Development of a Reliability, Availability and Maintainability (RAM) Simulation Model for Gas Lift and Gas Injection System

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***Abstract*—In the oil and gas industry, oil production will reduce over the time as oil fields become mature, causing depletion in reservoir pressure and less oil flow to the surface. When reservoir energy is insufficient to bring the oil flowing to the surface, it is essential to use an artificial lift as a primary oil recovery to maintain the reservoir pressure. After artificial lift have been applied to the reservoir, secondary recovery might be used as an initiative to increase the recovery of crude oil. Based on A significant failure occurred at a power plant in the USA in 1995 as a result of a turbine blading design fault. Surrounding auxiliary equipment was also damaged costing $11 million [1]. One of the reasons is due to the operating conditions inside gas turbines that can damage the blades through particulates adhering to the blades. Turbine blades are very sensitive, any damage can reduce mass flow and effective pressure ration. Therefore, it is crucial to identify which equipment/component in the system is the most critical and need to be paid attention. In this paper, the Reliability, Availability and Maintainability (RAM) studies have been conducted as a solution to identify the equipment/component criticality. The purpose of the study is to assess the facility equipment design and its configuration system which focus on the Gas Lift and Gas Injection System. Besides, to identify and rank the systems/components that could be a major contributor to the production efficiency losses in the facility, and to evaluate the impact of modifications and changes to the base case. Reliability Block Diagram (RBD) has been created based on ISO 14224. The modelling is conducted using reliability-based analytical models on selected equipment configuration and assumptions. The analytical calculation results are compared between various cases in this study and critical components required to have capital spare are identified in order to improve system reliability.**

***Keywords*— Gas Lift System, Gas Injection System, GTC, Production loss, RAM, RBD, Reliability analysis, Reliability-based analytical models.**

I. INTRODUCTION

In the current oil and gas industry business, profit margins are reduced while competition is increasing over the time. Desirable industries to increases their company's revenue make the reliability becomes a will for engineers to find ways of saving costs. Therefore, it is important to ensure the oil reserves of the field can be productively produced at maximum capacity with a lowest possible cost and highest profit margin.

However, any interruption in the system always occurs either in onshore or onshore due to unplanned and planned maintenance activity on equipment. Maintenance takes time and costs to repair or replace every single equipment in the system. Downtime of the equipment or component lead to the production losses in oil and gas upstream process and affect the efficiency of the Gas Lift and Gas Injection system. Thus, it is the most critical issues to find out which equipment or component in the system that contributes to major production losses as it may affect the industry economically.

For instance, if the Gas Lift System consists of a single gas compression system train (1x100% configuration), any maintenance activities associated with the compression system will cause interruption to the gas processing system, which contributes to the production loss when it needs to stop the gas process to repairs or replace the failed component. Therefore, gas lift injection rate throughout the reservoir will be affected and impact petroleum production.

The revenue lost due to unexpected shutdown of plants can range from $500-100,000 per hour [2]. Hence, selection of the design and configuration of the system should be selected to optimize plant availability based on risk, safety and reliability evaluation. In this paper, the Reliability, Availability, Maintainability (RAM) simulation models were developed to analyze the system production performance, which includes all failure equipment that may occur in the system with its repair rates in order to estimate the system behaviour over a given operational time. Due to the increased complexity of oil and gas upstream systems, reliability analysis is very essential for increasing the system availability. The reliability and maintenance system program has reduced maintenance costs by about 30% ($1 billion) while improving mechanical availability by about 2% [3].

RAM analysis determines the system availability, which in turn can be used to optimize design configuration, maintenance schedule, and logistics planning. A system is broken down into a number of subsystems. To simplify the model, only the critical equipment, component and part are analyzed. The availability is calculated and the critical items are ranked according to their influence on the unavailability.

Maintenance strategy such as providing a new spare component helps to reduce the delay time due to lack of maintenance resource logistics. However, its benefit and cost should be considered before making any decision. If the replacement failure equipment is implemented, the average efficiency of the system could be increased by 0.7% [4]. The higher criticality equipment that contributed to the production losses needs to be set as "high priority" by the maintenance management system since it required priority in the maintenance work

II. METHODOLOGY

A. *Collecting and Processing Data*

In this study, the RAM analysis has been performed based on the following documents:

- Piping and Instrument Diagrams (P&ID)
- Process Flow Diagrams (PFD)
- ISO 14224 guideline

- Offshore Reliability Data, 2002 (OREDA)

This study used a publicly available process equipment failure rate database such as OREDA. OREDA is one of the main reliability data sources comes from Norwegian Petroleum Directorate for the oil and gas industry on failure rates, failure mode distribution and repair times for equipment used in the offshore industry.

When used the generic database from OREDA, it means that the failure rates and repair times for the critical equipment is higher than in another country such as Malaysia due to different environments. Therefore, the reliability of the system should be higher in real cases compared to the reliability of the system in the North Sea and foreign oil companies since this study considered the worst case situation.

Besides, the OREDA is restricted to failure data collected on hardware components and systems, information about human errors is not included. The study was undertaken in the following phases:

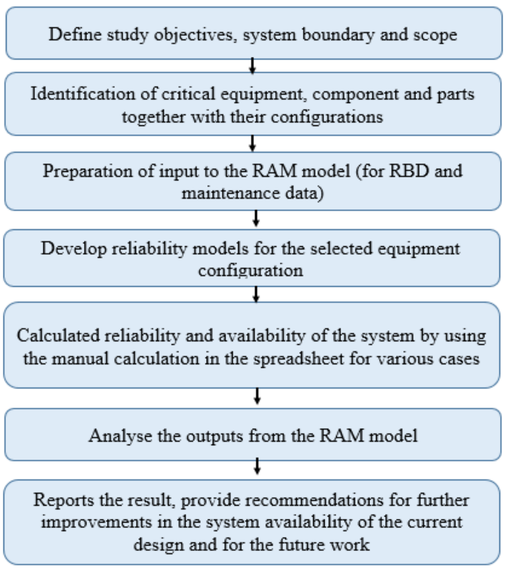

Figure 1: Flowchart of the study

B. RAM modelling

To quantify the consequence in term of reliability and availability, the model of Gas Lift and Gas Injection system was conducted as a Base Case (BC), Sensitive Case 1 (SC1) and Sensitive Case 2 (SC2) along with its own configuration as shown in Table 1. The availability of plants can be estimated using plant configuration with actual failure and repair of distribution time that can be obtained from the OREDA handbook.

Table 1: System Configuration for the study cases

Case study	GL system configuration		GI system configuration
Base case (BC)	1x100%	The single train is running with 100% capacity	1x100%
Sensitivity case 1 (SC1)	2x50%	Train A and Train B is running on 50% capacity each	
Sensitivity case 2 (SC2)	2x100%	Train A is running, Train B is on standby	

The Gas Lift and Gas Injection systems comprise various equipment, component and parts configured in series and parallel. However, this study only takes into account all of the critical equipment, component and parts in the Gas Lift and Gas Injection system. A basic model of RBD was developed demonstrating the interaction of equipment, component and parts. The gas Lift system is categories into four different equipment whereas Gas Injection system is categories into five different equipment as shown in Table 2.

Table 2: Description of main equipment for GL and GI system

Sub-system	Description	Unit
Gas Lift system		
Vessel	scrubber	4
Gas Turbines	industrial 3,000 - 10,000 kW	1
Compressor	Gas Turbine driver - centrifugal 3,000 - 10,000 kW	3
Heat Exchanger	Aftercooler	3
Gas Injection system		
Vessel	Glycol contactor	1
	Scrubber	1
Combustion Engine	Gas engine	1
Compressor	Gas engine driver – reciprocating (100 – 1000) kW	1
Heat Exchanger	Aftercooler	1

The gas treatment system was modelled as below:

- Gas Lift Compression System
  - 1st, 2nd And 3rd Stage Suction Scrubber
  - 3rd Stage-Discharge Scrubber
  - Gas Turbine
  - 1st, 2nd, 3rd Stage Centrifugal Compressor
  - 1st, 2nd, 3rd Stage Compressor Aftercooler (Heat Exchanger)
- Gas Injection System
  - Glycol contactor
  - Scrubber
  - Combustion engines
  - Reciprocating Compressor
  - Aftercooler (Heat Exchanger)

The critical equipment is only focused on gas turbines and centrifugal compressor of the Gas Lift System since it is the major contributor to the production losses due to its physical as a rotating and large equipment that assists in the system. This section is to rank which sub-unit and parts that contributed to the production loss based on the selected list in Table 3.

Table 3: List of critical equipment, sub-unit and parts

Equipment	Sub-unit	part
Gas Turbine	Starting System	Hydraulic Stater Pump
	Combustion System	Combustor
	Compressor	GT Compressor Rotor
		GT Compressor Stator
	Power Turbine/HP Turbine	Turbine Rotor
		Turbine Stator
	Control And Monitoring	Control Unit/PLC
	Lubrication System	Sensors
	Accessory Drive	Gearbox
		Bearing
GL Centrifugal Compressor	Power Transmission Unit	Gearbox/Pinion Shaft
		Bearings
		High-Speed Coupling To The Driver Unit
		Low-Speed Coupling The Driver Unit
	Compressor Unit	Rotor With Impeller
	Lubrication System	Pumps
	Shaft Seal System	Dry Gas Seal

C. *Reliability Block Diagram (RBD) Models*

A reliability block diagram is a graphical diagram represents the interaction of equipment from reliability perspective (parallel or series path) without indicating process flow. To understand the impact that loss of a system or component will have on the performance of the unit, the Process Flow Diagrams (PFDs) of the Gas Lift and Gas Injection system sections were translated into a series and parallel of reliability block diagrams (RDBs). The RBDs indicates the actual physical connections or process flow, and also used to illustrate the following:

- Equipment redundancy: Duty/duty or duty/standby for spared equipment.
- Equipment configuration: Series or parallel arrangement
- Equipment capacity: 1x100%, 2x50% and 2x100%

The critical equipment configuration PDF for the whole facilities is illustrated in Figure 2 as a Base Case for the study. All equipment listed in this section is assumed to be critical to production. For all equipment that has redundancy, it is assumed that there is only sufficient equipment on the line to allow 100% throughput. Hence, for a system with 2x100% equipment configuration, it is assumed that one train is running and one is on standby. Detail of the selected equipment is listed in Table 2, where the number of equipment required to indicate the train set for sensitivity analysis is indicated.

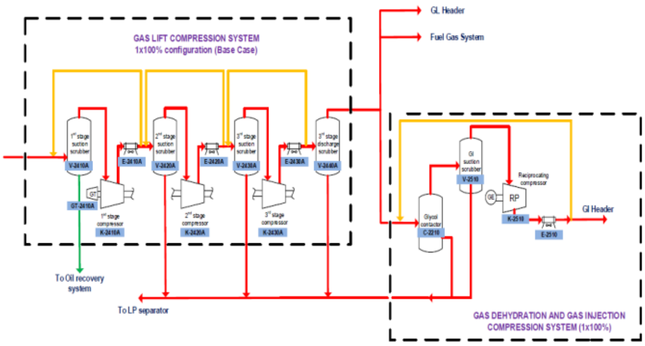

Figure 2: Simplified Process Flow Diagram (PFD) for Base Case

Figure 3 below contains detailed RBD of equipment level study for the Base Case that is converted from PDF in Figure 2. The equipment, component and part level are included in this study to find out the impact of every single equipment/component system towards the upstream production losses. Then, modifications in selected plant configurations and changes in maintenance strategies can be identified in this research in order to improve plant performance efficiencies.

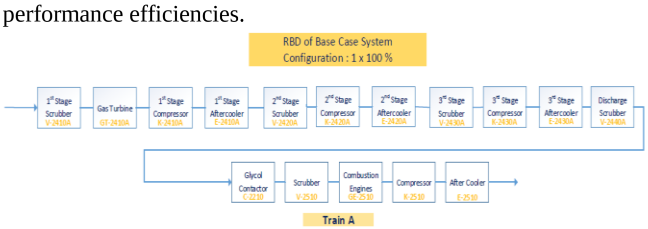

Figure 3: Reliability Block Diagram (RBD): Base Case system (equipment level)

D. *Reliability and Availability Calculation*

Reliability is the probability of an item/system that will perform a required function without failure under stated conditions for a stated period at a time. In this step, the goal is to model the system in terms of reliability aspects. The values of failure rate, repair time, and MTBF for individual equipment in the Gas Lift and Gas Injection system can be identified from OREDA data. As a result, the reliability of the system can be predicted through mathematical formulations for failure rate and related parameters in systems. The operational time is assumed as 30 years. The basic reliability formula for operational equipment used in this study is as below. This formula also applies to calculate the reliability of the component and part of the system.

$$R(t) = e^{-\lambda t} \tag{1.1}$$

Where, R: Reliability of the Component
e: Exponential
λ: Failure rate of the component
t: Operational time

For the system that has redundancy configuration such as SC2, two trains are assumed to have the same failure rate of the components over the duration of the system to operate, 30years. Only one operates at the time and it is assumed to have a perfect switch if the primary units fail. The redundancy system can be illustrated in Figure 4.

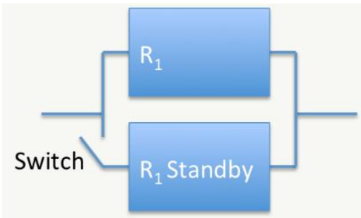

Figure 4: A simple diagram of a redundancy system

The equipment reliability of the standby redundancy configuration is calculated using equation below [5]:

$$R(t) = e^{-\lambda t}(1+\lambda t) \tag{1.2}$$

Availability in RAM study is referred to the ability of an item to perform a required function, under stated conditions at a specific time interval. High-reliability results in the high availability of a system. The general calculation of equipment availability is:

$$A = \frac{MTBF}{MTBF + MTTR} \tag{1.3}$$

Where, MTBF: Mean Time Between Failure
MTTF: Mean Time to Failure

A system that has 1x100% configuration is known as a series system. A series system is a common configuration used in engineering systems that represent if any one component of the system fails, the entire system will fail. An illustration of a series system is shown in Figure 5. The concept of reliability system (Rs) uses "block" to indicate each system element. Each block has its own reliability value at a given time [6].

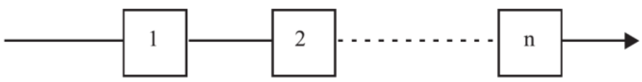

Figure 5: A series system of "n" components

The system reliability decreases as the number of series components increases. However, a small rise in the reliability of all items (say R of the two items rises) causes a larger rise in system reliability. The reliability of a series system is calculated using the equation below.

$$Rs = R1 \times R2 \times R3...Rn \tag{1.4}$$

A system that has 2x50% or 2x100% configuration is known as a parallel system. A parallel system configuration represents if not all of the system component fails, the entire system works. Besides, at least one of these units must operate normally for the system success. Conceptually, the total reliability of parallel configuration results in higher reliability compared to single system configuration [6]. An illustration of a parallel system is shown in Figure 6.

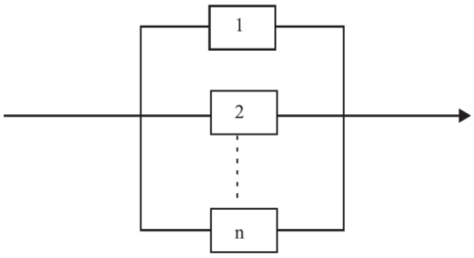

Figure 6: A parallel system of "n" components

The parallel system consists of two or more devices providing backups to reduce system risks for failure. The system reliability increases as the number of series components increase but costs become an issue since higher initial and maintenance costs are needed to operate the system. parallel system reliability is always higher than the most reliable item. The reliability of a parallel system is calculated using the equation below.

$$Rs = 1 – (1 – Rn) = 1 – (1 – R1) \times (1 – R2)…(1 – Rn) \quad (1.5)$$

Some system is consisting of combinations of several series and parallel configuration. To obtain system reliability is to break the total system configuration into homogeneous subsystems as shown in Figure 7. Then, calculate these subsystems reliability separately as a unit. Finally, add all the subsystems into a single system and obtain its reliability to reduce the complicated configuration.

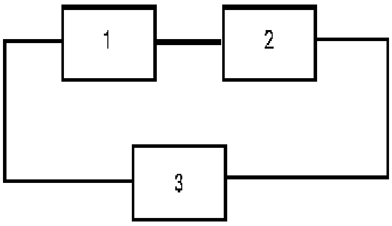

Figure 7: A combination system

III RESULTS AND DISCUSSION

E. The failure rate of the equipment

From provided data by OREDA, the failure rate is converted to unit per year to identify which equipment contributes to a higher tendency to cause downtime of the system [6].

Table 4: Failure Rate analysis

Equipment	No failure	failure rate (per 10^{-6} hours)	failure rate (per year)	Repair (manhours)
Gas Lift system				
Scrubber	11	22.98	4.97	8.80
Gas Turbines	128	235.25	0.49	59.90
Compressor	9	71.74	1.59	78.60
Heat Exchanger	29	13.64	8.37	45.5
Gas Injection system				
Glycol contactor	21	87.66	1.30	27.10
Scrubber	11	22.98	4.97	8.80
Combustio n Engine	31	69.68	1.64	20.80
Compressor	367	347.08	0.33	13.00
Heat Exchanger	29	13.64	8.37	45.50

Based on Table 5, it can be concluded that the heat exchanger results in higher failure rate than other equipment in both Gas Lift and Gas Injection system with 8.37 failure per. It means that the Heat Exchanger will fail approximately 8 times in a year.

In Gas Lift system, second equipment that has higher tendency to cause failure is Scrubber followed by Centrifugal Compressor and Gas Turbine with 4.97/year, 1.59/year and 0.49/year respectively.

In addition, second equipment in Gas Injection system that has higher tendency to cause failure is Scrubber followed by Combustion Engine, Glycol Contactor and Reciprocating Compressor with 4.97/year, 1.64/year, 1.30/year and 0.33/year respectively.

F. Summary of reliability and availability of various cases.

Table 5: Study cases total reliability and availability

RAM Case	System Reliability (%)	MTTFs (hours)	MTTRs (hours)	Estimated system availability (%)
Base Case (BC)	97.34	9.74×10^6	582.6	95.85
Sensitivity Case 1 (SC1)	98.69	19.94×10^6	1050.0	98.99
Sensitivity Case 2 (SC2)	98.71	20.24×10^6	1050.0	99.99

Result in Table 5 shows that SC2 has the highest system reliability with 98.71% compared to SC1 and BC with 98.69% and 97.34% respectively. Availability of the system increased as the reliability increased. Therefore, SC2 has the highest system availability with 99.99% followed by SC1 and BC with 98.99% and 95.85 respectively.

G. Reliability and Availability analysis by system configuration.

Table 6: Reliability analysis summary

Case study	GL system configuration	GL Reliability	GI system configuration	GI Reliability
Base case (BC)	1x100%	98.61%	1x100%	98.71%
Sensitivity case 1 (SC1)	2x50%	99.98%		
Sensitivity case 2 (SC2)	2x100%	99.99%		

Referring to Table 6, the result proved that a series configuration of Gas Lift system resulting in lower system reliability compared to the parallel configuration of SC1 and SC. BC contributed to 98.61% system reliability whereas SC1 and SC2 result 99.98% and 98.61% system reliability. However, SC2 gives higher reliability result compared to SC1 since SC2 have standby redundancy system. Increase number of redundancy system might increase the total system reliability.

Table 7: Availability analysis summary

Case study	GL system configuration	GL Availability	GI system configuration	GI Availability
BC	1x100%	95.85%	1x100%	99.95%
SC1	2x50%	99.89%		
SC1	2x100%	99.99%		

From table 7, SC2 shows the higher Gas Lift system availability, followed by SC1 and BC with 99.99%, 99.89% and 96.73% respectively. Therefore, the reliability of the system can be related to the system availability. As reliability increased, availability will have increased also.

H. *Critical Equipment contributor to production losses.*

Table 8: Critical equipment level production loss contributors

Equipment	Equipment total downtime over operational time.	Total production loss (%)	System Loss
Gas Lift compression system			
Scrubber	0.029175	78.31	5.38 %
Gas Turbines	0.005021	13.48	
Compressor	0.002692	7.23	
Heat Exchanger	0.000368	0.99	
Gas Injection system			
Glycol contactor	0.002166	64.46	2.82 %
Scrubber	0.000368	17.83	
Combustion Engine	0.002454	8.71	
Compressor	0.018545	7.69	
Heat Exchanger	0.005021	1.31	
Total Production Losses			8.19 %

Based on equipment downtime data from OREDA, the Gas Turbine equipment in Gas Lift system is identified as the most critical equipment level within the facility. The unit contributed approximately 78.31% of total production loss, followed by Heat Exchanger, Centrifugal Compressor and Scrubber with 13.48%, 7.23% and 0.99% respectively. Figure 8 below shows pie chart of production losses for the Gas Lift facility equipment.

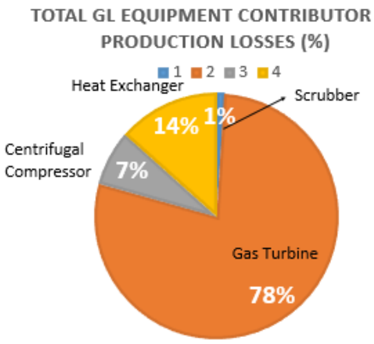

Figure 8: Main contributors to the production loss under the GL system

The Reciprocating Compressor equipment in Gas Injection system is identified as the most critical equipment level within the facility. The unit contributed approximately 64.62% of total production loss, followed by Combustion Engine, Glycol Contactor, Heat Exchanger and Scrubber with 17.83%, 8.71%, 7.69% and 1.31% respectively. Figure 9 below shows a bar chart of production losses for the Gas Injection facility equipment.

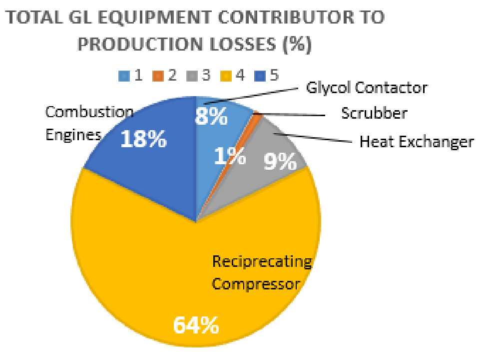

Figure 9: Main contributors to the production loss under the GI system

I. *Base Case analysis*

Based on Table 8, the reliability of the equipment is calculated using the formula described in equation 1.1. Then, equation 1.4 is used to calculated a series reliability system (Rs) of Gas Lift and Gas Injection system. However, the reliability of each equipment need to be multiplied by the number of unit equipment consists in the Gas Lift and Gas Injection system as listed in Table 2 in order to identify the total system reliability. Table 9 shows the summary of reliability that categories in term of equipment, system and total system.

Table 9: BC equipment reliability calculation data

Sub-system	Reliability (%)	Availability (%)	Rs (%)	As (%)
Gas Lift system				
Scrubber	99.94	99.98	98.61	96.73
Gas Turbines	99.44	98.63		
Compressor	99.83	99.44		
Heat Exchanger	99.97	99.94		
Gas Injection system				
Glycol contactor	99.79	99.76	98.71	99.09
Scrubber	99.94	99.98		
Combustion Engine	99.83	99.86		
Compressor	99.17	99.55		
Heat Exchanger	99.97	99.94		
Total Rs			97.34 %	
Total As			95.85 %	

To calculated availability of the equipment, equation 1.3 has been used. The steps to identify system availability is same as calculated system reliability, by replacing the equipment reliability with equipment availability in the formula 1.4. Then, system availability (As) result can be achieved as Table 9.

Total equipment downtime over operational time can be determined from OREDA. From Table 3, repair time needs to times with its number of failure to identify the total downtime of the equipment. Then, the probability of major contributor to the production losses can be calculated. Total production losses due to downtime of the equipment are 8.19% by assumed that all the equipment spares are available whenever required for maintenance.

J. *Sensitivity Case 1 (SC1) analysis*

Based on Table 10, the reliability of the equipment is calculated using the formula described in equation 1.1. Then, equation 1.5 is used to calculate a parallel reliability system (Rs) of Gas Lift whereas equation 1.4 is used to calculate a series reliability of Gas Injection system.

Table 10: SC1 equipment reliability calculation data

Sub-system	Reliability (%)	Availability (%)	Rs (%)	As (%)
Gas Lift system				
Scrubber	99.94	99.98	99.98	99.89
Gas Turbines	99.44	98.63		
Compressor	99.83	99.44		
Heat Exchanger	99.97	99.94		
Gas Injection system				
Glycol contactor	99.79	99.76	98.71	99.09
Scrubber	99.94	99.98		
Combustion Engine	99.83	99.86		

Compressor	99.17	99.55		
Heat Exchanger	99.97	99.94		
Total Rs			98.69 %	
Total As			98.99 %	

To calculated availability of the equipment, equation 1.3 has been used. The steps to identify system availability is same as to calculated system reliability for SC1, by replacing the equipment reliability with equipment availability in the formula 1.5 (GL system) and formula 1.4 (GI system). Then, system availability (As) result can be achieved as Table 9.

K. Sensitivity Case 2 (SC2) analysis

The reliability of the redundancy equipment is calculated using the formula described in equation 1.2 since this study case has standby redundancy system. However, the reliability of the operational equipment is calculated by using equation 1.1.

Then, equation 1.5 is used to calculate a parallel reliability system (Rs) of Gas Lift whereas equation 1.4 is used to calculate a series reliability of Gas Injection system. To calculated total reliability of the system, combinations of several series and parallel configuration method were used.

Table 11: SC2 equipment reliability calculation data

Sub-system	Reliability (%)	Standby redundancy Reliability (%)	Availability (%)	Rs (%)	As (%)
Gas Lift system					
Scrubber	99.94	99.99	99.98	99.99	99.99
Gas Turbines	99.44	99.99	98.63		
Compressor	99.83	99.99	99.44		
Heat Exchanger	99.97	99.99	99.94		
Gas Injection system					
Glycol contactor	99.79		99.76	98.71	99.09
Scrubber	99.94		99.98		
Combustion Engine	99.83		99.86		
Compressor	99.17		99.55		
Heat Exchanger	99.97		99.94		
Total Rs				98.71 %	
Total As				99.09 %	

L. Sub-unit and parts criticality of the GTC analysis.

The steps to identify the reliability of the GTC sub-unit and parts are calculated as equation 1.1. The result can be summarized based on Figure 10 until Figure 13.

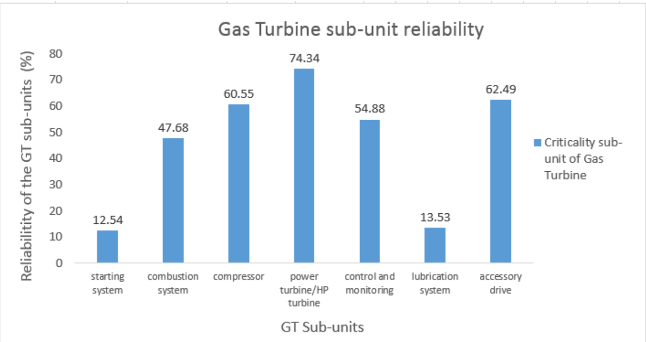

Figure 10: Reliability of GT sub-unit

From Gas Turbine sub-unit reliability figure above, starting system of Gas Turbine shows the lowest reliability which is 12.54%. Low in reliability values indicated that it is the most critical sub-unit of the equipment. In contrast, HP Turbine shows the highest reliability values with 94.34%. Thus, Gas Turbine Stator is less critical than other sub-unit/component shown in Figure 8. Top critical components that should be paid attention to prevent the highest possibility to cause failure are starting system, lubrication system and combustion system which contributed to 12.54%, 13.53% and 47.68%.

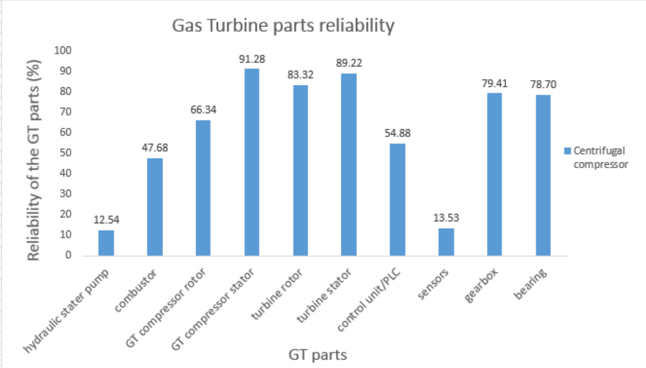

Figure 11: Reliability of GT parts

In the Gas Turbine parts, Hydraulic Stator Pump is the most critical with the reliability of 12.54% whereas GT Compressor Stator is the less critical parts with 91.28% of reliability values. Top critical parts that should be paid attention to prevent the highest possibility to cause failure are Hydraulic Stater Pump, Sensors and Combustor which contributed to 12.54%, 13.53% and 47.68%.

Therefore, it is necessary to plan a preventive maintenance towards the critical component/part. Lowest reliability values also indicated that the component/part had critical failure issues. Downtime of the components/part could affect the reliability and efficiency of the system.

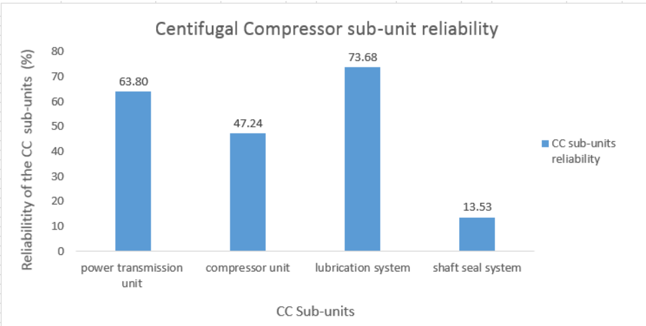

Figure 12: Reliability of CC sub-unit

Centrifugal Compressor components are categories as Power Transmission, Compressor Unit, Lubrication System and Shaft Seal System. Based on Figure 12, the most critical components in the Centrifugal Compressor is Shaft Seal System with 13.53% of component reliability, followed by Compressor Unit and Power Transmission Unit with the reliability of 47.24% and 63.80% respectively.

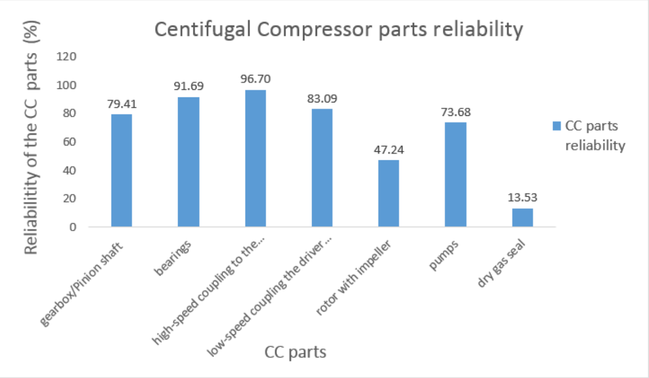

Figure 13: Reliability of CC parts

In the Centrifugal Compressor parts, Dry Gas Seal is the most critical with the reliability of 13.53% whereas High-speed Coupling to the Driver Unit is the less critical parts with 96.70% of reliability values. Top critical parts that should be paid attention to prevent the highest possibility to cause failure are Dry Gas Seal, Rotor with impeller and pumps which contributed to 13.53%, 47.24% and 73.68%.

IV CONCLUSION

Sensitivity Case 2 resulted in the highest reliability and availability values which are 98.71% and 99.99% respectively. It means that this option is the best configuration of Gas Lift and Gas Injection system which can be used to increase the production efficiency. However, the cost and benefit should be considered before making any decision since redundancy system in SC2 required a higher capital cost for standby a system. Hence, Extra input data/parameters need to be analysed to get a more accurate result.

The most critical equipment that contributed to the production loss of Gas Lift and Gas Injection system is Gas Turbine Compressor (GTC) with 78.31%. In the GT equipment, Starting System component and Hydraulic Stator part is the most critical event with a reliability of 12.54% for both. For Centrifugal Compressor equipment, Shaft Seal System component and a Dry Gas Seal part is the most critical event with a reliability of 13.53% for both.

Maintenance strategy such as providing a new spare component helps to reduce the delay time due to lack of maintenance resource logistics. The higher criticality equipment that contributed to the production losses needs to be set as "high priority" by the maintenance management system since it required priority in the maintenance work

IV RECOMMENDATIONS

Recommendations that can be taken for this thesis are divided into two which is for industry and for future work as stated below:

For industrial:

- Periodically inspecting materials/items which critical to determine their serviceability by comparing their characteristics of physical, electrical and mechanical with expected standard.
- Periodic replacement of limited-life items or wear degradation, to maintain the specified system tolerance and prevent incipient failure.
- The higher criticality equipment that contributed to the production losses needs to be set as "high priority" by the

For future work:

- Collecting economic data alongside with case study data might be advantageous. Benefit and cost should be considered before making any decision. Then, extra input/parameter need to be analyzed to get more accurate results.
- Develop a different model of reliability evaluation such as Markov model, Monte Carlo model, etc.

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