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Determining the Optimal Maintenance Strategy for Ammonium Hydroxide Production Unit Using Risk-Based Inspection and Analytic Hierarchy Process

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ABSTRACT

Ammonium Hydroxide production unit (AHPU) is one of the widely used and important units available in many industries such as oil and gas, petrochemical, and power plants. In this research, for the first time, a detailed systematic inspection and maintenance plan for AHPU is determined based on the prioritization of equipment using equipment's risk analysis. Equipment's failure risk is calculated based on probability and consequence of failure according to American Petroleum Institute Recommended Practice (API RP) 581. Different maintenance strategies were designed and compared considering several criteria like safety, cost, and feasibility using the analytic hierarchy process. Then risk-based optimal maintenance policy for each group of equipment was identified. Finally results showed that, the equipment identified as high or medium to high risk level such as liquid ammonia storage tank and its related pipes, should possesses preventive maintenance with an inspection period of 48 months. While for the medium risk equipment such as ammonium hydroxide storage tank and low-risk equipment such as ammonia absorption tank, should have corrective maintenance with inspection period of 72 and 90 months, respectively.

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1. INTRODUCTION

The occurrence of major accidents in industrial units leads to adverse effects on the main components of sustainable development, including the environment, economy, and society. According to recent studies, more than 80% of process unit accidents are related to 20% of equipment, which shows the importance of inspection in the industry [1-3]. Nowadays, there is an increasing attention to the risk-based methods for developing inspection, maintenance, and repair strategies in oil, gas, petrochemical, and power plant industries. The main reasons are the complexity of production processes in these industries, expensive equipment used, extra costs due to unexpected stops and overhauls, environmental contamination, and the importance of optimal usage of these processes [4, 5].

Risk-based inspection (RBI) is a management tool for identifying equipment risks and determining an inspection plan based on calculated risks. In RBI technique, first, the probability and consequence of equipment failure are calculated and the amount of risk is obtained by multiplying these two factors (probability and consequence). Then, based on the amount of the risk, equipment is prioritized and an inspection plan is defined for them. In this technique, unlike traditional inspection plans, which are based on a standard or manufacturer's suggestion, for each group of equipment, there will be a separate inspection schedule according to their level of risk [6].

In recent years, RBI and maintenance methods have become intertwined, and the tendency towards a risk-based approach for choosing an effective maintenance method has increased [1, 4, 7, 8]. On the other hand,

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choosing an appropriate maintenance plan is a very effective factor for decreasing maintenance time and cost in production units. A non-optimal maintenance plan may leads to unnecessary maintenance activities and wasting money and time or less maintenance activities resulting in more breakdowns and unwanted outages. Therefore, incorporating expert opinion and analysis in choosing the appropriate maintenance policy is an important factor that can improve the productivity of production units.

In 1990 Chen and Toyoda [9] developed a strategy for scheduling maintenance activities based on final risk. The RBI strategy was developed by the American Society of Mechanical Engineers (ASME) in 1991, [7]. In 2001 Dey [10] and Dey, Ogunlana and Naksuksakul [11] introduced a more general model for RBI and maintenance for offshore oil and gas pipelines. In these studies, the probability of failure in transmission pipelines is calculated by the AHP method by considering several criteria and sub-criteria among the known faults of pipelines. In 2007, Arunraj and Maiti [12] studied RBI methods and their application. The results of their study, which were performed on 25 RBI methods, showed that there is no unique method for conducting risk analysis and RBI. In 2009, Bertolini, Bevilacqua, Ciarapica and Giacchetta [13] reviewed the development of RBI and maintenance methods for oil refineries and proposed a method for RBI and maintenance. In 2010, Arunraj and Maiti [14] determined the appropriate maintenance plan for the benzene extraction unit of a chemical plant using the methods of Analytic Hierarchy Process (AHP) and goal programming. They provided a model for selecting risk-based maintenance (RBM) methods based on equipment failure and maintenance costs. This study illuminated that Condition-Based Maintenance (CBM) and Corrective Maintenance (CM) methods are suitable for high-risk and low-risk equipment, respectively. In 2012, Wang, Cheng, Hu and Wu [6] worked on the development of an RBM strategy using the FMEA method for the continuous catalytic reforming unit. The results of this study showed that the FMEA is a suitable approach for identifying critical equipment, and RBM policy can increase the reliability of high-risk equipment. In 2012, Kumar and Maiti [15] studied modeling the maintenance policy of an industrial unit using a fuzzy analysis network. The results show that the CBM is suitable when the risk of equipment is very high and the CM is preferred when the equipment risk is low and maintenance costs are significant. When both risk and maintenance costs are equally important, the Time-Based Maintenance (TBM) method is preferred. In 2018, Mohamed, Mahani and Razak [16] worked on the corrosion problem of equipment and lines of a floating platform in Petronance Company using the RBI method. Their research resulted in a 10-year and 15-year inspection and repair plan based on equipment risk classification. In 2019, Yazdi, Nedjati and Abbassi [17] developed a new maintenance strategy based on the intuitionistic Fuzzy AHP to obtain the weights of different investment factors for a separator system in an offshore process facility platform. The results indicate that the developed methodology estimates the risk more accurately, which enhances the reliability of future process operations. In 2020, Farizhendy, Noorzai and Golabchi [18] developed a model to select an optimal repair and maintenance method for jack-up drilling rigs in Iranian shipyards, they used genetic algorithm NSGA-II for solving multi-objective problem consists of cost, time, person-hour and environment-health. The results of this research help the experts of the Jack-up R&M make the right decision. In 2020, Eskandari, Charkhand and Gholami [1] provided a semi-quantitative management tool based on RBI on the de-ethanizer unit, to recognize and then prioritize the equipment's risks and, consequently, propose an inspection plan based on these risks. Their study results in saving a shutdown cost, inspection cost, reduction of failure, and increasing equipment reliability factor.

RBI is a regular method for determining and applying the failure rate of devices and equipment in the maintenance of facilities and making inspection decisions. RBI studies provide a more accurate understanding of the hazards and possible degradation mechanisms associated with pressurized reservoirs and piping. This information is very helpful in providing a complete asset integration plan and thus proper risk management. Moreover, RBI increases the time between technical inspections and periodic repairs. In this research, for the first time, an RBI plan will be determined for the equipment of the Ammonium Hydroxide Production Unit (AHPU), and the optimal maintenance strategy for the equipment of this production unit will be determined using the AHP method according to the risk level of equipment. In the AHPU, the consumed ammonia has a purity of 99.9%, and a 25% by weight solution of ammonia in water is prepared in this unit per day and at the same time, gaseous ammonia is sent to the consuming units. The main contributions of this study, which make this study original, are listed briefly in the following:

- Determining the risk types and levels governing equipment and process lines in AHPU for the first time
- Determining the intervals of technical inspection of equipment based on the level of risk of each equipment
- Determining maintenance policy based on the risk level of each equipment
- Increase the effectiveness of inspection operations and identify faults and their causes
- Determining the criteria affecting repair and maintenance in the AHPU

In the following, some related researches will be reviewed in section 2. In section 3, the proposed research method will be presented. In section 4, the results of implementing the proposed model in the AHPU will be presented and finally, the conclusion will be expressed in section 5.

2. THEORY OF MAINTENANCE, INSPECTION AND RISK ANALYSIS

Maintenance is a combination of management and engineering operations to maintain an object in a good working condition or to restore it to an acceptable condition. As stated, more than 80% of process unit accidents are related to problems in 20% of equipment (Figure). Common maintenance methods include Emergency Maintenance (EM), Breakdown Maintenance (BM), Preventive Maintenance (PM), CBM, TBM, Reliability-Based Maintenance (ReBM), and CM [4, 19]. One of the main objectives of each maintenance policy is to minimize hazards caused by unexpected equipment failure to humans and the environment.

Also, the maintenance policy should be cost-effective. Using a risk-based approach ensures that these goals are achieved. This approach uses the information obtained from the study of failures and their consequences [18]. Usually, risk can be determined qualitatively and quantitatively for the failure scenario. Based on the definition provided in American Petroleum Institute (API) 580 and API recommended practices 581(API RP 581) , risk can be calculated as follows [4, 7, 8]:

$$Risk = probability\ of\ failure \times Consequences\ of\ failure \quad (1)$$

After risk calculation for equipment, using the risk matrix, the priority of the assessed components is determined, and risk values are used to prioritize inspection and maintenance activities. In high and medium-risk areas, a centralized inspection, maintenance, and repair activity is required. That is while, in low-risk areas, maintenance-related activities are minimized to reduce the total inspection cost. RBI, which is a method for reducing the probability of an unpredictable failure, provides a set of suggestions on how to take preventive measures, including type, tools, and timing. The purpose of RBI is to identify more critical areas that need more attention in the inspection program. According to API RP 581, in qualitative analysis, first, the factor that indicates the possibility of a piece of equipment failure is identified, and then the factor for failure consequences is identified. By combining these two factors of failure and consequence, the position of the equipment in the risk matrix is determined and the equipment is ranked based on risk value [4, 8, 14].

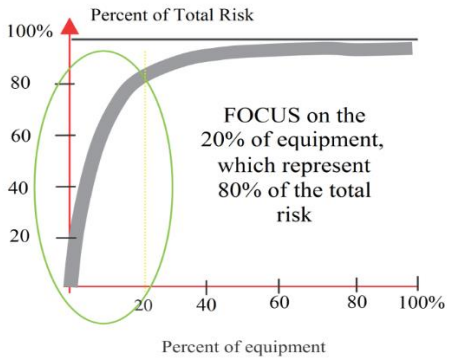

Figure 1. Total risk vs. quantity of equipment [4]

3. MATERIALS AND METHODOGY

3. 1. Ammonium Hydroxide Production Unit (AHPU) In this production unit, input ammonia has a purity of 99.9%. Liquid ammonia is discharged from the track to the storage tank then it is vaporized and reacted with water and converted to liquid ammonium hydroxide (AH). A 25% by weight solution of ammonia in water is prepared in this production unit, and at the same time, gaseous ammonia is sent to the consuming units. The schematic view of this production unit is shown in Figure 2. Liquid ammonia discharged from transportation tank to the storage tank. By passing through a vaporizer, it is converted to the gaseous form, then in the absorber ammonia gas is absorbed by water and liquid AH is produced. AH is widely used in various industries. The main application of this substance is in the production of chemical fertilizers, rubber, and plastics and as the main agent in household and industrial cleaners. It is also used in the chemical industry to neutralize acids. In the AHPU, there is a significant volume of ammonia gas and liquid and AH solution. The occurrence of failures in equipment and pipelines due to its toxic properties can greatly affect personnel health and the environment and waste of resources. AH is produced in almost the same method as in all AHPU; so it is necessary to ensure a reliable inspection and maintenance program. Identified damage mechanisms in the AHPU include; uniform corrosion, intergranular corrosion, galvanic corrosion, crevice corrosion, and pitting corrosion [20]. The equipment specifications of the AHPU are given in Table 1. The concept of the loop has been used to study the piping system.

3. 2. Methodology In Figure 3 steps designed for determining the optimal maintenance strategy for a typical AHPU are shown. Figure 3 was developed based on guidelines and procedures proposed in API RP 581 and intended to provide a systematic roadmap for

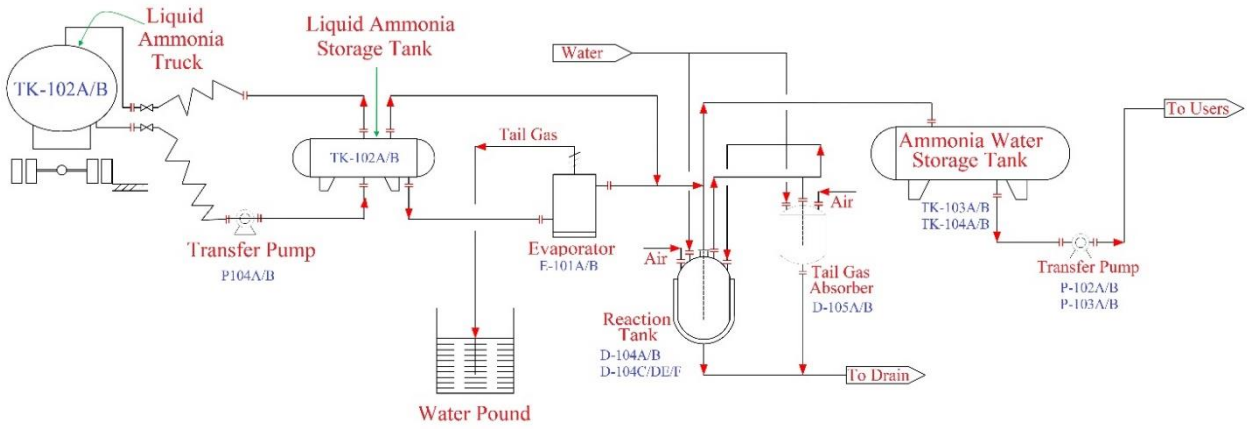

Figure 1. AHPU process flow diagram [21]

TABLE 1. Specifications of equipment and loops of AHPU [21]

Equipment ID	Type of Equipment	Operating pressure (barg)	Operating temperature (^{0}C)	Design Pressure (barg)	Design temperature (^{0}C)	Process fluid	Material of equipment
TK-102A/B	Pressure tank	18	45	22	85	Liquid ammonia	SA-516 Gr. 70N
E-101A/B/C	Evaporator	18	45	22	85	Gaseous and liquid ammonia	SA-516 Gr. 70N
D-104A/B/C/D/E/F	Double-walled tank under pressure	1	35	5	85	AH solution	SS-304
D-105A/B	Pressure tank	1	35	5	85	AH solution	SS-304
TK-103A/B	Pressure tank	1	35	5	85	AH solution	SS-304
TK-104A/B	Pressure tank	1	35	5	85	AH solution	SS-304
P-102A/B	Centrifugal pump	2.4	35	-	-	AH solution	SS-304
P-103A/B	Centrifugal pump	2.4	35	-	-	AH solution	SS-304
Loop 1	Pipe	18	45	-	-	Liquid ammonia	SS-304 300#
Loop 2	Pipe	18	45	-	-	Gaseous ammonia	SS-304 300#
Loop 3	Pipe	18	45	-	-	Liquid ammonia	SS-304 300#
Loop 4	Pipe	18	45	-	-	Gaseous ammonia	SS-304 300#
Loop 5	Pipe	1	45	-	-	Gaseous ammonia	SS-304 150#
Loop 6	Pipe	1	35	-	-	Gaseous ammonia	SS-304 150#
Loop 7	Pipe	1	35	-	-	AH solution	SS-304 150#
Loop 8	Pipe	1	35	-	-	AH solution	SS-304 150#
Loop 9	Pipe	2.4	35	-	-	AH solution	SS-304 150#

conducting similar researches. Research steps include data collection (technical and process information), identifying dominant corrosion mechanism of equipment, calculating probability and consequences of each equipment failure, equipment risk calculation, ranking and inspection plan determination and finally determining maintenance policy of equipment. In this research, according to API RP 581 standard, the equipment risk matrix has been determined and an inspection plan has been selected based on this matrix. Finally, using hierarchical analysis, the optimal method of maintenance is obtained. Based on the research topic and the prevailing conditions in the AHPU, the data collection method includes questionnaires, observations, interviews, available documents, information reports, and databases. According to Figure 3, in this study, first, the technical data of the equipment and process information of the AHPU are gathered.

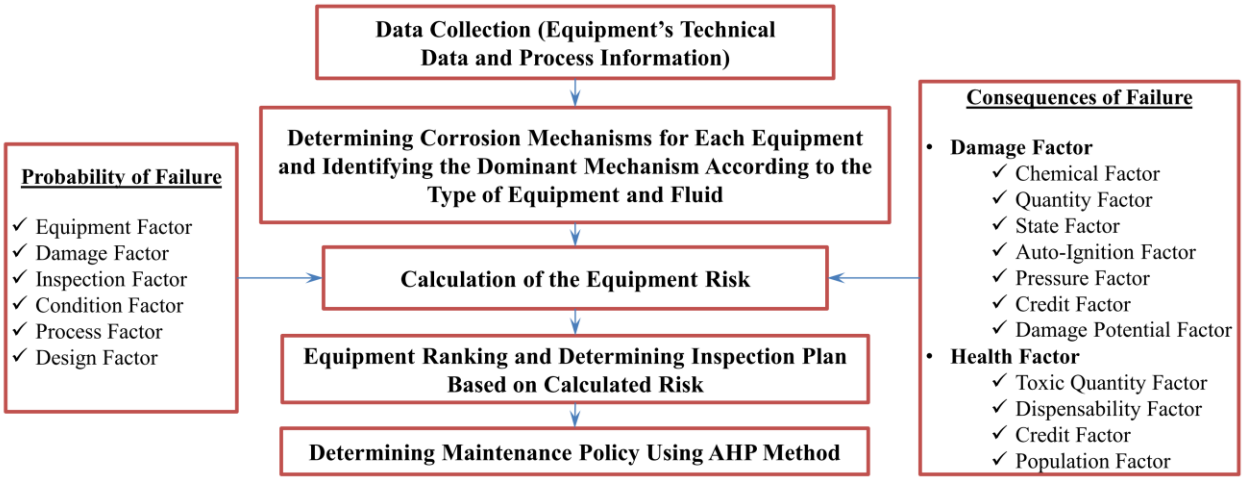

Figure 3. Risk-based inspection and maintenance planning process [21]

This data includes temperature, pressure, and type of equipment, equipment material, equipment safety systems, design-related data, equipment inspection history, and fluid properties, including corrosion, flammability, and toxicity. Then according to the type of equipment and the type of fluid carried with in it, the dominant corrosion mechanism for each equipment is determined. The risk of each equipment is calculated and the equipment is ranked based on the resulting risk. Then, according to the level of risk for each of the equipment and the results of previous inspections, the appropriate inspection plan is determined. Finally, the maintenance policy is determined using the AHP method.

3. 2. 1. Calculating Equipment Risk In this study, a qualitative risk analysis is performed according to the method given in API RP 581 with the help of a series of guideline tables designed to evaluate an industrial unit in a short time. The basics of qualitative risk analysis are the same as the semi-quantitative method, but this method requires less detail for risk analysis, so with less accuracy in comparison with the quantitative method. But it can be used to prioritize the inspection program. In the qualitative risk analysis, the risk level for each equipment is obtained from the classification of failure probability and the maximum categorization of health and injury outcomes in the risk matrix. These levels are divided into 4 levels including Low Risk, Medium Risk, Medium to High Risk, and High Risk. In the used risk matrix, as shown in Table 2 the failure consequence is displayed on the horizontal axis and the probability category of failure is displayed on the vertical axis. Then the position of each equipment on this matrix is determined and the risk level of the equipment is identified accordingly [8].

TABLE 2. Risk matrix [8]

Failure probability category						
	5	**Moderate High (MH)**	**Moderate High (MH)**	**Moderate High (MH)**	**High (H)**	**High (H)**
	4	Moderate (M)	Moderate (M)	Moderate High (MH)	Moderate High (MH)	High (H)
	3	Low (L)	Low(L)	Moderate (M)	Moderate High (MH)	High (H)
	2	Low (L)	Low (L)	Moderate (M)	Moderate (M)	Moderate High (MH)
	1	Low (L)	Low (L)	Moderate (M)	Moderate (M)	Moderate High (MH)
		A	**B**	**C**	**D**	**E**
		Consequences of Failure				

3. 2. 1. 1. Determining The Probability of Failure The method of calculating the probability of equipment failure using six factors shown in Figure 2 is stated in section A of the API RP 581 standard. These six factors, which affect the probability of the occurrence of a large leakage include the Equipment Factor (EF), DF, Inspection Factor (IF), Condition Factor (CoF), Process Factor (PF), and Mechanical Design Factor (MDF). The value of each factor is determined based on the guideline tables presented in API RP 581 section A. The sum of these six factors indicates the probability of total failure (Equation (2)). After calculating the failure probability, its category is determined for each equipment using Table 3 [8].

$$Probability\ of\ failure = EF+DF+IF+CoF+PF+MDF \quad (2)$$

TABLE 3. Determining failure probability categories [8]

Probability of Failure	Category of Probability of Failure
0-15	1
16-25	2
26-35	3
36-50	4
51-75	5

3. 2. 1. 2. Determining The Consequences of Failure Determining the consequences of failure includes the calculation of two separate factors namely, damage factor and health factor (the toxicity consequences of the fluids). To determine the consequence, seven sub-factors are determined based on guideline tables presented in API 581 sections B, including Chemical Factor (ChF), Quantity Factor (QF), State Factor (SF), Auto-Ignition Factor (AF), Pressure Factor (PRF), Credit Factor (CRF), and Damage Potential Factor (DPF). The health factor value obtained by determining the four sub-factors named Toxic Quantity Factor (TQF), Dispensability Factor (DIF), CRF, and Population Factor (PPF) using guideline tables presented in API 581 sections C. These two factors are calculated for each chemical using Equations (3) and (4). According to Table 4 the factor with the higher category will be used as the consequences of failure in risk calculation in Equation (1). In Table 4 the category of the consequence of failure is indicated alphabetically in the way that "A" is the lowest and "E" is the highest one. Bringing the definition of each of the factors in the two preceding sections is out of the scopes of this paper and can be fined as follows [7, 8]:

$$Damage\ Factor = ChF + QF + SF + AF + PRF + CRF + DPF \quad (3)$$

$$Health\ Factor = TQF + DIF + CRF + PPF \quad (4)$$

3. 2. 2. Determining the Inspection Period Usually, based on the equipment risk level and type of equipment and its failure mechanisms, the inspection programs are developed for periodic inspections, including in-service inspections and inspections during overhaul. In Table 5 the relationship between risk level, inspection level, and recommended equipment inspection period is given. Based on this table and according to the selected level of inspection and obtained risk level for equipment, the inspection period for each equipment can be determined [22].

TABLE 2. Determining the consequence of failure [7, 8]

Health factor	Damage factor	Category of Consequences of failure
>10	0-19	A
10-19	20-34	B
20-29	35-49	C
30-39	50-79	D
<40	<79	E

3. 2. 3. Determining the Inspection Period Choosing the most appropriate maintenance policy is a complicated task due to the diversity of possible alternatives and multiple criteria. For selecting the best maintenance strategy, the risk level obtained through RBI can be used to identify the equipment in critical condition and, if necessary, more maintenance resources can be allocated to them. The next step is to decide on the maintenance policy from various possible approaches according to the risk level of equipment. For this purpose, the AHP technique can be utilized [23]. The AHP is a structured method for handling complex decisions. AHP was developed by Thomas L. Saaty in the 1970s. The AHP gives a complete and rational agenda for structuring a decision problem, representing and quantifying its elements, relating those elements to overall goals, and evaluating alternative solutions. AHP has three main levels. For maintenance problems; the first level is the goal (in this case, choosing the best maintenance policy for each mentioned risk level). The second level consists of decision criteria and the third level is alternatives (in this case, applicable maintenance policies in AHPU).

Performing AHP analysis consists of three stages namely: building decision models' structure; carrying out comparative evaluation on the alternatives and the criteria; the combination of the priorities. In the first

TABLE 3. Relationship between risk level, inspection level and recommended inspection period [22]

			Risk Level			
			L	M	MH	H
Inspection Level	1	-There was no previous inspection history at all -There was not enough inspection history	60	48	36	24
	2	-At least 1 inspection has been performed -No depreciation found -Has at least 2 inspection records	90	72	48	36
	3	-There is at least 1 inspection history based on RBI -Unforeseen depreciation not found -There is at least 3 inspection records	120	96	72	48
	4	-At least 2 inspections have been performed based on RBI -Only predicted depreciation has occurred	120	120	96	60

stage, the decision problem is built as a hierarchy, by breaking down the complex decision construction problem into the hierarchy of objectives at the top, in the middle, and the alternatives at the bottom. In the second stage, the pairwise comparisons of the alternatives and criteria are carried out. Let $C=(C_j \mid j=1,2,...,n)$ be the set of criteria, an $(n\times n)$ evaluation matrix A, with elements of a_{ij} $(i,j=1,2,...,n)$ showing the quotient of weights of the criteria, summarizes the pairwise comparison on n criteria, as depicted in Equation (5). In this study, the pairwise comparison mechanism for each criterion and alternative is done based on Table 6 which was proposed by Saaty.

$$A=\begin{bmatrix} a_{11} & . & a_{1n} \\ . & . & . \\ a_{n1} & . & a_{nn} \end{bmatrix}, a_{ii}=1, a_{ji}=\frac{1}{a_{ij}}, a_{ij}\neq 0 \quad (5)$$

Finally, the normalized relative weight for each criterion is obtained by the right eigenvector (ω) corresponding to the largest eigenvalue (λ_{max}), as follows (Equation (6))

$$A\omega=\lambda_{max}\omega \quad (6)$$

In this study to select the criteria affecting the maintenance policy, 13 different policies were considered and a questionnaire was prepared to get experts' opinions on the importance of each criterion. These 13 criteria include surroundings and buildings safety, equipment failure number or intervals, ease of access of the inspection team to the equipment, toxic substances dispersion effects, added value, production stoppage time, accessibility of the equipment in risky areas, spare parts cost, expert manpower cost, equipment safety, equipment importance in the processes, feasibility, and availability of equipment, and personnel safety. The four criteria with the highest average importance namely; safety, cost, added value, feasibility, and availability of equipment were selected for choosing a maintenance policy. Accordingly, for maintenance alternatives, PM, CM, ReBM, and CBM were considered. After determining the criteria and options of the hierarchical model, the proposed model is depicted in Figure 4.

4. RESULTS AND DISCUSSION

In this study, 30 personnel working in the AHPU were identified as a statistical population based on the type of specialization and education for data gathering. They were specialists in various fields of maintenance, inspection, safety, engineering, and production. The required information was collected through questionnaires, interviews, and observations.

TABLE 6. Methodology for Judgment in AHP [23]

Judgment	Equally	Moderately	Strongly	Very strongly	Extremely
Score	1	2,3	4,5	6,7	8,9

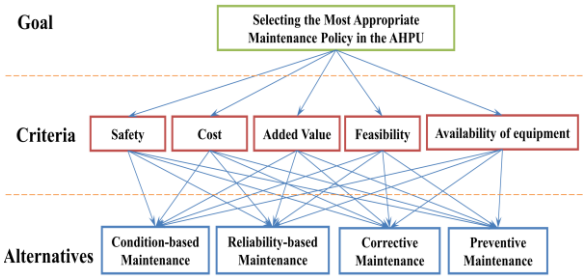

Figure 4. The proposed AHP model

4. 1. Determining Failure Probability Category and Consequence of Failure To determine the number of factors affecting the equipment failure, three experts were surveyed, and with the summation of amounts for included factors, the amount of failure probability and probability category for each equipment was determined according to Table 3. Due to the low flammability of ammonia, the damage factor is ignored in calculating the consequence of failure. Similarly, the values of health factors for equipment have been determined through interviews with relevant experts, and the failure consequence has been determined for each equipment based on Table 4. The Results of failure probability and consequence of failure category are shown in Table 7.

4. 2. Risk Level and Inspection Interval After identifying the failure probability category and consequence of failure for equipment, the risk level of each equipment is determined according to Table 3. On the other hand, since during the inspection, no damage was observed in the equipment and piping system of the AHPU, inspection level 2 for the equipment and piping system is considered, and inspection interval is identified according to Table 5, as shown in Table 8.

4. 3. Selecting the Optimal Maintenance Strategies using AHP Method As mentioned in the previous sections, to implement the AHP method, the criteria's weight must be determined according to pairwise comparisons. In this study, the expert choice software was used that works according to the AHP.

4. 3. 1. Pairwise Comparison Matrixes Calculation As mentioned before, risk matrix output consists of four main risk rating scales. A suitable maintenance policy must be assigned to each risk rating scale by calculating each policy priority using pairwise comparison matrixes. The most important point is that the ranking of criteria and alternatives are different for each risk rating scale, so

the pairwise comparison matrix must be calculated in each risk rating scale. As mentioned before, rankings are assigned to each criterion and alternative based on Saaty ranking table (Table 6). For the AHPU, the weights obtained for the selected criteria for each risk level are as described in Table 9. Accordingly, pairwise comparisons of maintenance strategies based on criteria chosen for different risk level has performed. Table 10 shows these pairwise comparisons in the low-risk range.

4. 3. 1. Pairwise Comparison Matrixes Calculation

As mentioned before, risk matrix output consists of four main risk rating scales. A suitable maintenance policy each policy priority using pairwise comparison matrixes. The most important point is that the ranking of criteria and alternatives are different for each risk rating scale, so the pairwise comparison matrix must be calculated in each risk rating scale. As mentioned before, rankings are assigned to each criterion and alternative based on Saaty ranking table (Table 6). For the AHPU, the weights obtained for the selected criteria for each risk level are as

TABLE 4. Classification of equipment probability of failure and consequences of failure in the studied AHPU

Equipment ID	LF	MDF	PF	CCF	IF	DF	EF	LC	TQF	DIF	CFR	PPF	HCF	HCC	DCC	OCC
TK-102A/B	23	0	3	6	-4	18	0	2	27	0	-0.5	20	47	E	-	E
E-101A/B/C	21	0	3	6	-4	16	0	2	15	0	0	20	35	D	-	D
D-104A/B/C/D/E/F	19	0	4	6	-4	13	0	2	15	-5	-1	7	16	B	-	B
D-105A/B	17	0	2	6	-4	13	0	2	15	-5	-1	7	16	B	-	B
TK-103A/B	20	0	2	6	-4	16	0	2	20	-5	-1	7	21	C	-	C
TK-104A/B	20	0	2	6	-4	16	0	2	20	-5	-1	7	21	C	-	C
P-102A/B	28	0	2	6	0	20	0	3	20	-5	-1.25	7	21	C	-	C
P-103A/B	28	0	2	6	0	20	0	3	20	-5	-1.25	7	21	C	-	C
Loop 1	28	0	3	9	0	16	0	3	15	0	0	20	35	D	-	D
Loop 2	28	0	3	9	0	16	0	3	15	0	0	20	35	D	-	D
Loop 3	28	0	3	9	0	16	0	3	15	0	0	20	35	D	-	D
Loop 4	28	0	3	9	0	16	0	3	15	0	0	20	35	D	-	D
Loop 5	28	0	3	9	0	16	0	3	15	0	-1.5	20	35	D	-	D
Loop 6	27	0	2	9	0	16	0	3	15	0	-1.5	7	21	C	-	C
Loop 7	27	0	2	9	0	16	0	3	15	-5	-1.5	7	16	B	-	B
Loop 8	27	0	2	9	0	16	0	3	20	-5	-1.25	7	21	C	-	C
Loop 9	3	27	0	2	9	0	16	0	20	-5	-1.25	7	21	C	-	C

TABLE 8. Recommended inspection interval for equipment of AHPU

Equipment title	Probability category	Consequence of failure	Risk Level	Inspection interval (month)
Under pressure tank	2	E	MH	48
Evaporator	2	D	M	72
Double-walled under pressure tank	2	B	L	90
Centrifugal pump	3	C	M	72
Piping line 1 to 4	3	D	MH	48
Piping line 6	3	C	M	72
Piping line 7	3	B	L	90
Piping lines 8 and 9	3	C	M	72

TABLE 9. The weight of each criterion for different risk levels

Criteria	Low Risk	Moderate Risk	Moderate to High Risk	High Risk
Safety	0.16	0.17	0.29	0.35
Added value	0.22	0.28	0.22	0.21
Feasibility	0.14	0.14	0.19	0.18
Cost	0.28	0.22	0.16	0.15
Availability of equipment	0.2	0.19	0.14	0.11

described in Table 9. Accordingly, pairwise comparisons of maintenance strategies based on criteria chosen for different risk level has performed. Table 10 shows these pairwise comparisons in the low-risk range.

According to values obtained in Tables 9 and 10, the priority of each maintenance strategy was calculated in the low-risk range, which is illustrated in Table 11. As can be seen, for low-risk equipment, the best strategy is the CM. Similarly, pairwise comparisons of maintenance strategies for other risk levels were performed and the relative importance of each strategy was determined, which is shown in Table 12.

According to the obtained results in section 4, the appropriate inspection levels for equipment with low risk, medium risk, medium to high-risk levels are 90, 72, and 48 months, respectively. It was also found that the optimal maintenance policies for equipment with different risk levels are shown in Table 13.

TABLE 10. Comparisons of maintenance alternatives in the low-risk range

	Criteria				
Maintenance Alternatives	**Safety**	**Feasibility**	**Added value**	**Cost**	**Availability of equipment**
PM	0.216	0.315	0.290	0.248	0.23
CM	0.281	0.228	0.220	0.345	0.3
RBM	0.269	0.238	0.262	0.224	0.17
CBM	0.234	0.219	0.290	0.183	0.3

TABLE 11. Optimal maintenance strategy in the low-risk range

Maintenance Alternatives	**The relative importance of each strategy**
PM	0.271
CM	0.296
RBM	0.233
CBM	0.200

TABLE 12. Optimal maintenance strategy based on risk level

Maintenance Alternatives	**The relative importance of each strategy for different risk levels**		
	High Risk	**Moderate to High Risk**	**Moderate Risk**
PM	0.298	0.300	0.286
CM	0.193	0.193	0.302
RBM	0.279	0.277	0.222
CBM	0.229	0.230	0.189

TABLE 13. The most appropriate maintenance policy based on risk levels

Risk Level	**Maintenance Strategy**
Low Risk	CM
Moderate Risk	CM
Moderate to High Risk	PM
High Risk	PM

5. CONCLUSION

In this research, an appropriate equipment inspection and maintenance plan for equipment in a typical AHPU was determined based on RBI and a multi-criteria decision system. AH is a widely used chemical in neutralizing acids in different industries producing chemical fertilizers, rubbers, plastics and exists as the main agent in household and industrial cleaners. AHPU is usually a separate part of different chemical industries and due to its important role in the chemical processes needs special inspection and maintenance strategy. Hence, contrary to traditional methods, which consider a fixed period for equipment inspection mostly based on the manufacturers' suggestions, in this study, the knowledge of the experts and equipment working and environmental conditions were used to determine the optimum period of inspections in a typical AHPU. The procedure considered in API 581 was employed to categorize the equipment based on their failure risk. Then based on RBI concepts, experts' opinions and using AHP decision methodology the appropriate maintenance policy considering were determined for each equipment categorized based on failure risk. Hence the equipment with high or medium to high risk level, such as liquid ammonia storage tank and the pipes entering or leaving it, needs PM plan with inspection period of 48 months. The equipment such as AH storage tank which has medium risk level needs CM plan with inspection period of 72 months. The equipment with low risk, such as ammonia absorption tank, requires CM plan with inspection period of 90 months. It is expected that by employing the proposed maintenance plan, the safety of the process in AHPU will be enhanced and additional cost imposed by equipment breakdowns will be reduced. Due to the widespread use of gaseous ammonia and AH solution in the industry; the obtained results can be use as guild for other similar production units as well

6. REFERENCES

1. Eskandari, D., Charkhand, H. and Gholami, A., "A semi-quantitative approach development for risk-based inspection in a petrochemical plant", ***Open Access Macedonian Journal of Medical Sciences***, Vol. 8, No. E, (2020), 425-433, doi: 10.3889/oamjms.2020.4391

2. Koteleva, N., Buslaevb, G., Valneva, V. and Kunshinb, A., "Augmented reality system and maintenance of oil pumps", ***International Journal of Engineering***, Vol. 33, No. 8, (2020), doi: 10.5829/ije.2020.33.08b.20.
3. Drożyner, P., "The impact of the implementation of management system on the perception of role and tasks of maintenance services and effectiveness of their functioning", ***Journal of Quality in Maintenance Engineering***, (2020), doi: 10.1108/JQME-09-2019-0089.
4. Calixto, E., "Gas and oil reliability engineering: Modeling and analysis, Gulf Professional Publishing, (2016).
5. Rahimi Komijani, H., Shahin, M. and Jabbarzadeh, A., "Optimal policy of condition-based maintenance considering probabilistic logistic times and the environmental contamination issues", ***International Journal of Engineering***, Vol. 31, No. 2, (2018), 357-364, doi: 10.5829/ije.2018.31.02b.21.
6. Wang, Y., Cheng, G., Hu, H. and Wu, W., "Development of a risk-based maintenance strategy using fmea for a continuous catalytic reforming plant", ***Journal of Loss Prevention in the Process Industries***, Vol. 25, No. 6, (2012), 958-965, doi: 10.1016/j.jlp.2012.05.009.
7. Inspection, R.-B., "Api recommended practice 580", ***American Petroleum Institute***, Vol., No., (2009), doi.
8. Segment, A.P.I.D., "Risk-based inspection technology, American Petroleum Institute, (2008).
9. Chen, L. and Toyoda, J., "Maintenance scheduling based on two level hierarchical structure to equalize incremental risk", in Conference Papers Power Industry Computer Application Conference, IEEE. (1989), 431-437.
10. Dey, P., "A risk based model for inspection and maintenance of cross country petroleum pipeline", ***Journal of Quality in Maintenance Engineering***, (2001), doi: 10.1108/13552510110386874.
11. Dey, P.K., Ogunlana, S.O. and Naksuksakul, S., "Risk based maintenance model for offshore oil and gas pipelines: A case study", ***Journal of Quality in Maintenance Engineering***, (2004), doi: 10.1108/13552510410553226.
12. Arunraj, N. and Maiti, J., "Risk-based maintenance—techniques and applications", ***Journal of hazardous materials***, Vol. 142, No. 3, (2007), 653-661, doi: 10.1016/j.jhazmat.2006.06.069.
13. Bertolini, M., Bevilacqua, M., Ciarapica, F.E. and Giacchetta, G., "Development of risk-based inspection and maintenance procedures for an oil refinery", ***Journal of Loss Prevention in the Process Industries***, Vol. 22, No. 2, (2009), 244-253, doi: 10.1016/j.jlp.2009.01.003.
14. Arunraj, N. and Maiti, J., "Risk-based maintenance policy selection using ahp and goal programming", ***Safety Science***, Vol. 48, No. 2, (2010), 238-247, doi: 10.1016/j.ssci.2009.09.005.
15. Kumar, G. and Maiti, J., "Modeling risk based maintenance using fuzzy analytic network process", ***Expert Systems with Applications***, Vol. 39, No. 11, (2012), 9946-9954, doi: 10.1016/j.eswa.2012.01.004.
16. Mohamed, N.A., Mahani, Z. and Razak, L.A.A., "Approach to corrosion management program and risk based inspection development for the world's first floating lng", in Offshore Technology Conference Asia, Offshore Technology Conference. (2018).
17. Yazdi, M., Nedjati, A. and Abbassi, R., "Fuzzy dynamic risk-based maintenance investment optimization for offshore process facilities", ***Journal of Loss Prevention in the Process Industries***, Vol. 57, (2019), 194-207, doi: 10.1016/j.jlp.2018.11.014.
18. Farizhendy, M.M., Noorzai, E. and Golabchi, M., "Implementing the nsga-ii genetic algorithm to select the optimal repair and maintenance method of jack-up drilling rigs in iranian shipyards", ***Ocean Engineering***, Vol. 211, (2020), 107548, doi: 10.1016/j.oceaneng.2020.107548.
19. Mokhtari, H., Molla-Alizadeh, S. and Noroozi, A., "A reliability based modelling and optimization of an integrated production and preventive maintenance activities in flowshop scheduling problem", ***International Journal of Engineering***, Vol. 28, No. 12, (2015), 1774-1781, doi: 10.5829/idosi.ije.2015.28.12c.10.
20. Cramer, S.D., Covino, B.S. and Moosbrugger, C., "Asm handbook volume 13b: Corrosion: Materials, ASM International Materials Park, OH, Vol. 13, (2005).
21. Ghasemi Vincheh, R., "Maintenance strategy selection at an ammonium hydroxide unit using a risk based inspection approach in pursuit of sustainable development", Department of Human Environment, College of Environment, Karaj, Iran, MSc, (2020),
22. Shuai, J., Han, K. and Xu, X., "Risk-based inspection for large-scale crude oil tanks", ***Journal of Loss Prevention in the Process Industries***, Vol. 25, No. 1, (2012), 166-175, doi: 10.1016/j.jlp.2011.08.004.
23. Maleki, N., Bagherifard, M. and Gholamian, M., "Application of incomplete analytic hierarchy process and choquet integral to select the best supplier and order allocation in petroleum industry", ***International Journal of Engineering***, Vol. 33, No. 11, (2020), 2299-2309, doi: 10.5829/ije.2020.33.08b.20.

Persian Abstract

چکیده

واحد تولید هیدروکسید آمونیوم (AHPU) یکی از فرآیندهای رایج و مهم موجود در بسیاری از صنایع مانند نیروگاه های نفت ، گاز ، پتروشیمی و نیروگاه ها است. با توجه به کاربرد گسترده AHPU ، ایجاد یک استراتژی نگهداری بهینه ضروری است. در این تحقیق ، برای اولین بار ، یک برنامه دقیق بازرسی سیستماتیک برای AHPU بر اساس اولویت بندی تجهیزات با استفاده از تجزیه و تحلیل خطر تجهیزات تعیین می شود. خطر تجهیزات بر اساس احتمال و نتیجه خرابی طبق استاندارد API RP 581 محاسبه می شود. بر خلاف روش های بازرسی سنتی ، که معمولاً براساس نظرات و رهنمودهای تولیدکنندگان استوار است ، چندین روش محیطی پیشنهادی روش بازرسی در نظر گرفته و تجزیه و تحلیل شد. علاوه بر این ، استراتژی های مختلف نگهداری با توجه به معیارهای مختلف مانند ایمنی ، هزینه و امکان سنجی با استفاده از فرایند سلسله مراتبی تحلیلی مقایسه شدند و در نتیجه سیاست تعمیر و نگهداری بهینه مبتنی بر ریسک برای هر گروه از تجهیزات مشخص شد. نتایج نشان داد که ، برای تجهیزات با خطر بالا و متوسط تا زیاد ، مانند مخزن ذخیره آمونیاک مایع و خطوط مربوط به آن ، روش نگهداری پیشگیرانه با دوره بازرسی ۴۸ ماه مناسب ترین روش است ، در حالی که برای خطر متوسط مانند ذخیره سازی هیدروکسید آمونیوم مخزن و تجهیزات کم خطر مانند مخزن جذب آمونیاک ، نگهداری اصلاحی به ترتیب با دوره بازرسی ۷۲ و ۹۰ ماه ، بهترین انتخاب است. سرانجام ، انجام تجزیه و تحلیل های لازم و تعیین مناسب ترین برنامه نگهداری برای هر گروه از تجهیزات با سطوح مختلف خطر در AHPU ، منجر به صرفه جویی در هزینه خاموش شدن ، هزینه بازرسی ، کاهش خرابی و افزایش ضریب اطمینان تجهیزات می شود.