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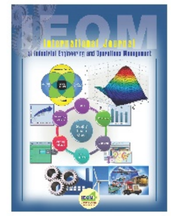

Developing Turnaround Maintenance (TAM) Model to Optimize TAM Performance Based on the Critical Static Equipment (CSE) of GAS Plants

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ABSTRACT

Many oil and gas companies have suffered major production losses, and higher cost of maintenance due to the total shutdown of their plants to conduct TAM event during a certain period and according to scope of work. Therefore, TAM is considered the biggest maintenance activity in oil and gas plant in terms of manpower, material, time and cost. These plants usually undergo other maintenance strategies during normal operation of plants such as preventive, corrective and predictive maintenance. However, some components or units cannot be inspected or maintained during normal operation of plant unless plant facilities are a totally shut downed due to operating risks. These risks differ from a company to another due to many factors such as fluctuated temperatures and pressures, corrosion, erosion, cracks and fatigue caused by operating conditions, geographical conditions and economic aspects. The aim of this paper is to develop a TAM model to optimize the TAM scheduling associated with decreasing duration and increasing interval of the TAM of the gas plant. The methodology that this paper presents has three stages based on the critical and non-critical pieces of equipment. At the first stage, identifying and removing Non-critical Equipment pieces (NEs) from TAM activity to proactive maintenance types. During the second stage, the higher risk of each selected equipment is assessed in order to prioritize critical pieces of equipment based on Risk Based Inspection (RBI). At the third stage, failure probability and reliability function for those selected critical pieces of equipment are assessed. The results of development of the TAM model is led to the real optimization of TAM scheduling of gas plants that operated continuously around the clock in order to achieve a desired performance of reliability and availability of the gas plant, and reduce cost of TAM resulting from the production shutdown and cost of inspection and maintenance.

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1. Introduction

Oil and gas plants consist of hundreds pieces of rotating and static equipment that operate continuously under harsh operating conditions resulting from excessive pressures and fluctuated temperatures. Some pieces of equipment usually subject to various maintenance strategies during the normal operation of plant such as preventive, corrective

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and predictive maintenance. However, there are critical pieces of these equipment cannot be inspected and maintained during the normal operation of plants unless plant facilities are totally shut downed to conduct the TAM event in order to overcome all expected failures, which may be caused high risks during the operation periods. This is justified to use widely TAM for most oil and gas plants during a certain period (TAM duration) at every few years (TAM interval). TAM can be defined as the largest maintenance activities in the oil and gas plants in terms of cost and time (Elfeituri and Elemnifi, 2007). Duffuaa and Ben Daya (2004); Lawrence (2012) also reported that TAM is a total shutdown of plants during a certain time period to carry out TAM activities associated with inspection, repair, modification, and replacement of new part or equipment according to Scope of Work (SoW) of TAM. Neikirk (2011) stated that TAM is a periodic activity of the plant that isolates all items from the service during a certain time. Consequently, TAMs have become necessary event for any processing plant operated continuously under rigorous operating conditions to mitigate risks between TAM periods (Prasad, 2014). Consequently, TAMs have become necessary event for any processing plant operated continuously under rigorous operating conditions to mitigate risks between TAM periods (Prasad, 2014).

Since the 1970s, interest in shutdown issues of gas plants has significantly increased due to the production losses and the inspection and maintenance cost. Many oil and gas companies have suffered losses in the production and enormity in the cost of TAM due to a stochastic estimation of duration and interval of TAM. The stochastic and permanent estimation of TAM scheduling (decreasing duration and increasing interval of TAM) based on the recommended periods of the Original Equipment Manufacturers (OEMs) mean that TAM scheduling was neither adopted on the residual life of the critical equipment and nor a real planning associated with operating conditions and maintenance strategy of the gas plant. TAM scheduling of the gas plant can be conducted based on the suggested period of the OEMs in the short-term. However, this strategy of OEMs cannot be represented the most optimum TAM scheduling in the medium and long-term, because operating conditions vary significantly from a company to another. Therefore, plant facilities must be shut downed during a certain time at every few years according to the operating conditions and the residual life of the critical pieces of equipment.

Through previous studies, it was found that there is a need to identify knowledge gap to solve TAM scheduling problem in the TAM field of gas plants to assist in the decision making, and bridge the existing gap in the literature. A few of previous studies focused on the improvement of interval of TAM based on an individual equipment during a planned and unplanned shutdown period without taking critical pieces of equipment into account. Large number of studies also focused on the improvement of TAM duration from business and management perspective such as an increase of human resources, development of contracts, skill development of TAM crew, culture and conflict resolution during TAM activities.

In addition, some previous studies have used a variety of application to optimise TAM scheduling. However, they have not adopted a model of the TAM event employed for any a processing plant run continuously under operating conditions in order to determine both duration and interval of TAM in the medium and long-term, and also have not covered all CEs of gas plants. Many previous studies also have covered the redundant rotating equipment from Preventive (PM), Corrective (CM) and Predictive (PdM) perspective. PM is a set of action should be taken before failure occurs. PdM is a step forward in PM, and CM is a step backward in PM as shown in Figure 1. These classifications are not able to overcome all failures related to inspection, repairs, replacement, development and renewal in the oil and gas plants. Therefore, it is arguably that TAM event is an evil unavoidable.

Utne et al. (2012) reported that shutdown can be a planned or unforeseen shutdown. However, In general, the planned shutdown is TAM event the predetermined scheduled in terms of TAM duration, TAM interval, allocated budget, contracts, manpower and spare parts to prepare for pre-shutdown (Duffuaa and Ben Daya, 2004). Unplanned shutdown can be broken down into expected or unexpected shutdown. Expected shutdown is a total shutdown of plant which occur based on pre-warning (run-to-failure) without planning of the maintenance duration. Unexpected shutdown is a total shutdown of plant which occur without any pre-warning due to unknown defects (these defect need to long time to its realization, access, and then its diagnosis.

Therefore, most processing plants are subjected to the previously planned shutdown during a certain time based on operating conditions and the residual life of critical equipment of plants to carry out the major activities: inspection and maintenance activities, modifications and replacements (Duffuaa and Ben Daya, 2004). Levitt (2004) stated that planned shutdown of any processing plant is the major maintenance activity that required the biggest financial supports.

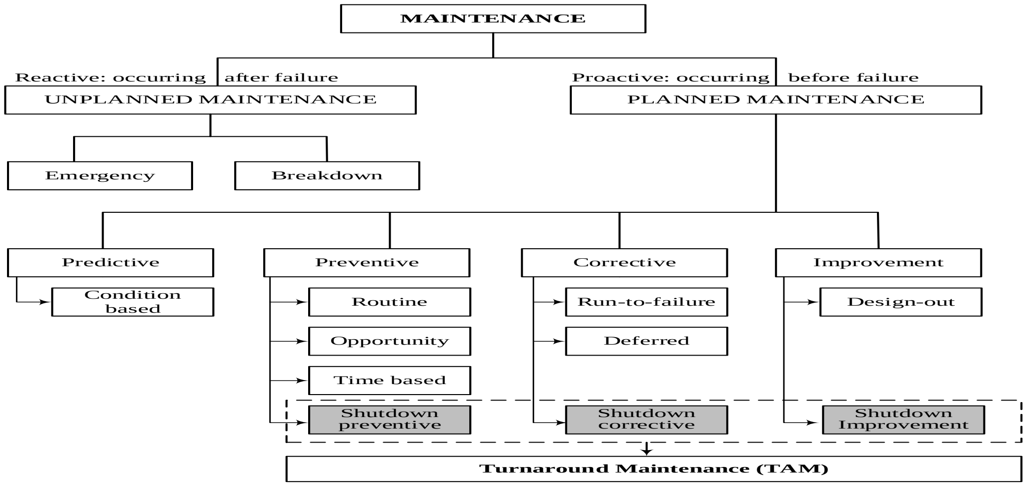

Figure 1. Maintenance classification

Figure 2 shows the life cycle of TAM that consists of four phases. These phases aim to achieve optimum TAM and enhance its performance. Therefore, each phase includes a specific set of critical activities during a given time period in which depends on several factors, weight of activity, budget, time, material and manpower.

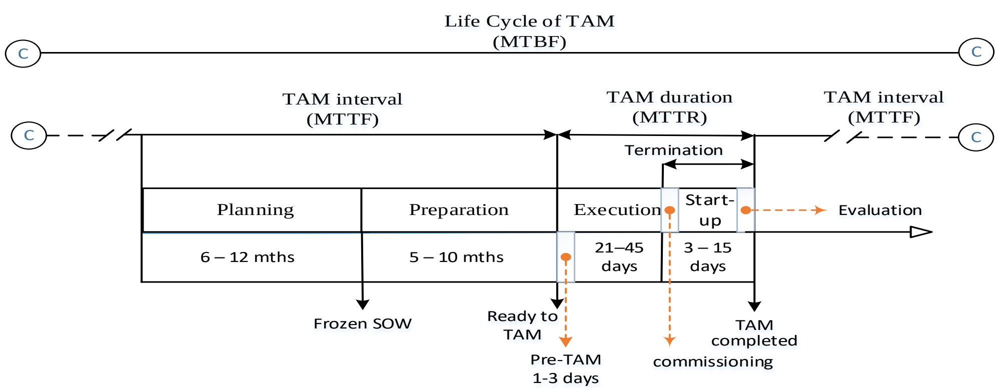

Figure 2. Life cycle of TAM

Duffuaa and Ben-Daya (2004); Levitt (2004); Lenahan (2006) highlighted the execution phase of TAM from a management perspective. Krings (2001); Oliver (2002); Mclay (2003) all reported that successful TAM depends on the planning phase in the long term to estimate budget and time of TAM. However, Brown (2004) discussed the planning and executing phases of TAM cycle life.

2. Related Work

The scheduling TAM has several effects on the operational performance of plants in terms of time, cost, and risk. The relation between the duration and cost of TAMs are considered direct relationship, the relation between the interval and risk are also considered direct relationship. This means that, once a decrease of TAM duration would lead to the decreased cost of TAM, and increased interval of TAM. However, an increase of TAM interval may result in increasing risk unless taking RBI approach of CSE pieces into account. For this reason, oil and gas companies have spent thousands of man-hours on volume of the work in the execution phase of TAM because of their voluminous activities.

Number of contractors should also be consistent with size of TAM activities to avoid the prolonging TAM duration of and complete all activities according to a previously planned duration of TAM. Duration of TAM is the time period which a plant subjects to a total shut down to conduct TAM activities. These activities include two stages: execution and termination phase that require considerable time, cost and efforts to execute it. Oliver (2002) identified many performance aspects to measure TAM, which included duration, budget, Start-up incidents and safety. Lenahan (2006) also identified several performance indicators that contributed in the improvement of TAM performance such as

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safety, cost and efficiency. Elfeituri, and Elemnifi (2007) also presented the optimisation of TAM duration for refinery plant by removing redundancy rotating pieces which can be maintained during the normal operation of plant to routine maintenance plan in order to minimise downtime of a plant. The results of optimisation were recommended to reduce duration of TAM to 23 days rather than 30 days. Schroeder and Vichich (2009) studied essential relationships between costs, quality and duration of TAM. (Halib et al., 2010), suggested four weeks as an average to execute the TAM duration of petrochemical companies and 11 days to carry out the TAM duration of refinery plants. This means that estimation of TAM duration is not based on the residual of the critical equipment life. (Megow et al., 2011) developed a model of scheduling TAM for chemical plants contained two phases. At first phase supported the project manager to find a good duration and observe risks priorities, and the 2nd phase was associated with optimizing resources used during the chosen duration of TAM. However, this study focused on only optimisation of TAM duration in terms of different features time-cost, trade-off external resource equipment, resource levelling, and risk analysis, also it has not covered interval between TAM periods.

Emiris (2014) highlighted the challenges encountered in development of TAM using Project Management Office (PMO) based on high cost, short duration, risk, and scope of work according to the standards recommended by the Project Management Institute. Consequently, random planning of TAM duration can impact availability and financial performance of a plant. Therefore, any additional day of duration of TAM can result in increasing cost of TAM, and lost millions of dollars due to shutdown of production (Rajagopalan et al., 2017). Rajagopalan et al. (2017) also proposed a systematic approach via a multistage stochastic programming model that developed TAM reschedule. (Akbar and Ghazali, 2017) developed a model of an organizational and management for a processing plant in Malaysian associated with management functions of leading and performance for processing plant to enhance the performance of TAM duration using team alignment.

The TAM Interval is the time period which plant facilities is normally under operation. The suggested TAM intervals may not be the most optimum time to TAM strategy due to operating conditions that may vary significantly from a company to another. Most oil and gas industries are continuously subjected to the pre-planned shutdown every life cycle of a plant according to several aspects availability, reliability, risk, production rate of plant to attain optimal performance and revitalise efficiency, and reliability of plants (Halib, et al., 2010). However, pre-planned TAM every life cycle should be based on CEs which cannot be inspected or maintained during the normal operation of the plant and that represented a high risk on the plant in order to achieve the optimal performance to the next cycle of the TAM.

Tam, et al. (2006) reported that interval of shutdown is often determined by the Original Equipment Manufacturers (OEMs). However, OEMs suggestions of TAM interval may be perfect only during warrantee period (early failures period) for some pieces of equipment. However, OEMs suggestions are not feasible in the medium and long term due to operating conditions and the production requirements for plant facilities. Therefore, the optimization of TAM interval for any a processing plant identifies according to specific conditions associated with a real operating conditions and the residual life of CEs. Megow, et al. (2011) stated that the TAM interval of a large plant can be repeated every more than one year. Swart (2015) reported that historically, intervals of TAM identified without any real strategic associated with operating process.

Dyke (2004) presented several steps in the improvement of TAM performances of the refinery plants using best practice model and as well as applied benchmarking technique to measure performance of TAM that included duration and interval of each major process units. Krishnasamy et al., (2005) identified the critical pieces of equipment using risk assessment along with the Weibull and Exponential approach to develop cost-effective maintenance policies of critical equipment by reducing the overall risk of the power plant. Elfeituri and Elemnifi (2007) applied RBI approach to identify vessels that have high risk on the refinery plant to inspect and maintain them during TAM periods. Khan et al. (2008) presented a risk-based methodology to estimate the optimal inspection and maintenance intervals using availability modelling to minimize failure risk and enhance the overall availability of the system. Ghosh and Roy (2009) proposed methodology for optimising the maintenance intervals using maximising the reliability function based on cost and benefit ratio. Keshavarz et al. (2011) proposed a risk-based shutdown management of maintenance using active and stand-by redundancy to optimize the TAM interval for liquefied natural gas equipment pieces. Shuai et al. (2012) applied RBI technique to predict inspection interval for shell and bottom of crude oil tank in China to determine rate of corrosion and thickness of shell and bottom.

Obiajunwa (2012) reported that interval of TAM for petrochemical and refinery plants were conducted every two years and power plant executed every four years. Rusin and Wojaczek (2012) presented optimizing maintenance intervals of power machine by taking the risk into account. Hameed and Khan (2014) also presented a framework to identify the risk-based shutdown interval to prolong intervals between TAM periods based on heat exchangers for a

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processing plant, taking risk-based shutdown interval into account. Hameed and Khan (2014) stated that is very difficult that a shutdown period included totally inspection and maintenance of equipment of pieces. Hameed and Khan (2014) also presented a framework to estimate the risk-based shutdown interval in order to extend intervals between shutdowns for a processing plant based on the individual equipment. They also proposed the Weibull model to determine interval of TAM based on the Probability of Failure (PoF) and Consequences of Failure (CoF). Swart (2015) also stated that the cause of the current interval of TAM is either indiscriminate or has become as a redundant.

The random and permanent estimation of the TIME interval, means that TAM activity is not based on the residual life of the equipment that can increase the risk due to fixed-interval. Therefore, the important aspects associated with both duration and interval of TAM were covered in most previous studies. Most previous studies were focused on the improvement of the TAM interval based on the individual equipment whether series or parallel system. Other previous studies were concerned with improving of the TAM duration based on an increase of human resources, development of contracts, skill development of TAM crew, quality maintenance management and conflict resolution during TAM activities. In addition, both shape and scale parameters were randomly estimated outside of operating conditions of gas plants. Many previous studies focused on redundant rotating pieces of equipment from PM, CM and PdM perspective.

3. Research Contribution

This study is to develop the TAM model in order to address TAM scheduling associated with decreasing duration and increasing interval of TAM in the medium and long-term. The development of TAM model will go further to reduce cost of TAM and production losses, and improve reliability and availability of gas plants. This model includes three stages, as given in Figures 3, 4 and 5.

Stage 1: Removing Non-critical Equipment (NE) from TAM to Proactive Maintenance

Identifying TAM activity depends on several factors associated with size, technology, reliability and safety of plant (Halib, et al., 2010). However, the size of plant is the main characteristic that involves all static and rotating equipment pieces. Consequently, this stage focused on the identification of all equipment pieces listed within gas plant to classify and remove non-critical pieces from TAM list as shown in Figure 3.

This Stage involves a precise description of each static and rotating equipment for removing non-critical static and rotating equipment "which can be inspected and maintained without the need to a total shutdown of the plant" from SoW of TAM to combine to proactive maintenance plan in order to decrease duration and increase interval according to the following steps:

a) Pieces of equipment were identified related to the gas plant,
b) Pieces of equipment were separated into Static Equipment (SEs) and Rotating Equipment pieces (REs),
c) Static equipment pieces were classified into Critical and Non-critical Static Equipment (NSEs and CSEs).

Based on Equation (1) given in the Figure 3, NSEs was excluded from a TAM index and CSEs was included to the next stage to consider in the stage II. This equation is a tool used to assess effects of equipment pieces on the functional performance of the plant in terms of cost, availability, production and safety (Afefy, 2010; Vishnu and Regikumar, 2016).

$$\text{EC (Critical Equipment)} = \frac{15\%\,\text{C} + 25\%\,\text{A} + 30\%\,\text{P} + 30\%\,\text{S}}{3} \qquad (1)$$

Table 1 shows the impact levels of each equipment on the operational performance of a plant in terms of Cost (C), Availability (A), Production, and Safety (S) according to weights of the affecting (15%, 25%, 30% and 30%). These weights were considered indicator for many oil and gas companies to assign critical equipment pieces. Many companies have used 50%P and 50%S as a scale to identify CEs. Therefore, these weights identified based on layout of the gas plant and experts of Metallurgy and Inspection (M&I), Mechanical Analyses Group (MAG), Operation & Maintenance engineers of SOC gas plant. In addition, the scale used to determine the score for the variables P, S, C, A is a three point scale: (3) Very important, (2) Important, and (1) Normal (a minimum effect on all these parameters due to failures).

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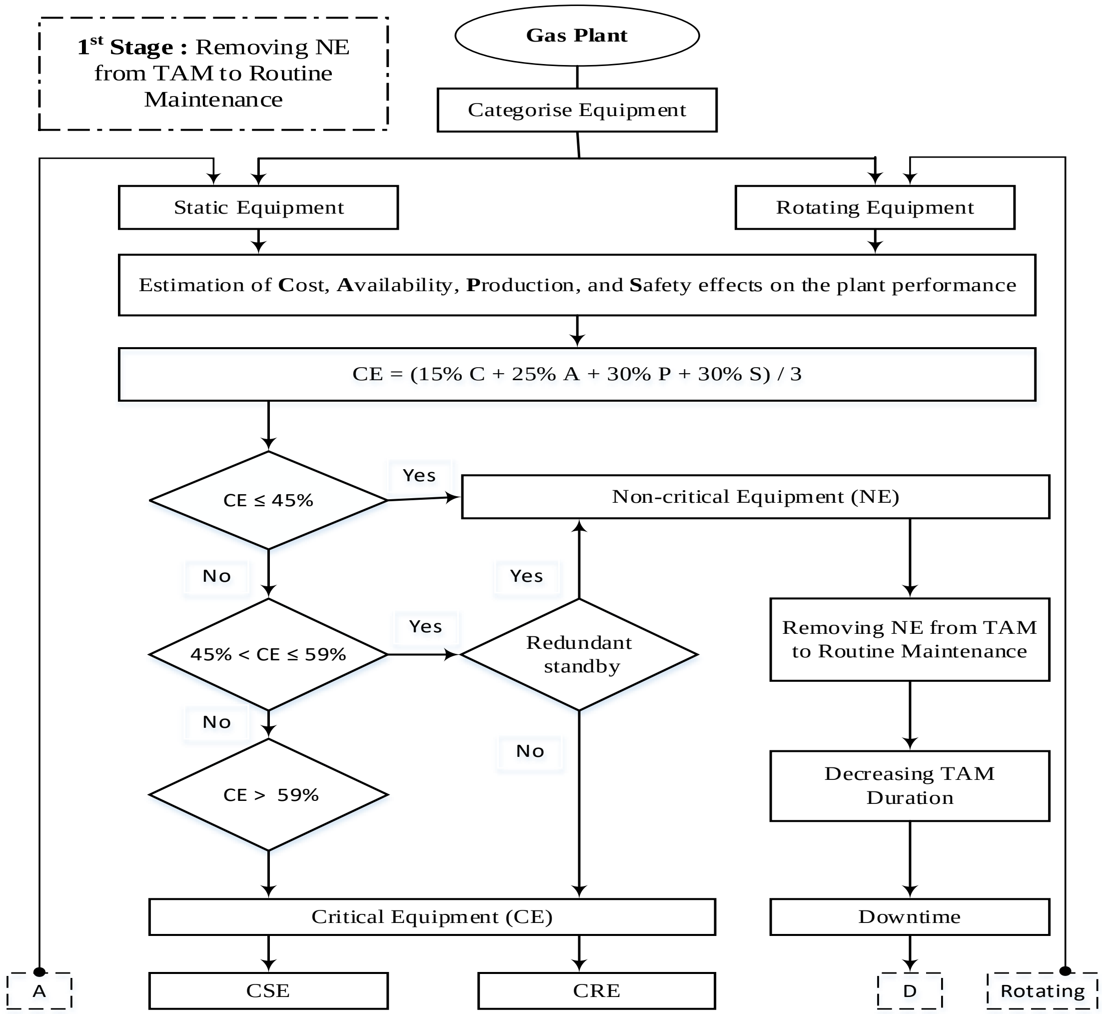

Figure 3. 1st Stage of removing NE from TAM to proactive activity

Table 1. Classifying critical and non-critical equipment

Factors Affecting	Critical Weight (%)	Scales					
		1		2		3	
		Level	%	Level	%	Level	%
Cost (C)	15	L	15	M	30	H	45
Availability (A)	25	H	25	M	50	L	75
Production (P)	30	N	30	I	60	V	90
Safety (S)	30	N	30	I	60	V	90

L: Low, **M**: Medium, **H**: High, **N**: Normal, **I**: Important, **V**: Very important.

Stage 2: Risk Assessment of CSE Using RBI Approach

Most processing plants are started with focusing on RBI techniques due to the complex processes that required a higher availability and reliability (Kumar, 1998). RBI is a crucial approach in decision-making process that plays an important role in the optimization of maintenance (Ahmed et al., 2015). Based on RBI, the second stage is focused on the CSEs extracted from the first stage to identify CSEs that represented the highest risk on the production, company assets and environment issues in terms of corrosion, erosion factors, fluctuating in pressure and temperatures due to continuously operation and under rigorous operating conditions. Figure 4 illustrates the process that can identify pieces

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of equipment that have the highest risk on the company/plant to assist the operation and maintenance engineers in the estimation of the TAM interval for gas plants.

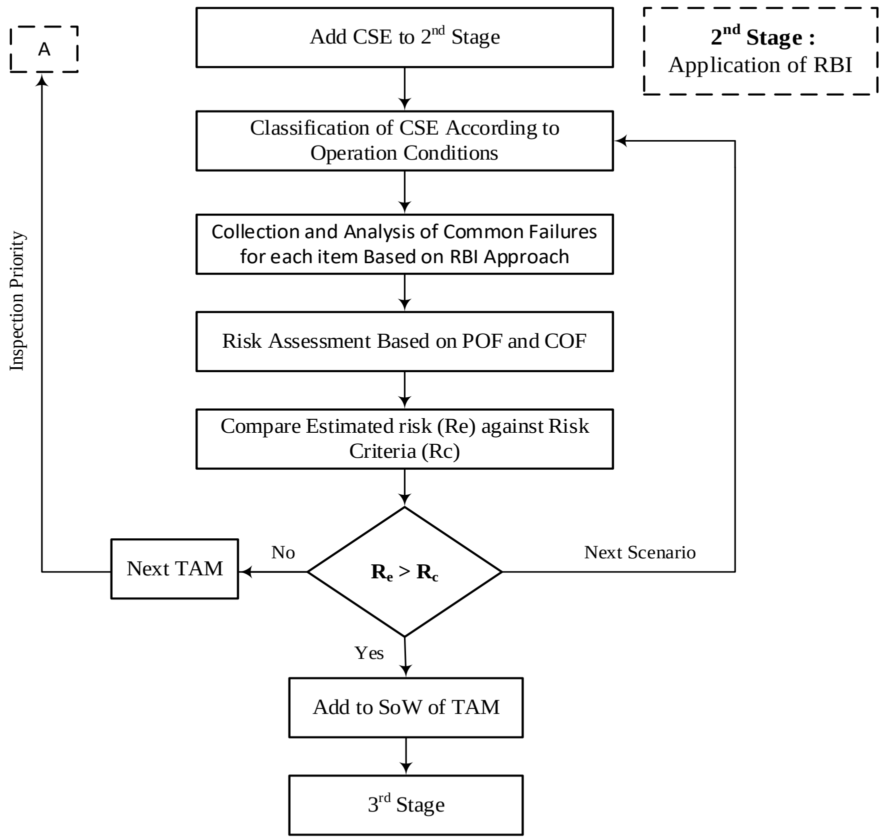

Figure 4. 2nd Stage of risk assessment of CSE based on the RBI approach

RBI is a commonly used risk analysis technique employed in the higher risks zones, especially oil and gas plants, where one estimates PoF and CoF and compare the estimated risk against a pre-defined criteria to prioritise critical pieces of static equipment according to the risk (5x5) matrix.

Stage 3: Application of Failure Distribution on the Highest Risk CSE Pieces:

At the third stage, failure probability and reliability function for those selected components are assessed through the stage 2. Figure 5 shows applications of failures distributions to determine optimum interval of TAM based on shape and scale parameters (β, η), which estimated according to failures behaviour Time-to-Failure (TTF). Minitab software is a tool used to compute $R(t)$ and $h(t)$ in order to determine a failure mode for each critical equipment. A failure mode is an indicator which can specify any value of random variable falling within a range of curve. An availability was also implemented in this stage as an indicator to optimise TAM scheduling.

$$A = \frac{\text{TAM Interval}}{\text{TAM Interval} + \text{TAM duration}} \qquad (2)$$

The downtime is equivalent to the duration of TAM and the uptime is equivalent to the interval of TAM.

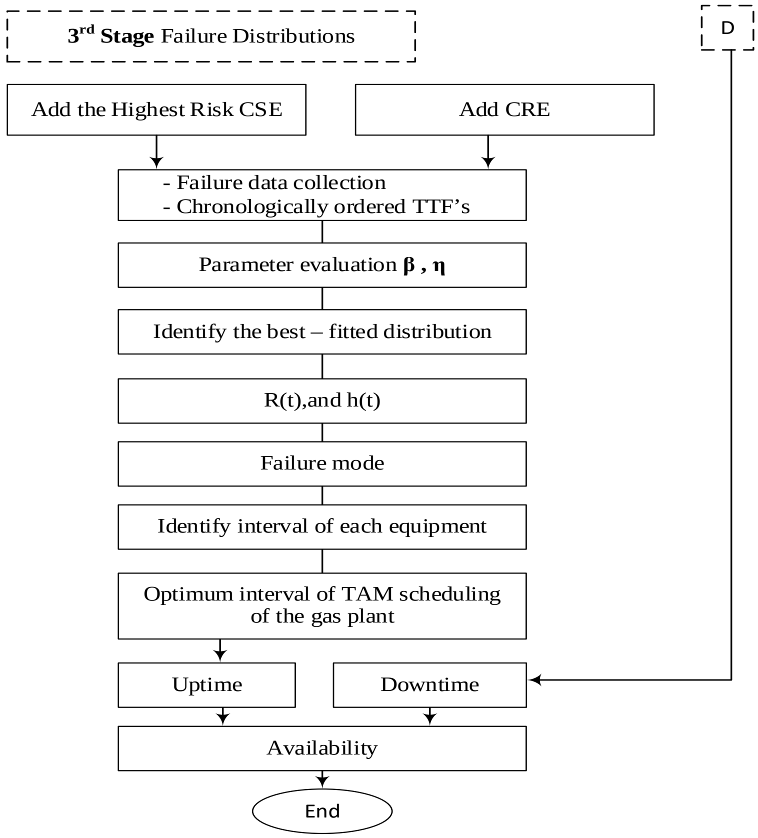

Figure 5. 3rd Stage of estimation of interval of TAM

4. Results and Discussions

The main purpose of this study is to develop the TAM model that consists of three stages for optimizing TAM scheduling associated with decreasing duration and increasing intervals of TAM for gas plants in order to reduce production losses and TAM cost and improve reliability and availability of plants.

4.1 Decreasing Duration of TAM

Gas plants consist of thousands pieces of static and rotating equipment that operate continuously under harsh operating conditions. Some of these pieces can be inspected and maintained during normal operation of the plant. Therefore, this stage is designed to identify and remove pieces that can be inspected and maintained during normal operation of plant (Non-critical Equipment-NE) from TAM worklist to proactive maintenance plan to decrease the TAM duration in order to reduce the TAM cost and the production losses.
Table 2 illustrates number of NSEs which were removed from TAM worklist to proactive maintenance plan. These NSEs identified according to a layout of the gas plant that included Gas Liquid Recovery Unit (GLRU), Treating, Drying and Fractionation (T, D &F), Salt Water Bay (SWB) and utilities unit.

Table 2. Identified and removed NSES and NRES of the gas plant

Stage No	**Static Equipment**		**Rotating Equipment**	
	In	**out**	**In**	**Out**
1^{st}	186 + 91 pipe	120 + 56	118	114
	In (186-120, 91-56)		**In** (118-114)	
2^{nd}	66 + 35 (S) Pipelines		4	

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Based on the Equation (1) that consists of four constrains: Cost, Availability, Production, and Safety effects on the plant performance as shown in Figure 3, 120 NSEs out of 186 static equipment pieces and also all safety and relief valves were removed. Consequently, this is obvious that, once the number of equipment pieces are reduced, the duration of TAM is expected to 21 days rather than 30 days and total cost of TAM to 2 million or less rather than 2.5 million. 21 days is represented plant downtime to perform TAM event based Critical Static Equipment (CSEs).

4.2 Increasing Interval between TAM Periods

This case presents approach to prioritize CSEs that represented the highest risks on the production losses, operating assets and environment issues to increase the TAM interval in order for potential improvements in all reliability, availability, and maintainability aspects.
In this stage highlighted 66 vessels and 35 pipelines, which exposed to fouling, leakage, corrosion, and crack resulting from continuously operating condition based on descriptive information was collected by Metallurgy and Inspection (M&I), the operation and maintenance experts, and failure records of the Libyan gas plant. These vessels and pipelines could be conveniently divided into four categories: heat exchangers, drums, processing columns, and pipelines as shown Table 3.

Table 3. Classification of CSEs

CSE	No	Codes
Heat exchangers	18	E-401, E-410, E-601, ME-601, E-601A, E-601B, E-602A, etc.
HP Drums	32	D-701, D-702/703, D-704/757, D-705A/B, D-706, D-712, etc.
Columns	16	DR-401 C/D, T-701, T-702, T-703, T- 401, T-402, etc.
Pipelines	35	lines (PL.20"- 84")
Total	68 + 35	

According to the above results, Stage II of the TAM model includes four categories of equipment pieces. These pieces are considered critical elements (CSE) in the gas plant that can be contributed in the estimation of interval between the TAM periods based on the RBI approach. Consequently, CSE pieces were distributed on the risk (5x5) matrix according to two factors namely; PoF and CoF to avoid an expected and unexpected consequences. These factors can be expressed as illustrated in Equations (2, 3, 4, and 5).

Risk = Probability of failure x Consequence of failure

$$R_{ENC} = POF \text{ X } COF_{\text{Environment}} \quad (2)$$

$$R_{PL} = POF \text{ X } COF_{\text{Production Losses}} \quad (3)$$

$$R_{AD} = POF \text{ X } COF_{\text{Operating Assets Damage}} \quad (4)$$

The highest risk (R_s) can be selected using the equation (5):

$$R_s = Max\,(R_{ENC}, R_{PL}, R_{AD}) \quad (5)$$

4.2.1 Risk Assessment of 18 Heat Exchangers

Table 4 shows risk ranking limits arising from PoF and CoF which can have an impact on the plant performance. The risk ranking limits between 3 and 12, where 10 and 12 represent high-risk zone that consider an unacceptable risk zone. Heat exchangers pieces located in this zone should be added to the TAM list to represent TAM event, because these pieces of equipment have the highest risk due to the fouling effect. These pieces should be taken into consideration to consider in the next stage and to avoid the main causes of leakage and corrosion in the middle and long-term.

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Table 4. Estimated risk and risk criteria

Rating	Failure Scale	R_e	R_c	Decision
1	Very Low Risk	$0 < R_e \leq 3$	Insignificant Risks	Omitting Equipment from TAM list to next TAM (Priority).
2	Low Risk	$3 < R_e \leq 6$	Acceptable Risks	Omitting Equipment from TAM list to next TAM (Priority).
3	Moderate	$6 < R_e \leq 9$	Acceptable Risks	Omitting Equipment from TAM list to next TAM (Priority).
4	High Risk	$9 < R_e \leq 12$	Unacceptable Risks	Adding Equipment to next stage IV
5	Very High Risk	$R_e > 12$	Catastrophic Risk	Plant Shutdown

Six pieces out of 18 pieces of heat exchangers were classified in the high risk zone as shown in Table 5. These pieces included a cooling, a Cryogenic Colum Heat Exchanger (MCHC), and 4 pieces of Feed Gas Heat Exchangers (shell and tube heat exchangers) of gas plant. These heat exchangers were rated in the high risk zone due to accumulated fouling layers through the tubes. This table shows 6 pieces located in the high risk zone require immediate attention by preparing to commence shutdown of a plant and conduct further control measures to implement TAM activity in order to avoid the increase in both PoF and CoF and the jumping to very high risk zone.

Table 5. Estimated risk of heat exchangers

Code	Equipment	No	PoF	CoF	Estimated Risk	Risk Level	Priority
E-601	Cooling	1	3	4	12		1
E-601A	Feed Gas	1	4	3	12		2
E-601B	Feed Gas	1	4	3	12		3
E-602A	Feed Gas	1	4	3	12		4
E-602B	Feed Gas	1	4	3	12		5
ME-601	Main Cryogenic	1	2	5	10		6
E-424	Butane cooler	1	3	3	9		7
E-411	Reboiler	1	2	4	8		8
E-413	Kettle reboiler	1	2	4	8		9
E-415	Reboiler	1	2	4	8		10
E-401	Catacarb reg.	1	2	3	6		11
E-412	Condenser	1	2	2	4		12
E-414	Condenser	1	2	2	4		13
E-423	Caustic solution	1	2	2	4		14
E-1500	LPG cooler	1	2	2	4		15
E-410	Overhand	1	4	1	4		16
E-426		1	2	1	2		17
E-428		1	2	1	2		18

Figure 6 shows distribution of 18 pieces of heat exchangers located in the gas plant based on accumulated fouling layers through tubes. Two pieces of heat exchangers were rated in the very low risk zone, 6 heat exchangers were

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estimated in low risk zone, 4 pieces were located in moderate risk zone, 6 heat exchangers were classified in high risk zone, and no pieces in very high risk zone. Therefore, 12 pieces of heat exchangers that are rated in very low risk, low risk, and moderate risk zone do not need to TAM activities. 12 pieces of heat exchangers should be dropped from TAM list to inspect during the next cycle of TAM. However, 6 equipment pieces that are classified in high risk zone require TAM activities. Thus, these heat exchangers can be added to TAM list work to consider in the stage III of the TAM model to estimate interval between TAM periods in order to inspect and maintain during the plant shutdown.

Risk Matrix						
Consequnces Rating	Environmental Contamination (EC)	No effect	Minor	Moderate	Major	Massive
	Production Losses (PL)	Less 5 %	5 – 10 %	10 - 30 %	30 - 60 %	More 60 %
	Asset Damage (AD)	Very Low	Low	Moderate	High	Very High
Failure Frequency	**FOF / COF**	**1**	**2**	**3**	**4**	**5**
High Probable	**5**	5	10	15	20	25
Probable	**4**	4 1	8	12 4	16	20
Possible	**3**	3	6	9	12	15
Unlikely	**2**	2	4 4	6	8 3	10
Very Unlikely	**1**	1	2	3	4	5

Figure 6. Risk assessment of 18 heat exchangers

4.2.2 Risk Assessment of 32 Drums

Out of 32 static drums included in the study, 12 drums (3, 2, 2, 2, 3) were classified in the very low risk zone, 9 (1, 5, 3) drums were rated in low risk area, 9 (3, 4, 2) were estimated in moderate risk zone, 2 (1, 1) drums were located in high risk zone due to corrosion resulting from decreasing in shell thickness of shell, and no pieces in very high risk area as shown in Figure 7. Therefore, 29 drums that located in very low, low and moderate risk zone can be dropped from TAM list to inspect during next cycle of the TAM according to risks priority, because these equipment pieces do not represent a high risk on the production, asset of plant and environment due to corrosion factor. However, equipment pieces (D-409 and D-704) that rated in the high risk zone require TAM activities. Therefore, D-409 and D-704 can be added to TAM list to consider in 3rd Stage in order to identify optimum interval of the TAM and to maintain or inspect during plant shutdown to avoid unexpected consequences associated with environmental contamination, losses in production or asset damage, etc.

Risk Matrix						
Consequnces Rating	Environmental Contamination (EC)	No effect	Minor	Moderate	Major	Massive
	Production Losses (PL)	Less 5 %	5 – 10 %	10 - 30 %	30 - 60 %	More 60 %
	Asset Damage (AD)	Very Low	Low	Moderate	High	Very High
Failure Frequency	**FOF / COF**	**1**	**2**	**3**	**4**	**5**
High Probable	**5**	5	10	15	20	25
Probable	**4**	4	8 3	12	16	20
Possible	**3**	3	6 1	9	12	15
Unlikely	**2**	2	4 5	6	8	10
Very Unlikely	**1**	1	2	3 3	4	5

Figure 7. Risk assessment of 32 drums

4.2.3 Risk Assessment of 16 Processing Columns

Out of 16 columns included in this study as shown in Figure 8. Seven columns (DR-402 C/D, DR-401 C/D, T-402 and T-403, and T-401) were rated in the low risk zone, 7 pieces of columns (T-405, T-406, T-407, T-408, T-404, T-703, and T-410) were estimated in moderate risk zone, 2 columns (T-701 and T-702) were classified in high risk

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zone, and no pieces in very high risk area. As a result, fourteen pieces of columns are located in low risk, and moderate risk zone. Therefore, these columns are not required TAM program and should be dropped from TAM list to inspect during next cycle of TAM. However, there are two columns are classified in high risk zone require TAM activities. These pieces should be added to TAM list to consider in 3rd Stage of the TAM model in order to identify interval of between the TAM periods.

Risk Matrix

Consequnces Rating	Environmental Contamination (EC)			No effect	Minor	Moderate	Major	Massive
	Production Losses (PL)			Less 5 %	5 – 10 %	10 - 30 %	30 - 60 %	More 60 %
	Asset Damage (AD)			Very Low	Low	Moderate	High	Very High
Failure Frequency	**Range per Mth**	**P(t)**	**FOF / COF**	**1**	**2**	**3**	**4**	**5**
High Probable	$t \geq 24$	1	**5**	5	10	15	20	25
Probable	$18 \leq t < 24$	0.8	**4**	4	8	12	16	20
Possible	$12 \leq t < 18$	0.5	**3**	3	6	9 (4)	12 (1)	15
Unlikely	$06 \leq t < 12$	0.3	**2**	2	4 (5)	6 (2)	8 (3)	10 (1)
Very Unlikely	$03 \leq t < 06$	0.1	**1**	1	2	3	4	5
Key for Ranking	Risk Ranking			$R \leq 3$	$3 < R \leq 6$	$6 < R \leq 9$	$9 < R \leq 12$	$R > 12$
	Risk Catogery			V. Low	Low	Moderate	High	V. High
	Risk Level							

Figure 8. Risk assessment of 16 processing columns

4.2.4 Risk assessment of 35 pipelines

12 samples of pipelines were located in very low risk zone, 20 samples were rated in the low risk zone, a sample was rated in the moderate risk zone, 2 samples were located in the high risk zone, and without any samples were located in very high risk zones. Thus, 12 samples of pipelines were rated as (2+5+5) in very low risk, 20 samples were rated as (3+10+2+1+4) in the low risk zone and a sample was rated in the moderate risk zones. These samples must be dropped from the current TAM list to the next TAM. However, 2 samples of gas pipelines that were rated as (2) in the high risk zone must be taken into account to add to TAM list in order to maintain or repair during plant shutdown to carry out TAM activities, and to avoid disastrous consequences, which may generate environmental contamination, losses in production or asset damage, etc. Therefore, these samples located in the high risk region that include PL5-26" and PL6-26" in which located underground of SWB and utility unit, respectively require immediate attention by 3rd Stage to identify the interval of TAM to execute TAM tasks with a minimum cost. Concentrating on the high risk equipment can be improved the level of availability and reliability of the plant.

Consequnces Rating	Environmental Contamination (EC)			No effect	Minor	Moderate	Major	Massive
	Production Losses (PL)			Less 5 %	5 – 10 %	10 - 30 %	30 - 60 %	More 60 %
	Asset Damage (AD)			Very Low	Low	Moderate	High	Very High
Failure Frequency	**Range per Mth**	**P(t)**	**FOF / COF**	**1**	**2**	**3**	**4**	**5**
High Probable	$t \geq 24$	1	**5**	5	10	15	20	25
Probable	$18 \leq t < 24$	0.8	**4**	4	8	12	16	20
Possible	$12 \leq t < 18$	0.5	**3**	3	6 (3)	9	12	15
Unlikely	$06 \leq t < 12$	0.3	**2**	2 (2)	4 (10)	6 (2)	8 (1)	10 (2)
Very Unlikely	$03 \leq t < 06$	0.1	**1**	1	2 (5)	3 (5)	4 (1)	5 (4)
Key for Ranking	Risk Ranking			$R \leq 3$	$3 < R \leq 6$	$6 < R \leq 9$	$9 < R \leq 12$	$R > 12$
	Risk Catogery			V. Low	Low	Moderate	High	V. High
	Risk Level							

Figure 9. Risk assessment of 35 pipelines

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4.2.5 Failure Probability and Reliability Function

The Weibull distribution can be utilized to identify the optimal interval of TAM that cleaned or replaced a bundle of tubes of heat exchangers, inspected and maintained corroded shell, replaced bolts, caps and trays of processing columns due to fluctuating feed temperatures, and inspected and maintained thickness of pipelines due to corrosion resulting from water steam. It can also be introduced the advice as to whether interval of TAM for an upcoming shutdown. Therefore, each item include an especial function and failure rate. Therefore, each item has an especial parameters (β, $\boldsymbol{\eta}$) based on Time to Failure (TTF) for four items as shown in Table 6.

Table 6. Estimated shape and scale parameters of CSE of gas plant.

Equipment Code	Configuration system	Description	Shape Parameter $\boldsymbol{\beta}$	Scale Parameter $\boldsymbol{\eta}$ (hrs)
E-601A	Series system	Feed Gas H. Exchanger	2.30	58,000
E-601B		Feed Gas H. Exchanger	2.30	58,000
E-602A		Feed Gas H. Exchanger	2.30	58,000
E-602B		Feed Gas H. Exchanger	2.30	58,000
E-601		Cooling	1.80	390,000
ME-601		Cooling	1.80	390,000
D-704	Single	Reflux/Surge drum shell	5.52	76141
D-409	Single	Regeneration drum shell	4.65	82853.7
T-701	Series system	Trays of Splitter tower	6.3	80800
T-702		Trays of Debutanizer	6	97376
PL-26"	Single	Two Steam Header Lines	8.97	115006

Table 7 shows a sample of these results related to Stage III that included reliability function R(t), hazard rate h(t), failure mode of four items: heat exchangers, drums, columns, and pipelines in which located in the highest risk zone based on the production losses, asset damage and environment. These equipment pieces that extracted from Stage II would be classified into four scenarios:

$$\mathrm{R}i(\mathrm{t}) = \mathbf{e}^{-\left(\frac{t}{\eta}\right)^{\beta i}} \qquad where\ \boldsymbol{i} = 1,2, \ldots \boldsymbol{n}\ of\ equipment \qquad (6)$$

$$\mathrm{h}(\mathrm{t}) = \frac{\beta}{\eta} \cdot \left(\frac{t}{\eta}\right)^{\beta-1} \qquad \beta, \eta > 0 \text{ and } t \geq 0 \qquad (7)$$

General expression of the Probability Density Function (pdf):

$$f(t) = \frac{\beta}{\eta} \cdot \left(\frac{t}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad \text{for} \quad t \geq 0 \qquad (8)$$

4.2.5.1 Estimated risk of the plant

It is the estimated operational risk of a plant (Re), which increase with an operation time of plant. Estimated risk associated with any processing plants is usually expressed as the following mathematical Equation (9).

$$R_e = F(t)_{plant} \text{ x } \sum CoF(\$) \qquad (9)$$

A failure due to fouling, leakage and corrosion in the static equipment pieces during an operational process may result in the release of a large amount of hydrocarbons, especially if a gas plants operates under extreme pressure and fluctuated temperatures. The consequences of these failures are not only limited to environment issues but may also affect considerable on the production and operating assets. Therefore, consequences of these failures can be converted in the economic consequences ($) based on production losses, operating assets damage and environment issues as shown in Table 7.

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Table 7: Economic consequences of failures

Critical Equipment	Production Losses ($)	Operating Assets ($)	Environment Issues ($)	Sum CoF ($)
Heat exchangers	16,047,000	11,479,768	1,105,499	28,632,268
Drum-704	10,698,000	51,067,767	3,703,000	65,468,767
Drums-409	1,248,1000	55,048,950	4,025,690	71,555,640
Processing columns	2,852,8000	35,070,000	2,460,000	66,058,000
Pipelines	5,349,000	85,185,300	5,807,915	96,342,215

In order to estimate risk plant should be taken acceptable risk into consideration to compare with estimating risk according to Equation (9) that subjects to the following constraint:

$$R_e \leq Risk_{acceptable}$$

In general, acceptable risk varies from a company to another due to operating conditions and economic aspects. Based on the economic aspects, each processing company has its own tolerable risk criteria can be used in the estimation of TAM scheduling associated RBI (API 581, 2008).

Table 8. R(t), h(t), and f(t) scenarios of results of CSEs

CSE Scenarios	TAM interval	R(t)	PoF	h(t)	FM	R_e ($)
1st Scenario of six heat exchangers (series system)	23,000 hr	0.620	0.379	4.901E-05	2.9594E-05	471.97
	24000 hr	0.591	0.408	5.174E-05	2.9781E-05	487.73
	24,700 hr	0.570	0.429	5.257E-05	2.9824E-05	498.10
	24,800 hr	**0.567**	**0.432**	**5.284E-05**	**2.9825E-05**	**499.53**
	24,900 hr	0.564	0.435	5.312E-05	2.9824E-05	500.96
	25,000 hr	0.561	0.438	5.450E-05	2.9821E-05	502.37
	30,000 hr	0.415	0.584	7.323E-05	2.7979E-05	557.83
2nd Scenario of D-704	70,000 hr	0.533	0.466	4.957E-05	2.6781E-05	436.47
	72,000 hr	0.479	0.520	5.630E-05	2.7107E-05	473.02
	73,000 hr	0.452	0.547	5.992E-05	2.713E-05	490.83
	73,500 hr	**0.439**	**0.560**	**6.180E-05**	**2.714E-05**	**499.57**
	73,600 hr	0.436	0.563	6.218E-05	2.712E-05	501.31
	74,000 hr	0.425	0.574	6.372E-05	2.698E-05	508.20
	75,000 hr	0.398	0.601	6.771E-05	2.671E-05	525.05
3rd Scenario of trays of T-701&T-702	70,000 hr	0.581	0.418	4.829E-05	2.8099E-05	394.56
	72,000 hr	0.524	0.475	5.598E-05	2.9354E-05	436.38
	75,000 hr	0.434	0.565	6.935E-05	3.01509E-05	497.86
	75,100 hr	**0.431**	**0.568**	**6.984E-05**	**3.01519E-05**	**499.85**
	75,150 hr	0.430	0.569	7.008E-05	3.01517E-05	500.84
	80,000 hr	0.287	0.712	9.731E-05	2.79788E-05	588.31
	100,000	0.006	0.993	0.0003140	2.06347E-06	656.24
4th Scenario of PL-26"	113,000	0.425	0.574	6.778E-05	2.8859E-05	489.62
	113,100	0.422	0.577	6.826E-05	2.8866E-05	491.65
	113,200	0.419	0.580	6.87E-05	2.8871E-05	493.67
	113,300	0.417	0.582	6.923E-05	2.8875E-05	495.69
	113,500	**0.411**	**0.588**	**7.0217E-**	**2.8879E-05**	**499.72**
	113,600	0.408	0.591	7.0712E-	2.8878E-05	501.73
	114,000	0.396	0.603	7.2721E-	2.8858E-05	509.73

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An acceptable risk criterion for SOC is assumed to be equal or lower than **500$/h**. Any criterion higher than this, the risk is considered unacceptable.

$$R_e\,(S) = F(t)_{HE} \text{ x } \sum [PL(\$) + OA(\$) + EI(\$)]$$

$$R_e\,(S) = [1 - R(t)_{HE}] \text{ x } [\$16{,}047{,}000 + \$11{,}479{,}768 + \$1{,}105{,}499]$$

$$R_e\,(S) = 0.432 \text{ x } \$28{,}632{,}268 = 499.5\$/hr$$

The operational risk of each critical equipment was determined based on Probability of Failure (PoF) and economic consequences as shown in Table 8. Consequently, the optimum TAM interval of heat exchangers, drums, processing columns and pipelines were found as followed: 24800 hr, 73500 hr, 75100 and 113500 hr, respectively when compared operational risk for each equipment to an acceptable risk (500 $/hr).

On the other hand, based on shape and scale parameters as shown in Table 6. It is normal that, reliability function usually decreases gradually with TAM interval for all equipment pieces that operated continuously, especially in oil and gas industries. Hazard rate also increases continuously with TAM interval for all equipment pieces. Although, a decrease of reliability and increase of hazard rate, the failure mode would also be increased with TAM interval to reach a peak 0.00003, 0.000027, 0.00003, and 0.000029 at 24800, 73500, 75100, and 113500 hrs for heat exchanger, drum, column, and pipeline and to become R(t) 57%, 44%, 43% and 41%, and h(t) 5 failures, 6 failures, 7 failures, and 7 failures per 10^5 hours, respectively. A peak point is an indicator to address issues associated with these equipment pieces. When R(t) and h(t) reach to these values, this means that, it is prudent to make decision to select an optimum TAM interval of the plant among the following critical times: 24800, 73500, 75100, and 113500 hrs of heat exchangers, drums, columns, and pipelines, respectively.

Table 9 shows the current availability of gas plant and the suggested availability for duration and interval of TAM. As can be seen from this table that an increase in the TAM interval from 2 years to 2 years and 10 months and decrease in the TAM duration from 30 days to 21 days would result in the increased availability from 95.89% to 98%. In addition, the processing cost of TAM could also be reduced during the TAM event when compared to previous and current TAMs. Therefore, the gas plant must be completely shut downed at 24800 operational hours to greatly reduce the TAM costs and production losses avoid any threats may cause in the production losses, damage of company asset and environment. Consequently, these Stages II and III have illustrated great optimizations in the interval of TAM for static equipment.

Table 9. Gas plant availability

Year	**Duration**	**Interval**	**Availability (A)**	**Status**
	Downtime (day)	Uptime (Yr.)		
1960	30	1		OM
2000	30	1	91.78%	Previous
2001	30	1	91.78%	Previous
2002	30	1	91.78%	Previous
2004	30	2	95.89%	Previous
2006	45	2	93.84%	Previous
2008	30	2	95.89%	Previous
2010	30	2	95.89%	Current
Suggested	21	2.10	98%	Target

Year = 365 days   OM: Original Manufacturer

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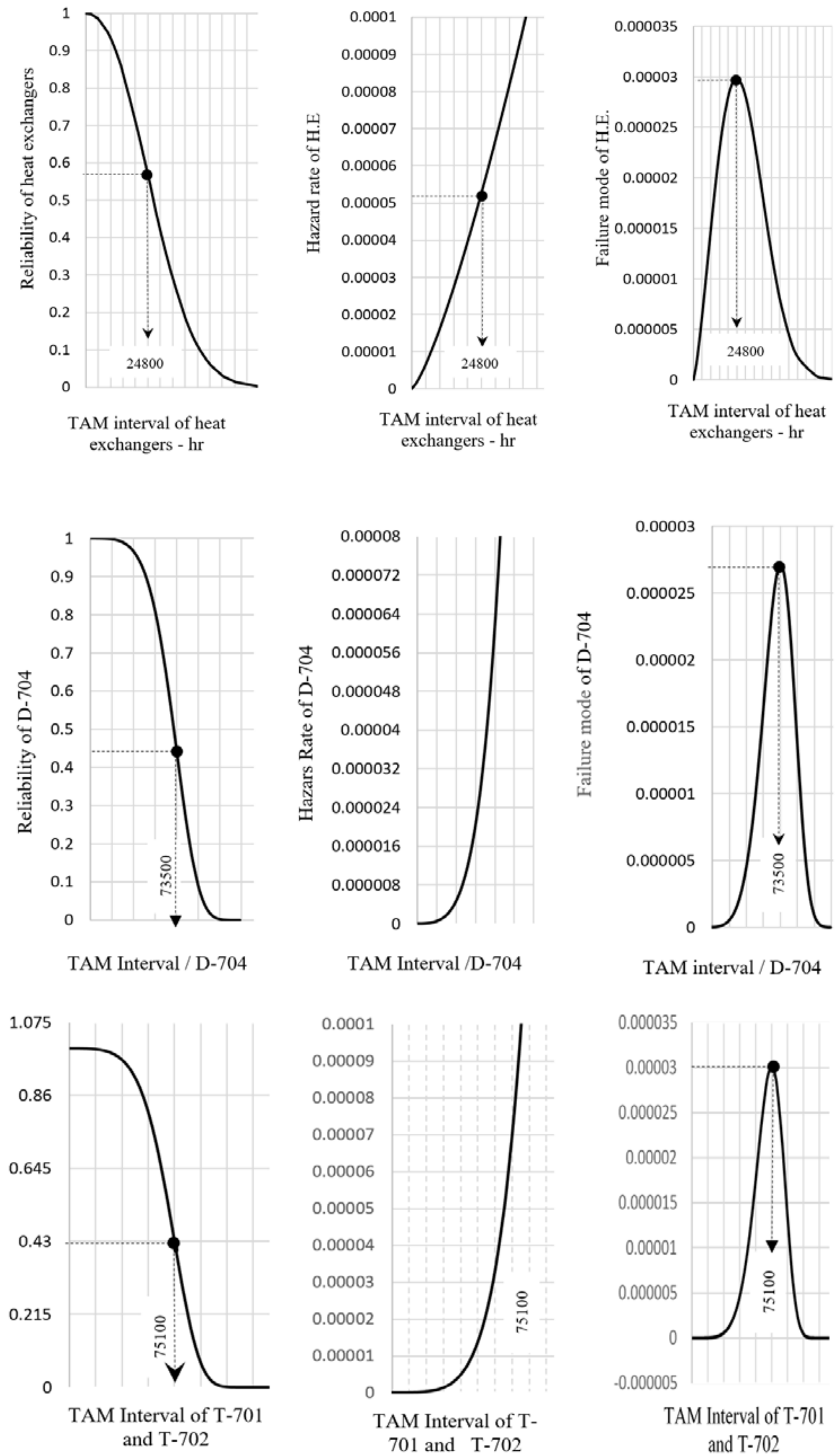

Figure 10. R(t), h(t) and FM of heat exchanger, drums and columns

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Since the interval of TAM is equivalent the plant uptime, therefore, the optimum TAM interval of the gas plant is the period that represents the lowest period to avoid an unexpected shutdown and risks consequences due to deterioration in the critical pieces of equipment between TAM cycles caused by fluctuating temperatures and overpressures. 24800 operational hour of heat exchangers is the optimum TAM interval of gas plants when compared to other pieces of equipment. Consequently, the gas plant facilities must be totally shut downed during this the time to execute the TAM event based on 6 pieces of heat exchangers due to cumulated fouling layers through tubes of heat exchangers that could be caused in the detraction of the flow of fluid, an increase in the pressure drop, change in heat transfer during the operating process, increase in overall heat transfer coefficient loss, increase in electrical consumption and high vibrations throughout the bundle.

Table 10. Optimal interval of TAM of the gas plant

2nd Stage				
Risk Category	**Heat Exch.**	**Drums**	**Columns**	**Piping**
Total equipment	**18**	**32**	**16**	**35**
V. Low	2	12	0	12
Low	6	9	7	20
Moderate	4	9	7	1
High	6	2	2	2
V. High	0	0	0	0
Major equipment	6 Series	2 Separated	2 Series	2 An item
Main Causes	Fouling	Shell corrosion	Trays, Caps, bolts	Wall corrosion
3rd Stage				
Scenarios	**1st Scenario**	**2nd Scenario**	**3rd Scenario**	**4th Scenario**
R(t)	0.57	0.44/0.49	0.43	0.41
h(t)	0.00005	6/5E-5	0.00007	0.00007
MF	0.00003	2.7/2E-5	0.00003	0.000029
TAM Interval (**hr**)	**24800**	**73500**	**75100**	**113500**
Optimum Interval	[minimum time] = **24800** hrs (2 years and 9 months)			

5. Summary and Conclusions

The purpose of the paper was to develop the TAM model to optimize scheduling the TAM at gas plants. The TAM model included three stages:

- 120 and 65 of 186 and 91 vessels and pipelines were removed, respectively from TAM worklist to proactive maintenance plan.
- 66 vessels and 35 pipelines were assessed based on RBI and risk matrix approach.
- Then Weibull distribution model was applied on six pieces of heat exchangers, two drums, two of process columns, and two 26"- steam water lines, which represented the highest risk on the plant performance to determine optimum interval of the TAM in order to improve reliability productivity, and availability of the plant.

The frequency of scheduling TAM during a fixed period and constantly, means that there are two concerns:

- The plant will undergo a fixed duration to conduct TAM activities, every a fixed TAM cycle. This is an indicator to operational risk.
- The estimation of TAM budget will also be a fixed during duration of TAM. This means that TAM activities be always similar to the pervious events of TAM without taking critical equipment into account.

These concerns can drive to a high cost due to plant shutdown for a long time and TAM cost, or unscheduled outage occur between cycles of TAM due to an unplanned TAM interval in which can effect on the functional performance

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of the plant. Therefore, application of the TAM model is considered a vital to address these concerns in order to improve outage planning, minimize TAM costs, avoid unanticipated consequences of failure between TAM intervals, and insure operation of the plant more safely and effectively. The results of the developing TAM model in the gas plant illustrated that scheduling TAM could be optimized without any threats on the plant performance due to decreasing duration and increasing interval of TAM.

Analysis showed that the TAM duration of the gas plant could be decreased from 30 to 21 days with reduced in the budget of TAM to less $2 million rather than $2.5 million, and interval of TAM could be prolonged from 2 years to 2 years and 10 months, without any threats of fouling layers that accumulated through tubes of heat exchangers. Availability could also be improved to 98% rather than 95.89%, which supports the TAM optimization in the gas plant. Consequently, TAM is not only necessary for minimizing the risk of failures resulting from rigorous operating conditions, but is also essential to improve productivity and increasing availability of the plant.

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Acronyms and abbreviations

A	**Availability**		
P	**Effect of equipment downtime on the**	**FM**	Failure mode
S	**Effect of equipment downtime on the safety**	**h(t)**	Hazard rate
R_e	**Estimated risk of system**	**R(t)**	Reliability function
CE	**Critical Equipment**	**F(t)**	Unreliability function
Rc	**Risk criteria**	β	Shape parameter
TAM	**Turnaround Maintenance**	η	Scale parameter
PL	**Production Losses**	**MTBF**	Mean Time Between Failures
AD	**Asset Damage**	**MTTF**	Mean Time To Failure
ED	**Environment Damage**	**MTTR**	Mean Time To Repair
SoW	**Scope of Work**	**RBD**	Reliability Block Diagram
NE	**Non-critical Equipment**	**PoF**	Probability of Failure
NRE	**Non-critical Rotating Equipment**	**CoF**	Consequences of Failure
NSE	**Non-critical Static Equipment**	**RBI**	Risk-Based Inspection
CRE	**Critical Rotating Equipment**	**RBD**	Reliability Block Diagram
CSE	**Critical Static Equipment**	**TTF**	Time to failure

Biographies

Mr. A. Elwerfalli received his MSc degree in Quality assurance from the University of Teesside, United Kingdom in 2003. He is currently a PhD candidate in the Automotive Research Centre at University of Bradford. He has worked as a head of engineers in Maintenance Engineering Division (MED) at Sirte Oil Company, Libya, since 1997. His research interests include optimizing turnaround maintenance scheduling to oil and gas plants.

Professor M. Khurshid Khan received his BEng, PhD and MBA degrees from the University of Bradford in 1983, 1987 and 1997, respectively. His PhD area of research was experimental and theoretical study of air turbulence. During 1987 to 1990, he worked for Pepsi-Cola International as a Technical Services Manager in the Middle East, Far East and Africa Regions. In 1990, he joined the School of Engineering, University of Bradford, where he is currently a Professor of Manufacturing Systems Engineering. His research interests are in the area of Artificial Intelligence (AI)/Knowledge-Based Systems and their applications to Manufacturing & Quality Systems, Strategy, Planning, Control, Scheduling, and Supply Chain Management.

Dr. J. Eduardo Munive-Hernandez is a Lecturer in Advanced Manufacturing Engineering at the Faculty of Engineering and Informatics, University of Bradford. He received his Ph. D in Total Technology from the University of Manchester Institute of Science and Technology in 2003. His major research interests include the analysis, development and implementation of knowledge management initiatives to support strategic management decisions in the context of manufacturing organizations, their supply chains and other operational functions, including SMEs.

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