in prioritization. The classification of risks has been done by considering the expected value of the risk factors in the decision node according to the categories illustrated in Fig. 6. If the risk number is more than 0.75, the risk is placed in the category of unacceptable, 0.5–0.75 unfavorable, 0.25–0.5 acceptable but need to be revised, and less than 0.25 is classified as acceptable. As shown in Fig. 6, the risk factors of Amine treatment unit and Fuel unit with expected values of 0.51037 were recognized as the dominant risk factors in the risk assessment model and were placed in the category of unfavorable risks. The risk factors of Sour water stripper unit, Sulfur recycling and solidification unit, Water system, Steam and electricity unit, Plant air & Instrument air system, and Pipeline with expected values of 0.37555, 0.36302, 0.35499, 0.34601, 0.34197, 0.30446 were classified as the acceptable but need to be revised risks.

4. Discussion

4.1. sensitivity analysis

In this section, three approaches namely predictive, diagnostic, and considering only one risk factor were applied. In the predictive

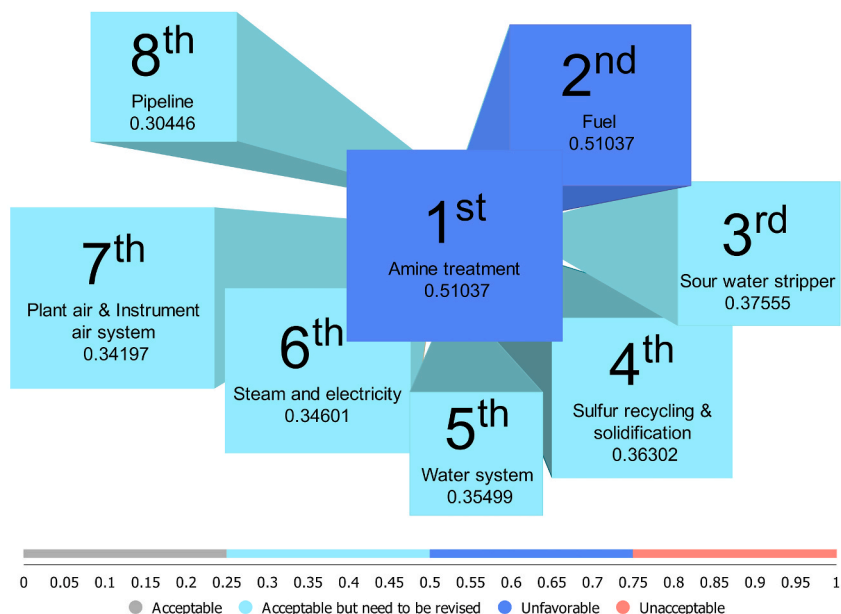


Fig. 6. Prioritizing the risk factors.

approach, the probability value of one state in one or more parent nodes is considered 100% and the changes in the probability distribution of the child nodes are examined [5]. In this model, the high state value in the air pollution and noise pollution nodes were changed to their highest level, separately. In the case of Air pollution node, satisfactory state in the human health node altered significantly from 73.3 to 9.7. Though high state value in Noise pollution node underwent greater changes, applying predictive approach for this node did not affect satisfactory state value in the Human health node substantially, lowering from 73.3 to 60.5%. The results of sensitivity analysis with the predictive approach show that finding remedies for air pollution is more efficient for improving human health issues. On the other hand, in the diagnostic approach, the probability value of one or more offspring nodes is considered to be 100%, and changes in the probability distribution of the parent nodes are investigated. The satisfactory state of Human health node was fixed at 100%, after that the changes in the probability distribution of Air pollution and Noise pollution nodes were investigated. The value of the high state in the Air pollution and Noise pollution nodes changed from 23.1 to 3.06 and 9.38 to 7.74, respectively. The result of sensitivity analysis with this approach confirmed that in order to address human health issues, there should be remarkably more attention to reduce air pollutants in the atmosphere than the noise pollution, as subtle changes in high state value in Air pollution node could stimulate greater enhancement in satisfactory state in Human health node.

Moreover, in another approach, only one of the risk factors in the model is considered, subsequently the changes in the probability distribution of other nodes are scrutinized. In this approach, the role of one specific risk factor solely in the occurrence of all environmental consequences is investigated and the dominant impacts are reported. Thereby, first only Amine treatment unit was considered in the model, next the impact of this factor on the poor state in the Habitats, Plants & wildlife, and Human health nodes was examined. The probabilities pertaining to the poor state in the Habitats, Plants & wildlife, and Human health nodes were 92.9%, 6.81, and 52.5%, respectively, which indicates this unit has a greater impact on the Habitats node. Also, the probabilities related to the high state in water, soil, air, and sound pollution nodes were observed as 5, 1, 55, and 5, respectively, which indicate this unit solely is more effective in the occurrence of air pollution than the other types of pollution. This approach was also applied for the other units, and the impact of different units on the high state in the water, soil, air, and sound pollution nodes, as well as on the poor state in the habitats, plants and wild life, and human health nodes were examined separately. The results of utilizing this approach separately for all units were exploited as input data for the statistical analysis. A breakdown of the analysis has been depicted in Fig. 7. The outcome of comparing results from the sensitivity analysis indicate that the Steam and electricity unit has a dominant impact on the water environment compared to the other units, while regarding the soil, air, and sound, the Pipeline, Amine treatment along with Fuel, and Plant air & Instrument air system, respectively, have played pivotal role in this field than others. Further to that, all the units affect the habitats almost equally, while in the case of plants and wild life, the Steam and electricity unit and in the case of Human health, the Amine treatment and Fuel units outstrip other units. On the other hand, if the purpose of prioritization is to considering all the endpoints simultaneously, the decision would be based on the risk numbers obtained from the BN in Section 3.2 (Fig. 7c). However, in case of considering one specific endpoint (e.g. air) (Fig. 7a) or one of the habitats, plants and wild life, and human health nodes (Fig. 7b), the decision would be based on the results obtained from the sensitivity analysis by considering only one risk and their statistical analysis. It should be noted that decision-making in the context of prioritizing different units so as to process the waste materials originated from the units for achieving the sustainable development goals in the refinery, apart from the predetermined environmental goals, depends on some other factors vis. The cost of upgrading technologies required for the waste treatment, as well as the added-value that each unit creates for the production of final products, which could be evaluated in the future researches. Sustainable development means improving the quality of life in such a way as to procure a basis for living in a healthy environment as well as improving the social, economic, and environmental status of the current and future generations. Sustainable development goals in industries are related to the design of industrial processes to rationally and effectively use of resources. According to the sustainable development goals, industrial processes should be designed in such a way that the environmental impacts of the processes through

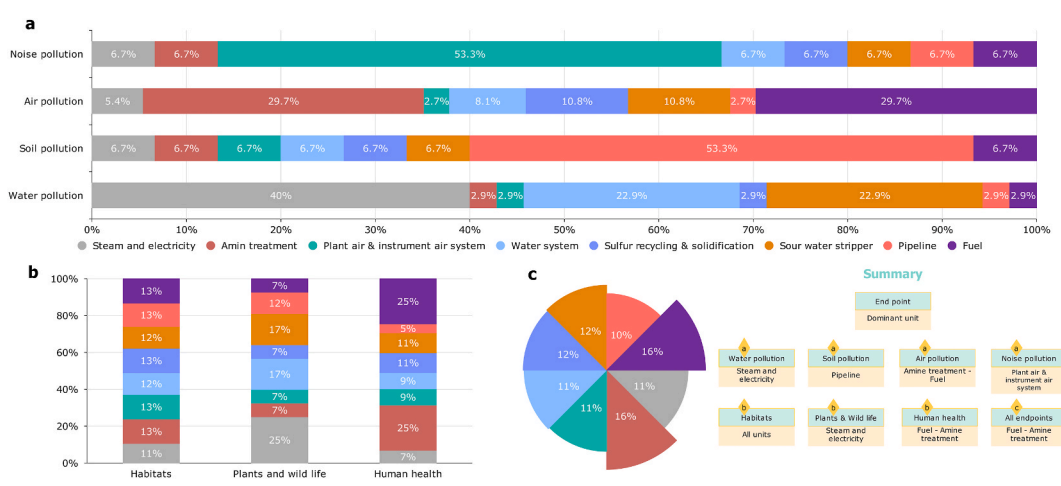


Fig. 7. Determination of dominant units pertaining to the different end points. (a) Considering water, soil, air, and sound as end points. (b) Considering habitats, plants and wild life, and human health as end points. (c) Considering all endpoints concurrently.

waste treatment systems are solved effectively and efficiently [21]. In order to design and implement instrumental waste treatment systems in a refinery, it is first necessary to determine the environmental goals before designing and upgrading efficient waste treatment systems in different units of the refinery in line with the predetermined goals. Due to the existence of economic and time limitations in the field of implementing waste treatment systems, it might not be possible to completely eliminate the environmental impacts in a refinery concurrently. This is why, in this research, by utilizing the BN model and the related analyzes, in line with different environmental goals, the priority of different units of the refinery for implementing waste treatment systems was determined, so that relatively achieving sustainable development goals related to the industry and industrial processes would be facilitated.

4.2. Limitations

One of the limitations in BN modeling could be the positive correlation between the number of variables that determine the casual relations in the model, and the occurrence of biased estimates. Thereby, in this research an attempt has been made to designate rational number of chance nodes for designing the BN in the risk assessment. Clearly, in case of removing this limitation in the future researches, the ground will be provided for defining a large number of variables in the model, which in turn contributes to describe the nexus between the man-made system and the environment appropriately, additionally enhances stochastic inferences remarkably.

Another limitation in the BN modeling is to determine the conditional probability tables of the model, which could affect the uncertainty issue in the BN models owing to the lack of accessibility to the comprehensive data sets. For instance, in this research, due to the lack of access to premeasured data in the field of soil and sound pollution monitoring, conditional probability distributions were determined by relying on domain knowledge. This is why, the determination of conditional probability tables of the model might intensify uncertainty issue. In addition, the mobility of the air pollutants could influence accuracy of the results obtained from the air monitoring systems and consequently uncertainty.

Also, the design of the BN is based on the existence of the independencies between the variables which have not direct casual relations with each other. This condition facilitates calculations related to conditional probability probabilities and distributions. However this condition is not likely to be entailed in the real cases, and consequently the obtained inferences involve inherent errors. Neglecting this condition makes the calculations corresponding to the conditional probability distributions extremely complicated thus practically makes BN applications significantly restricted.

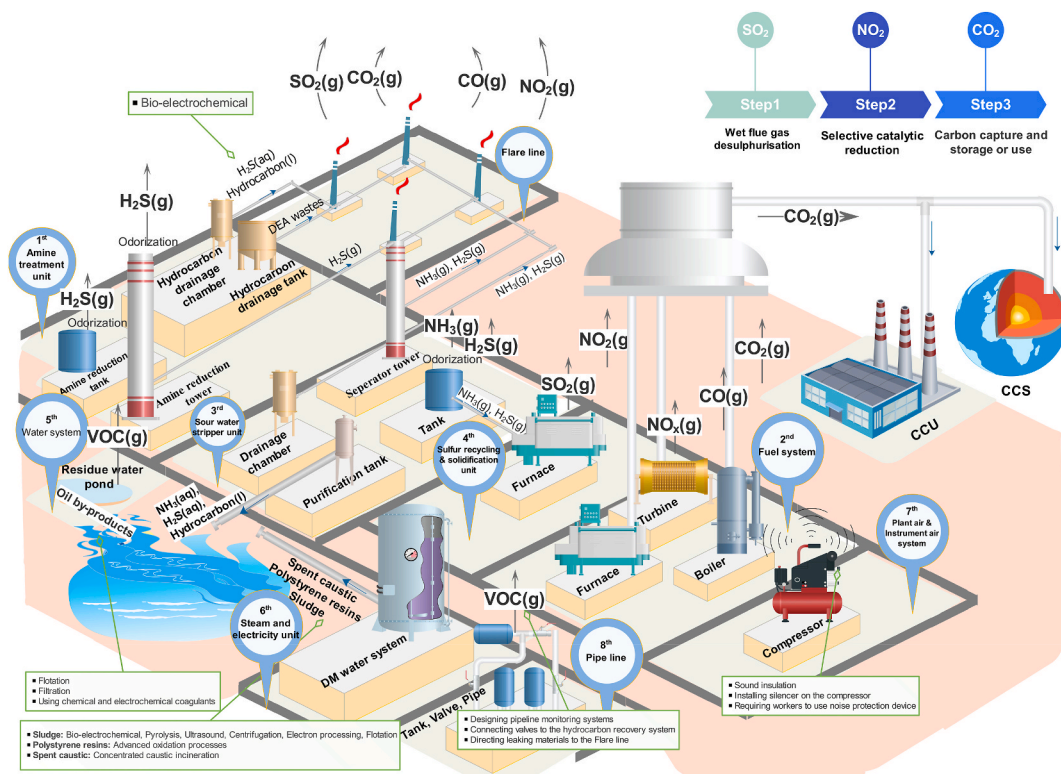


Fig. 8. Suggested solutions.

4.3. Suggested solutions for reducing the risk levels

As shown in Fig. 8, some promising remedies have been proposed for some groups of the contaminants in different units. Gaseous pollutants that can be liberated into the air account for CO(g), CO₂(g), SO₂(g), NO₂(g), H₂S(g), and VOC(g). Whereas, H₂S(aq), NH₃(aq), spent caustic, polystyrene resins, hydrocarbon(l), and sludge are likely to be discharged in the water and soil environments. The units that have the potential to emit gaseous pollutants consist of Sour water stripper, Fuel system, Amine treatment, and Sulfur recycling & solidification. Meanwhile, hydrocarbon(l), H₂S(aq), and NH₃(aq) from the Sour water stripper unit; spent caustic and polystyrene resins from the Steam and electricity unit, and hydrocarbon(l) from the Water system trigger impacts on the water environment; and finally hydrocarbon(l) from the Pipe line can be diffused in the soil environment. In researches conducted in the field of waste material treatment, the method of carbon capture and storage or use has been recommended for eliminating CO(g) and CO₂(g). In this regard, wet flue gas desulphurisation and selective catalytic reduction methods are used as pre-processing to purify SO₂(g) and NO₂(g) gases; While H₂S(g), NH₃(aq), and a wide range of hydrocarbons can be processed effectively by a bio-electrochemical system. On the other hand, the methods of concentrated caustic incineration and advanced oxidation processes provide high efficiency in spent caustic and polystyrene resins treatment, respectively. Further to that, bio-electrochemical, ultrasound, pyrolysis, centrifugation, electron processing, and flotation make up suitable methods for sludge processing in refineries. On the other hand, the emission of volatile organic compounds can be controlled to a great extent through filtration and floatation, and utilizing chemical and electrochemical coagulants.

4.3.1. CO(g), CO₂(g), SO₂(g), and NO₂(g)

CO(g), CO₂(g), SO₂(g), and NO₂(g) gases can be eliminated by the Carbon capture and storage or use process. CCS and CCU can be applied in the furnace, boiler, and gas turbine of the Fuel system for CO(g), CO₂(g), CO(g), SO₂(g), and NO₂(g), in the furnace of the Sulfur recycling and solidification unit for SO₂(g) and NO₂(g), in the Flare line for CO(g) and CO₂(g) originated from the liquefied hydrocarbons and DEA-generating waste materials of Amine treatment drainage chamber. In this method, before CO₂(g) emitted from the chimney, a chemical substance is used to absorb carbon dioxide [2]. In carbon capture and use (CCU), when carbon dioxide is absorbed, it can be converted to the new products such as synthetic fuels, plastic materials, and construction materials. The reaction between carbon dioxide and minerals and saline water causes carbon dioxide to be well stabilized in the earth layers (Fig. 8). Thereby, CCS is considered safe and permanent method to manage carbon emissions in the long term [3]. Carbon capturing method is classified into three categories: post-combustion, pre-combustion, and oxy fuel-combustion. However the application of post-combustion method is currently more simple and feasible [22]. There is anticipated to be a reduction of 64–80% in the amount of greenhouse gas emissions in a system during its life cycle with the aid of carbon capturing method [23]. The implementation of carbon capturing method requires a pre-treatment process for eliminating NO_x(g) and SO_x(g). Accordingly, the pre-treatment operation can be considered as a solution for removing NO_x(g) and SO_x(g). Selective catalytic reduction (SCR) and non-catalytic reduction (SNCR) methods are used in pre-processing operations to remove NO_x(g). In this process, NO_x(g) is converted into N₂(g) and water. It should be noted that the Selective Catalytic Reduction method can be performed at low temperatures and its application has been more developed than the non-catalytic reduction method. SO_x(g) can be processed in a pre-designed Wet flue gas desulphurisation (WFGD) unit. The acidic nature of SO_x(g) makes this gas to be processed well by CaCO₃(aq). The SO_x(g) treatment can also be materialized by dry FGD or semi-dry FGD methods, but the WFGD method has been more developed than the other methods [24].

4.3.2. Hydrocarbon(l), H₂S(g), and NH₃(aq)

Hydrocarbon(l), H₂S(g), and NH₃(aq) treatment can be materialized by a bio-electrochemical system. This method can be applied in the Amine treatment unit for the H₂S(g) odors and liquid hydrocarbons discharged from the hydrocarbon drainage chamber; in addition to the Sour water stripper unit for the NH₃(aq) and liquid hydrocarbons released from the purification tank and for the H₂S(g) odors of the Sour water unit tank (Fig. 8).

Bio-electrochemical method is capable of processing organic waste materials such as hydrocarbons, PAHs, sludge, as well as inorganic waste materials such as sulfides and ammonia. The mechanism of a bio-electrochemical system is based on the activity of microorganisms that transfer electrons from the reduced electron donor to an electrode and later to the oxidized electron acceptor, which is also accompanied by the generation of electricity. It comprises two main processes, namely fermentation (substrate oxidation) and respiration (reduction). These two processes necessitate using an electron source (substrate) to facilitate the microbe's metabolism and an electron acceptor (sink or electrode) as a complement to the electron chain. The two processes of fermentation and respiration are separated by a permeable membrane layer. Thereby, the ground is provided to trap the produced energy. In a biochemical system, caustic and chlorine, or sodium hypochlorite are used as H₂S(g) scrubber. Using the biochemical system to process H₂S(g) provides economical energy up-sides, beside its application descend the amount of generated wastes in the environment. Though, In traditional processes, H₂S(g) is converted into elemental sulfur through Claus process, which are energy intensive and accompanied by the liberation of heat energy extravagantly. This is why, they could not be considered as environmental friendly methods.

Another approach that can be implemented to prevent the SO₂(g) emissions to the air environment, posed by the incineration of latent sulfur in the feedstock or fossil fuels, is that before feedstock injection to the refinery processes a combination of biochemical system and electrochemical process could be used; in such a way that in the first step the feedstock is processed by the bio-electrochemical system. Since the operation of the bio-electrochemical system might lead to the production of H₂S(g), subsequently the electrochemical process is used to convert H₂S(g) into elemental sulfur. In this way, SO₂(g) emissions originating from the burning of petroleum products and by-products as well as H₂S(g) emissions resulting from the refinery processes would be hindered, further this strategy encompasses energy up-sides compared to the pure biochemical process [2].

$\text{NH}_3(\text{aq})$ in the effluent from Sour water stripper unit can be purified by a bio-electrochemical system. Ammonia is the most abundant among nitrogenous waste materials in refineries. The removal rate of this substance by a microbial fuel cell including two bio-cathodes can reach to 96% [25]. In the bio-electrochemical system, ammonia nitrogen is first oxidized by means of bacteria so that the bacteria absorb nitrite or nitrate ions. Denitrogenation later occurs so that the absorbed ion is removed from the bacteria and nitrogen gas is released. In general, the performance of bio-electrochemical system in the field of nitrogen removal from wastewater systems dominates other biological methods.

The hydrocarbon output from the Amine treatment and Sour water stripper units, which are directed to the Flare line and residue water ponds, respectively, can be processed by a bio-electrochemical system. The removal rate of the total petroleum hydrocarbons in the wastewater can reach to 41.8%, and in case of providing anaerobic conditions, the higher efficiencies are achievable. Besides, aromatic hydrocarbons can be processed more efficiently than other existing methods [26, 27]. The application of bio-electrochemical methods to process refinery waste materials has the advantages of energy production, low design and start-up costs, high flexibility [2], acceptable efficiency at low temperature and conductivity, complying with the requirements related to disposal of waste materials in the environment [28].

4.3.3. Spent caustic, polystyrene resins, and sludge

Disposal of spent caustic and polystyrene resins expelled from the DM water system, can be performed by concentrated caustic incineration and advanced oxidation processes, respectively. Meanwhile, the produced sludge can be purified and processed by various methods such as bio-electrochemical, pyrolysis, ultrasound, centrifugation, electron processing, and flotation.

Several methods have been developed for the spent caustic treatment, some of which are based on incineration process. Since incineration methods demands extravagant energy, solely cost a fortune. To overcome this challenge, before incineration, the spent caustic is concentrated with the aid of some evaporation and freezing methods, among which freezing method is more energy efficient, economical and environmental friendly. In the freezing technology, with water containing spent caustic is being gradually frozen, ice crystals gradually grow. In this way, by directing the spent caustic to the liquid phase, its concentration ascends, thus make it possible for the concentrated caustic to be incinerated, while the frozen water recovered [29]. Therefore, the freezing method has been considered for concentrating the spent caustic released from the DM water system.

Polystyrene is a plastic material that is produced by polymerizing styrene monomers, therefore it is considered as an aromatic hydrocarbon polymer [30]. The use of advanced oxidation processes is specifically suitable for the processing of non-biodegradable aromatic polymers. Therefore, this method can be widely used to process polystyrene resins. This method can be used in Steam and electricity unit to preclude the release of polystyrene resins from DM water system to the sea. In AOP, highly reactive radicals are used to complete the process of oxidizing organic pollutants in wastewaters [31]. Hence, radicals absorb organic compounds containing active electrons to complete decomposition process of organic compounds. In this regard, the hydroxyl radical benefit from a robust performance compared to other chemical agents in the decomposition process. AOP methods cover a wide range of organic pollutants and convert them to inorganic compounds [32]. This is despite the fact that in the traditional methods, due to their stability, as well as their low solubility in water, their complete separation is not viable [31].

4.3.4. VOC(g) and noise

When it comes to the VOC(g) which liberates from the Water system, filtration and floatation processes, as well as the use of chemical and electrochemical coagulants are considered more suitable options. While in the case of VOC(g) that can be emitted from the pipeline, some solutions vis. directing leaking materials to the flare line, connecting valves to the oil recovery system, and designing a pipeline monitoring system can be used.

Sound insulation, installing silencer on the compressor, and requiring workers to use noise protection device are among the solutions to control noise in the environment [8].

5. Conclusion

In this research, with the aim of providing a framework for achieving clean production and sustainable development goals, BN model was used for Bandarabbas refinery risk assessment. According to the obtained results from the risk assessment model, Amine treatment and Fuel unit were determined as unfavorable risks, whereas Sour water stripper, Sulfur recycling and solidification, Water system, Steam and electricity, Plant air & Instrument air system, and Pipelines were placed in the category of acceptable risks. To perform sensitivity analysis three approaches namely predictive, diagnostic, and considering only one risk factor were applied. What is more, in the sensitivity analysis by applying the third approach, the impact of the each unit separately on environmental endpoints vis. Water, soil, air, and sound environments as well as the Habitats, Plants and Wild life, and Human health nodes was investigated. Attaining sustainable development goals in refinery necessitates appropriate resource management and the design of efficient waste treatment systems. The results of BN model and sensitivity analysis facilitated sustainable development goals achievement in Bandarabbas refinery by introducing preference of the refinery units when it comes to the paralyzing impacts of the wastes on the environment and the design of instrumental waste systems. Furthermore, these results provided a framework for managers and policy makers in decision making process based on their predetermined environmental targets and in line with sustainable development goals regarding the extinguishing environmental adverse effects.

Author contribution statement

Meysam Saeedi; Bahram Malekmohammadi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

Supplementary content related to this article has been published online at [URL].

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.heliyon.2023.e15264>.

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