LIFE CYCLE ASSESSMENT OF TURBOMACHINERY FOR OFFSHORE APPLICATIONS—UPDATED WITH FIELD DATA

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ABSTRACT

About 40 to 50 percent of the power required for the operations of a typical offshore oil and gas platform is used for gas compression. Miranda and Brick (2004) described a comprehensive procedure that could be applied to decide between mechanical or electric drives for the main compression units. The case studies demonstrated that, in most cases, the best configuration would be to combine a larger and more efficient power generation system with all electric driven machinery, including the large injection pumps and the main export and gas lift compressors. Since then, five major offshore platforms with electric driven compressors were put into operation in the Brazilian offshore province of Campos Basin. This paper describes an updated life cycle evaluation of the power generation and main compressor drivers for these “new generation” offshore oil and gas production platforms. The authors present operational data collected at these recently installed platforms, which are configured with all electric driven machinery, and make direct comparison with data collected from “previous generation” platforms, installed in the same offshore province, where the main compression units are gas turbine driven. Predicted life cycle behavior is compared to actual results for the “new generation” platforms.

INTRODUCTION

Miranda and Brick (2004) presented a comprehensive life cycle cost (LCC) analysis procedure that was developed primarily as a decision-making tool for assessing alternative configurations for the design of turbomachinery systems on offshore platforms. The model had predicted that new generation offshore platforms should preferably be provided with a larger and more efficient power generation system, combined with electric driven main compressors. Since then, five major offshore platforms using this strategy (i.e., having electric driven compressors) have been put into operation in the Brazilian offshore province of Campos Basin. Now, after three years of operation with this strategy in place, very significant operational data are available for both the new generation and previous generation platforms. The intent of the analysis described in this paper is to evaluate the robustness of the model used to select the most cost-effective configuration for turbomachinery systems, and, after all, to answer the question: *Was the option for all electric drives a good strategy?*

This paper describes an updated evaluation, considering power generation systems for offshore oil and gas production platforms. The authors present operational data, which were collected at new generation platforms with an all-electric driver solution, and compare them with previous generation platforms, where the compressors are gas turbine driven. The predicted life cycle behavior is also compared to actual results for the new generation systems. The reliability, availability and maintainability analysis is performed as part of the LCC calculations. The reliability, availability, and maintainability (RAM) analysis developed by Miranda and Brick (2004) was based on an analytical Markov chain method. In the evaluation presented in this paper, the RAM analysis is performed by running event-driven simulation software, which is a design tool that allows the development and comparison of systems by predicting their life cycle behavior pattern. The simulator viewer provides the production efficiency results throughout the life cycle of the system, for each of the system configurations under analysis.

THE LCC MODEL

The purpose of the turbomachinery system is to provide energy for platform operations. The system provides three types of energy: mechanical, electrical, and thermal. The demand profile for each type of energy is developed as a function of the platform liquid and gas production profile. The power generation system and major drivers can then be configured based on system purpose and requirements. Configuration decisions should be made based on the lowest cost throughout the life cycle, or the lowest total cost of ownership.

According to Miranda and Brick (2004) the life cycle cost analysis of turbomachinery systems should consider total life costs, from the conception of the system up to its retirement, including costs associated with development, construction, commissioning, testing, and operation. The cost breakdown structure defines the cost categories for each phase of the life cycle. Figure 1 shows the proposed cost breakdown structure.

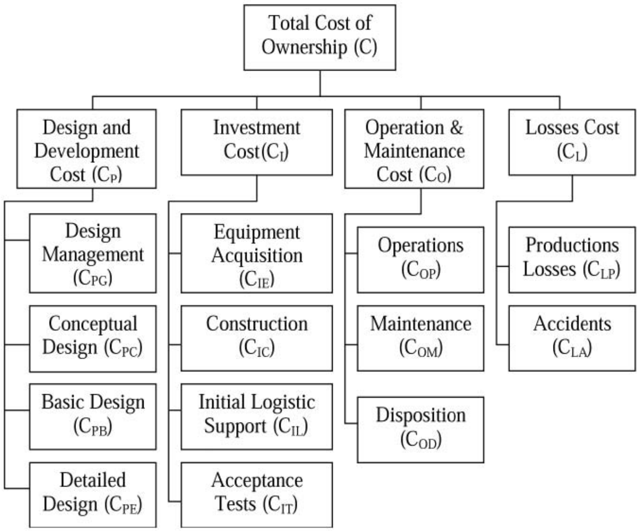


Figure 1. Cost Breakdown Structure.

THE RAM MODEL

In order to calculate production losses, the RAM analysis is performed with event-driven simulator software, which is a design tool that permits the development and comparison of different systems by predicting their life cycle behavior pattern. The simulator viewer provides the production efficiency results, throughout the life cycle of the platform for each system configuration, which is the same parameter defined as *production regularity* by Miranda and Brick (2004):

$$\mathrm{Pr}oduction\ Efficiency = \frac{Actual\ \mathrm{Pr}oduction}{Potential\ \mathrm{Pr}oduction} \times 100\% \qquad \mathbf{(1)}$$

The simulator reports the production efficiency for any discrete period of time of the life cycle, with annual, quarterly, monthly, or daily frequency. The simulation analysis also provides the following information:

- Predicted production losses due to system downtime, expressed in volume of oil and gas production deferred throughout the life cycle of the platform
- Predicted gas flaring throughout the life cycle
- Predicted revenue losses for each year of the life cycle
- Predicted forced outages throughout the life cycle
- Average system annual unavailability
- Predicted reliability for a defined life period, for instance five or 10 years
- Operational cost (OPEX) expressed as nominal yearly basis or in discounted present value, taking into account labor and spare parts for repair and maintenance

The simulator software considers the three types of fluid flows through the system: oil, gas, and water. The annual flows vary according to the production profiles. The effects of logistics such as mobilization delays, backlogs, and spare parts availability can also be configured for each component relevant to the analysis. Unscheduled events can be configured with both failure and repair distribution parameters. Scheduled events are configured based on the scheduled maintenance program for each component.

In order to simulate platform life cycle, the software is configured with a logical model representing each component with blocks. The so-called reliability block diagram (RBD) identifies each component and their relationship and configuration (series, parallel, standby, etc.). Figure 2 shows the RBD deployment of an offshore platform, for a typical configuration with three gas turbine driven compressors in parallel, combined with two gas turbine driven generators that provide power to the remaining platform loads. The configuration for both the compression and the generation has at least one standby unit (passive redundancy).

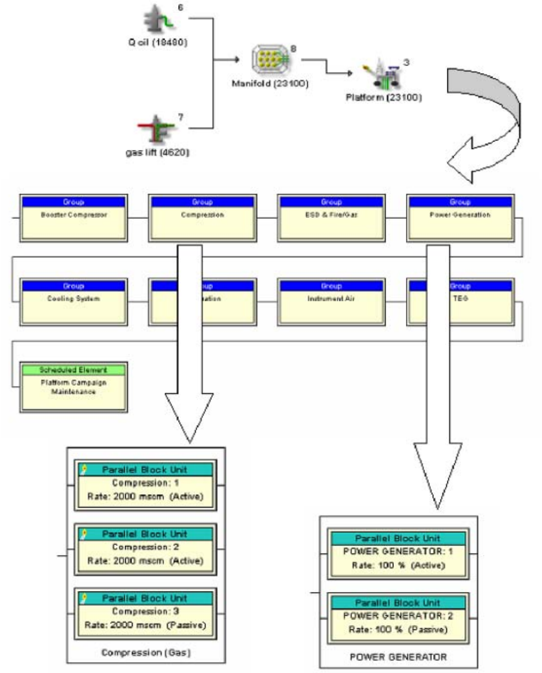


Figure 2. Deployment of the Reliability Block Diagram.

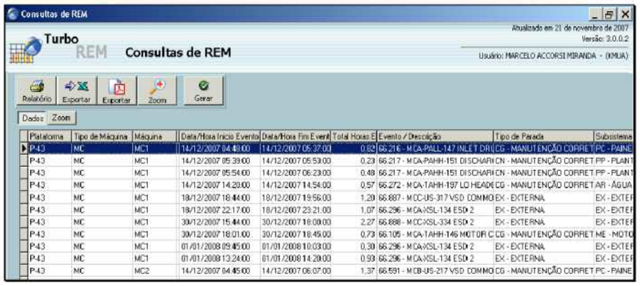
Failure modes and scheduled activities are assigned to each block of the RBD. For unscheduled events, the simulator generates events according to the probability distribution assigned to each failure mode. Scheduled events are generated according to the timing parameters assigned to each scheduled activity.

This paper considers the same four cases analyzed in the Miranda and Brick (2004) paper:

- 4TG6MC: Four turbogenerators and six motocompressors (compressors driven by fixed speed electric motors). Three out of the four generator sets are required for the peek production phase. The compression system is a series-parallel system with three low pressure (LP) compressor bodies in series with three high pressure (HP) compressor bodies, each one with its own fixed speed electric motor driver.
- 2TG3TC: Two turbogenerators and three turbocompressors. One generator set is sized for 100 percent of the platform load; the other one is a standby unit. Each gas turbine drives both LP and HP compressor casings, in tandem configuration.
- 3TG3TC: Three turbogenerators and three turbocompressors. Each generator set is sized for 50 percent of the peek load. The compressors are turbine driven, in tandem configuration.
- 4TG3MC: Four turbogenerators and three motocompressors (compressors driven by VFD electric motors). Three generator sets in operation, one standby. The variable frequency drives (VFDs) drive the LP and HP compressor casings, in tandem configuration.

FAILURE DATA ANALYSIS—THE WEIBULL METHOD

Failure and repair data utilized to generate the probability distributions were obtained directly from the data bank called TurboREM, initials in Portuguese for turbomachinery events record. The platform operators issue daily reports with a list of events with trip and start time, type of event, subsystem affected, brief description of the possible causes of the failure, time to repair, time to perform scheduled activities, and so on. After three years running, the authors were able to perform a comprehensive reliability data analysis. Figure 3 shows a TurboREM events report.

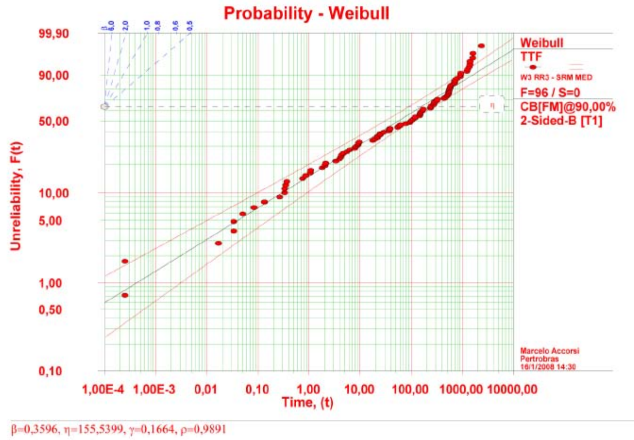


Atualizado em 21 de novembro de 2007
Versão: 3.0.0.2
Usuário: MARCELO ACCORSI MIRANDA - (KMUA)

Plataforma	Tipo de Máquina	Máquina	Data/Hora Início Evento	Data/Hora Fim Event	Total Horas E	Evento / Descrição	Tipo de Parada	Subsistema
P-43	MC	MC1	14/12/2007 04:48:00	14/12/2007 05:37:00	0,82	66.216 - MCA-PALL-147 INLET DR	CG - MANUTENÇÃO CORRET	PC - PAINE
P-43	MC	MC1	14/12/2007 05:39:00	14/12/2007 05:53:00	0,23	66.217 - MCA-PAHH-151 DISCHAR	CN - MANUTENÇÃO CORRET	PP - PLANT
P-43	MC	MC1	14/12/2007 05:54:00	14/12/2007 06:23:00	0,48	66.217 - MCA-PAHH-151 DISCHAR	CN - MANUTENÇÃO CORRET	PP - PLANT
P-43	MC	MC1	14/12/2007 14:20:00	14/12/2007 14:54:00	0,57	66.272 - MCA-TAHH-197 LO HEAD	CG - MANUTENÇÃO CORRET	AR - ÁGUA
P-43	MC	MC1	18/12/2007 18:44:00	18/12/2007 19:56:00	1,20	66.887 - MCC-US-317 VSD COMMO	EX - EXTERNA	EX - EXTER
P-43	MC	MC1	18/12/2007 22:17:00	18/12/2007 23:21:00	1,07	66.296 - MCA-XSL-134 ESD 2	EX - EXTERNA	EX - EXTER
P-43	MC	MC1	30/12/2007 15:44:00	30/12/2007 18:00:00	2,27	66.888 - MCC-XSL-334 ESD 2	EX - EXTERNA	EX - EXTER
P-43	MC	MC1	30/12/2007 18:01:00	30/12/2007 18:45:00	0,73	66.105 - MCA-TAHH-146 MOTOR C	CG - MANUTENÇÃO CORRET	ME - MOTO
P-43	MC	MC1	01/01/2008 09:45:00	01/01/2008 10:03:00	0,30	66.296 - MCA-XSL-134 ESD 2	EX - EXTERNA	EX - EXTER
P-43	MC	MC1	01/01/2008 13:24:00	01/01/2008 14:20:00	0,93	66.296 - MCA-XSL-134 ESD 2	EX - EXTERNA	EX - EXTER
P-43	MC	MC2	14/12/2007 04:45:00	14/12/2007 06:07:00	1,37	66.591 - MCB-US-217 VSD COMMO	CG - MANUTENÇÃO CORRET	PC - PAINE

Figure 3. TurboREM Events Report.

In order to estimate the parameters and select the statistical distribution for each failure mode, the authors have utilized a commercial software package. This software performs the life data or Weibull analysis. The intent of the analysis is to make predictions about the life of all products in the population by "fitting" a statistical distribution to life data from a representative sample of units. Figure 4 shows an example of an electric driven compressor life data analysis, based on data for the year 2007. The parameterized distribution for the data set can then be used to estimate important life characteristics of the product, such as reliability or probability of failure at a specific time, the mean life for the product, and failure rate.



$\beta=0{,}3596$, $\eta=155{,}5399$, $\gamma=0{,}1664$, $\rho=0{,}9891$

Figure 4. Weibull Analysis for Electric Driven Compressor (2007).

DATA COLLECTION—CRITICAL REVIEW

The life cycle cost analysis process is a prediction of the future. In order to make such predictions, a close look at the historical data is necessary, but not sufficient in itself. Consider the case of initial investment or capital costs. Account needs to be taken for market effects that led to high cost increases in the last decade. Therefore when comparing a system that was commissioned one decade ago (usually with mechanical driven compressors), with the newer VFD driven systems, it is necessary to consider the influence not only of cost inflation for international resources, but also certain significant localized issues. For instance, some compressor modules that were assembled in Brazil suffered from increased costs as a result of bottlenecking of shipyards due to the highly concentrated demand in the last five years.

And as concerns operational costs, at least one major cost contributor, fuel consumption, has also increased significantly due to both local and international fuel price escalation.

This paper reports a revisited analysis taking into account the observed historical data along with the necessary critical review of the major cost and performance contributors.

CAPITAL AND OPERATIONAL COSTS

The investment or capital cost for each turbomachinery configuration considered in this paper was based on the latest acquisitions for different platforms put into operation from 2000 until today. These values were corrected to account for inflation during the correspondent period and referenced to the same date in order to have a fair basis for comparison.

Operational costs for each turbomachinery configuration (previously described in "THE RAM MODEL"section) were based on fuel consumption, taking into account the efficiency of each system due to the production profile and power demand. Another contributor to total operational costs was accounted for based on scheduled and unscheduled maintenance, considering failure rate and repair costs. All these costs are shown in discounted present value, taking into account fuel price, maintenance and operation labor, and spare parts for repair. The costs related to each turbomachinery configuration can be seen in Table 1.

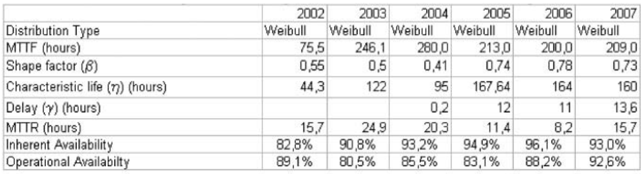
Table 1. Capital and Operational Costs.

	4TG6MC	2TG3TC	3TG3TC	4TG3MC
Design and Development	6.865.371	6.998.663	6.378.655	7.050.129
Investment (CAPEX)	135.770.272	142.427.397	130.493.748	140.290.151
Equipment Acquisition (C_{IE})	60.703.877	55.584.273	54.852.901	65.092.109
Construction (C_{IC})	67.110.585	78.779.378	67.110.585	67.110.585
Initial Logistic Support(C_{IL})	1.411.460	1.515.838	2.238.726	1.411.460
Acceptance Tests(C_{IT})	2.709.917	2.516.999	2.632.632	2.709.917
Operation & Maintenance (OPEX)	168.451.246	172.963.659	177.680.224	168.754.105
Operations (C_{OP})	146.805.587	149.735.148	150.780.816	146.805.587
Maintenance (C_{OM})	21.070.740	22.599.480	26.257.451	21.357.196
Disposition (C_{OD})	59.042	113.153	126.080	75.445

RELIABILITY, AVAILABILITY, AND MAINTAINABILITY

In order to determine production efficiency, failure and repair data were collected for five different offshore oil production systems, with oil production in the range of 100,000 to 150,000 barrels per day and gas compression varying from 70 to 140 million cubic feet per day (2 to 4 million cubic meters per day). Of the five platforms studied, two platforms were configured with conventional compression systems utilizing gas turbine drivers ("previous generation" platforms). Two "new generation" platforms were also selected, configured with variable frequency drives for the compression units. The fifth offshore production platform analyzed has fixed speed electric motors as compressor drivers. Data for the gas turbine driven compressor case are presented in Table 2. The data were gathered from 2002 to 2007. The calculated parameters of the Weibull analysis are also presented in Table 2, as well as two important availability figures.

Table 2. Reliability and Availability Data for Gas Turbine Driven Compressors.



	2002	2003	2004	2005	2006	2007
Distribution Type	Weibull	Weibull	Weibull	Weibull	Weibull	Weibull
MTTF (hours)	75,5	246,1	280,0	213,0	200,0	209,0
Shape factor (β)	0,55	0,5	0,41	0,74	0,78	0,73
Characteristic life (η) (hours)	44,3	122	95	167,64	164	160
Delay (γ) (hours)			0,2	12	11	13,6
MTTR (hours)	15,7	24,9	20,3	11,4	8,2	15,7
Inherent Availability	82,8%	90,8%	93,2%	94,9%	96,1%	93,0%
Operational Availabilty	89,1%	80,5%	85,5%	83,1%	88,2%	92,6%

The definition of "inherent availability" can be described as the probability that a system or equipment will operate satisfactorily at any point in time, under stated conditions. It excludes preventive maintenance actions. Inherent Availability is also known as "reliability." Although this "nickname" is very popular, it is not academically correct, because the reliability function, R(t), is time dependent.

$$Inherent\ \ Availability = \frac{MTTF}{MTTF + MTTR} \tag{2}$$

where:
MTTF = Mean time to failure
MTTR = Mean time to repair

However, in order to account for the overall effect of all influences on production efficiency, the relevant parameter is the "operational availability." This last parameter considers, besides unscheduled events, all the scheduled preventive maintenance activities, and also includes both logistics and administrative delay times.

$$Operational\ \ Availability = \frac{Operational\ Time}{Operational\ Time + Ma\,\mathrm{int}\,enance\ Time} \tag{3}$$

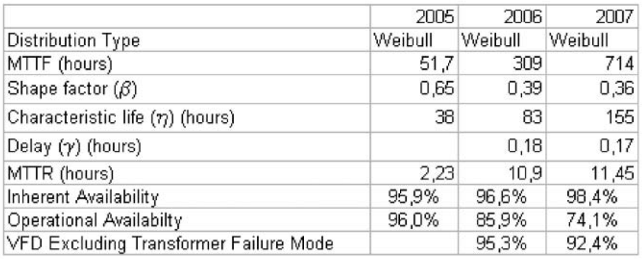
The *maintenance time* is the total time required to perform scheduled and unscheduled maintenance, including all logistics and administrative delays.

The adjusted Weibull distribution parameters b, h, and g areshown in Table 1. The first parameter is shape factor b. The distribution shape factor gives an idea of the "maturity" of the system installation. When the shape factor is less than unity, a b<1.0 indicates that the product has a decreasing failure rate and the product is failing during its "burn-in" period (the equipment is said to be in the "infant mortality" phase). A b=1.0 indicates a constant failure rate. It is not uncommon for components that have survived burn-in to subsequently exhibit a constant failure rate. A b>1.0 indicates an increasing failure rate. This is typical of products that are wearing out. The Weibull characteristic life, called h, is a measure of the scale, or spread, in the distribution of data. The parameter g is the location or "delay" in the probability distribution. If the location parameter is positive the origin of the distribution will be shifted to the right.

OLD CHARACTER, NEW VILLAIN

Table 3 shows the data related to the variable frequency (VF) driven compressors, in the period from 2005 to 2007. It is important to notice the availability deterioration that occurred from 2006 onward in the VFD compressors. There is one special cause for this fact. The VFDs are composed of a combination of transformers, frequency converters, and harmonic filters. Most attention is usually directed to the relatively new technology of the frequency converters and harmonics correction. However, despite the fact that transformers have been in the market since the victory of alternating current over direct current in the "war of currents" of the 1880s, the villain this time was the old-fashioned transformer instead of the frightening power electronics. Unfortunately, the same vendor manufactured all the VFD systems analyzed, and the transformers used were clearly undersized for the application. Since the very beginning of operation, the transformers experienced overheating, even when running at partial load. Thermographic pictures taken of the transformer coils showed temperatures in excess of 374°F (190°C). Expected temperatures for class F insulated systems would be in the range of 248°F (120°C). The overheating led to early failure due to coil short-circuit. Weibull analysis of data collected for the failed transformer coils indicated MTTF of just 9311 hours (Figure 5). According to the Institute of Electrical and Electronics Engineers (IEEE), the expected life of a dry transformer, running under design load, is 277 years!

Table 3. Reliability and Availability Data for Compressors with VF Drive.



	2005	2006	2007
Distribution Type	Weibull	Weibull	Weibull
MTTF (hours)	51,7	309	714
Shape factor (β)	0,65	0,39	0,36
Characteristic life (η) (hours)	38	83	155
Delay (γ) (hours)		0,18	0,17
MTTR (hours)	2,23	10,9	11,45
Inherent Availability	95,9%	96,6%	98,4%
Operational Availabilty	96,0%	85,9%	74,1%
VFD Excluding Transformer Failure Mode		95,3%	92,4%

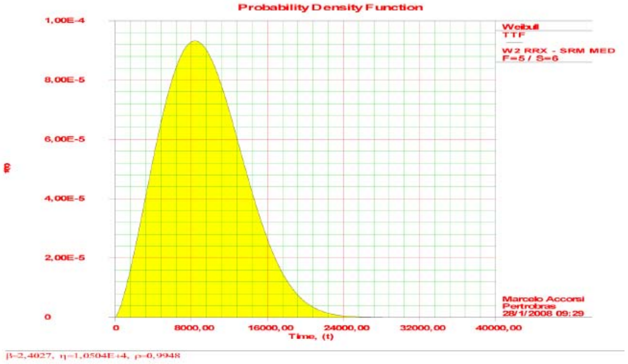


Figure 5. Failure Distribution of Transformers Due to Overheating.

In order to mitigate the overheating problem, and therefore allow continued operation, forced ventilation was installed. Other than the high failure rate, the most relevant issue with the transformers as it affects system availability was the very difficult logistics of changing the coils offshore. The unexpected demand for coils also became a problem regarding manufacturer delivery. The combined effect of coil replacing time and delays in delivery led to a MTTR of 3262 hours. The last coil replacement improved to 800 hours, with spare coils available, but this still represents a very long downtime.

The influence of the drivers on reliability can be visualized in Figure 6, for the parameter MTTF. A comparison with the OREDA (2002) benchmark is also shown in the same figure.

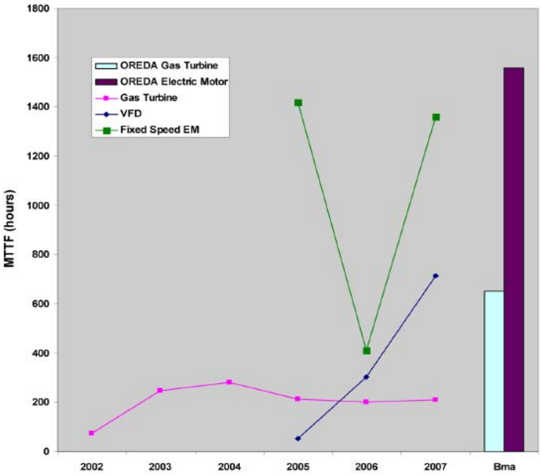


Figure 6. Driver Influence on Reliability for Centrifugal Compressors.

Figure 7 shows the influence of the type of driver on inherent availability, as well as the comparison with OREDA (2002). Figure 8 shows the effect on operational availability, where the poor performance of the VFD system is clear, but the same figure shows a speculation on the achievable availability if the transformer early failure mode was corrected.

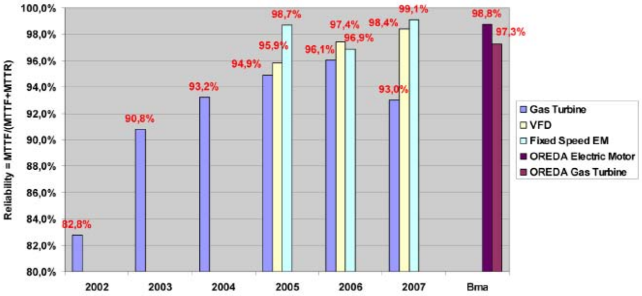


Figure 7. Driver Influence on Inherent Availability.

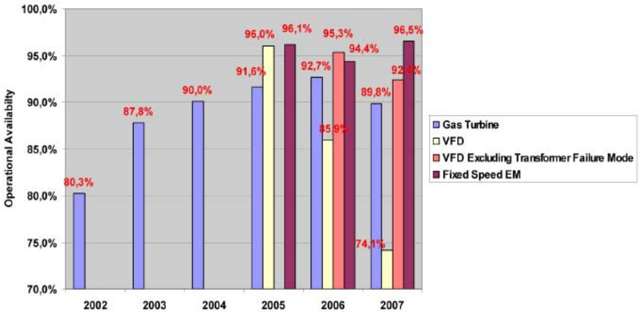


Figure 8. Driver Influence on Operational Availability.

THE CONSTANT SPEED OPTION

The use of speed variation in centrifugal compressor applications is always a controversial subject. Users tend to accept this as mandatory, and it has long been the paradigm in the upstream oil industry. Granted, if the application requires several operating points with different inlet and discharge pressures, and the molecular weight is expected to change during the life cycle, then this certainly represents a case for variable speed operation; however, a closer look at the operating requirements may indicate something different.

For example, in typical offshore applications, the compressor inlet pressure is defined by the oil/gas separation pressure. Once the system starts up, separation pressure will remain constant for years. Only over the long term, in order to boost declining production, will the separation pressure be gradually reduced, thereby reducing the backpressure to the wells. At the same time, the discharge pressure of the system is usually kept constant for the entire life cycle, as required by the gas lift header.

Also consider the other variables that affect the operating point of the compression system: inlet temperature, gas composition and mass flow. After separation, the gas is cooled down to knock-out and recovers the liquid fractions. This is a controlled process, and as such, compressor inlet temperature is held relatively constant, with at most an 18°F (10°C) variation. This represents a change of less than 4 percent of absolute inlet temperature. Regarding gas composition, this is often a significant concern for two reasons. The first one is the uncertainty inherent in the early phases of the basic design, where little is known about the hydrocarbon reservoir. (Keep in mind though that for some projects this is not an issue—for instance in mature oil provinces, where other platforms are already installed on the same reservoir). The other concern is mole weight variation over operational life due to changes in process, recent nearby discoveries, etc. If a constant speed system is to be considered, then the design engineers have to provide a means to mitigate the above concerns.

The constant speed case considered in this paper is related to a well-known oil province, with two other platforms already installed and in operation for many years. To summarize, the fixed speed case analyzed has the following characteristics:

- Inlet temperature and gas composition variations expected to be small

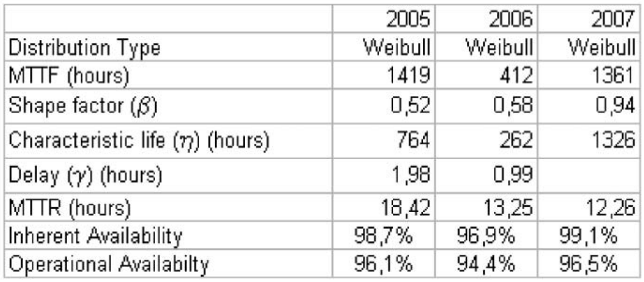
- Head expected to increase gradually by the end of life, due to inlet pressure reduction

- Mass flow expected to decline over time

This represents a typical application for a constant speed compressor, i.e., a reduction in flow with a corresponding increase in head, over a long period of time. However the design basis should consider alternative cases and to this end, the gearbox should be designed to allow for a replacement gear set with a different speed ratio, thereby providing the required operating speed for the alternate cases. Of course the drawback to this is the necessary downtime to replace the gear set, but the impact on production efficiency can be neglected if this happens only once or twice during the life cycle and opportunity is taken to do the replacement as part of a scheduled compressor overhaul. Even if, for some unforeseen reason, an unscheduled gear replacement takes place, the overall reliability and availability figures would be affected by just 0.1 to 0.2 percent (provided the alternative speed gear set is readily available).

For the fixed speed case considered in this paper, the LP and HP compressor gearboxes were designed for two different gear sets: one for 95 percent and the other for 100 percent of maximum continuous speed. This allows for four possible LP/HP speed combinations, and therefore four possible overall performance curves, covering a very reasonable operating envelope. The reliability and availability data for the fixed speed case are shown in Table 4.

Table 4. Reliability and Availability Data for Compressors with Fixed Speed Electric Motor.

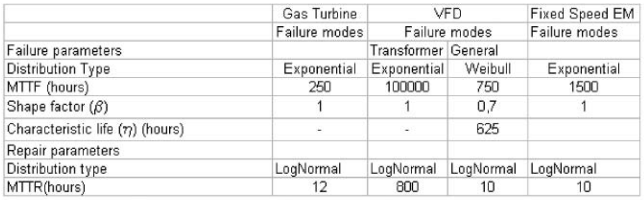


	2005	2006	2007
Distribution Type	Weibull	Weibull	Weibull
MTTF (hours)	1419	412	1361
Shape factor (β)	0,52	0,58	0,94
Characteristic life (η) (hours)	764	262	1326
Delay (γ) (hours)	1,98	0,99	
MTTR (hours)	18,42	13,25	12,26
Inherent Availability	98,7%	96,9%	99,1%
Operational Availabilty	96,1%	94,4%	96,5%

SIMULATIONS

In order to perform the life cycle cost analysis and the event-driven simulation, it is necessary to define the failure and repair parameters. Based on the observed behavior of the existing systems, the authors have inferred the possible life cycle behavior for the four configuration cases being analyzed. The lesson learned with the transformer case demonstrates that, although considered rare, this event can happen. Therefore, as a conservative measure, the simulation of the variable speed drive (VSD) case has considered this failure mode, but with taking into account improvements both on MTTF and MTTR. The well-known case of the gas turbine drive has a very predictable behavior. Nevertheless some improvement is also expected, given the distance to the OREDA (2002) performance, and some progress in shape factor and failure rate can be predicted. Table 5 shows the parameters that were adopted to perform the life simulation, for each configuration case.

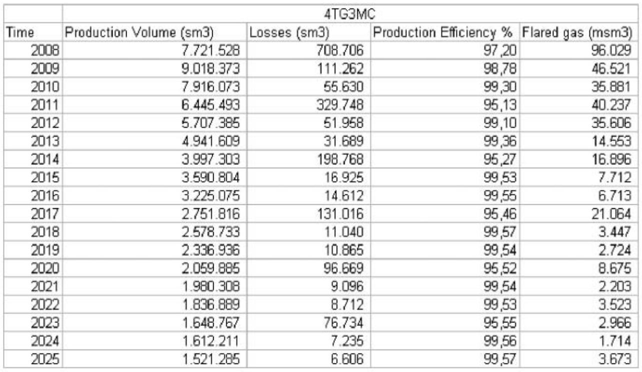
Table 5. Failure and Repair Parameters for RAM Simulation.



	Gas Turbine	VFD		Fixed Speed EM
	Failure modes	Failure modes		Failure modes
Failure parameters		Transformer	General	
Distribution Type	Exponential	Exponential	Weibull	Exponential
MTTF (hours)	250	100000	750	1500
Shape factor (β)	1	1	0,7	1
Characteristic life (η) (hours)	-	-	625	
Repair parameters				
Distribution type	LogNormal	LogNormal	LogNormal	LogNormal
MTTR(hours)	12	800	10	10

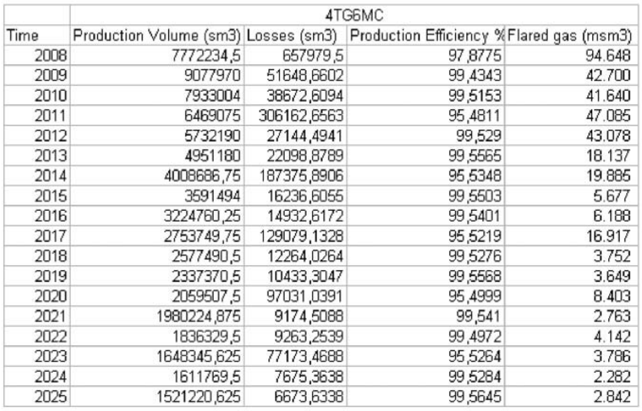
After running the simulator the results for each configuration analyzed are shown in Tables 6, 7, 8, and 9. These tables also present the oil production annual volume profile.

Table 6. Simulation Results—Production Losses, Efficiency, and Flared Gas for the System with Four Turbogenerators and Three VFD Driven Compressors.



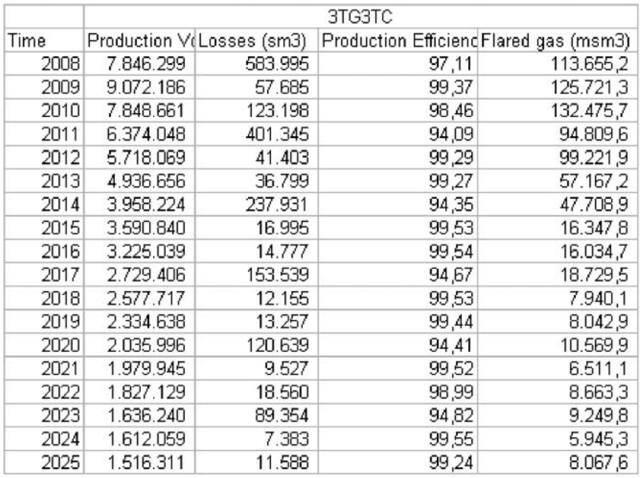
	4TG3MC			
Time	Production Volume (sm3)	Losses (sm3)	Production Efficiency %	Flared gas (msm3)
2008	7.721.528	708.706	97,20	96.029
2009	9.018.373	111.262	98,78	46.521
2010	7.916.073	55.630	99,30	35.881
2011	6.445.493	329.748	95,13	40.237
2012	5.707.385	51.958	99,10	35.606
2013	4.941.609	31.689	99,36	14.553
2014	3.997.303	198.768	95,27	16.896
2015	3.590.804	16.925	99,53	7.712
2016	3.225.075	14.612	99,55	6.713
2017	2.751.816	131.016	95,46	21.064
2018	2.578.733	11.040	99,57	3.447
2019	2.336.936	10.865	99,54	2.724
2020	2.059.885	96.669	95,52	8.675
2021	1.980.308	9.096	99,54	2.203
2022	1.836.889	8.712	99,53	3.523
2023	1.648.767	76.734	95,55	2.966
2024	1.612.211	7.235	99,56	1.714
2025	1.521.285	6.606	99,57	3.673

Table 7. Production Losses, Efficiency, and Flared Gas for the System with Four Turbogenerators and Six Fixed Speed EM Driven Compressors.



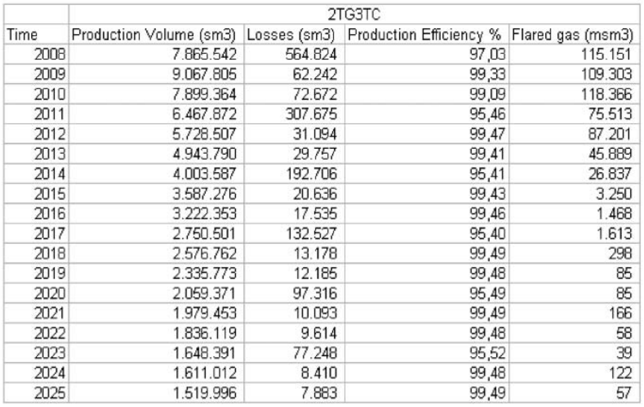
	4TG6MC			
Time	Production Volume (sm3)	Losses (sm3)	Production Efficiency %	Flared gas (msm3)
2008	7772234,5	657979,5	97,8775	94.648
2009	9077970	51648,6602	99,4343	42.700
2010	7933004	38672,6094	99,5153	41.640
2011	6469075	306162,6563	95,4811	47.085
2012	5732190	27144,4941	99,529	43.078
2013	4951180	22098,8789	99,5565	18.137
2014	4008686,75	187375,8906	95,5348	19.885
2015	3591494	16236,6055	99,5503	5.677
2016	3224760,25	14932,6172	99,5401	6.188
2017	2753749,75	129079,1328	95,5219	16.917
2018	2577490,5	12264,0264	99,5276	3.752
2019	2337370,5	10433,3047	99,5568	3.649
2020	2059507,5	97031,0391	95,4999	8.403
2021	1980224,875	9174,5088	99,541	2.763
2022	1836329,5	9263,2539	99,4972	4.142
2023	1648345,625	77173,4688	95,5264	3.786
2024	1611769,5	7675,3638	99,5284	2.282
2025	1521220,625	6673,6338	99,5645	2.842

Table 8. Production Losses, Efficiency, and Flared Gas for the System with Three Turbogenerators and Three Gas Turbine Driven Compressors.



	3TG3TC			
Time	Production Vc	Losses (sm3)	Production Efficienc	Flared gas (msm3)
2008	7.846.299	583.995	97,11	113.655,2
2009	9.072.186	57.685	99,37	125.721,3
2010	7.848.661	123.198	98,46	132.475,7
2011	6.374.048	401.345	94,09	94.809,6
2012	5.718.069	41.403	99,29	99.221,9
2013	4.936.656	36.799	99,27	57.167,2
2014	3.958.224	237.931	94,35	47.708,9
2015	3.590.840	16.995	99,53	16.347,8
2016	3.225.039	14.777	99,54	16.034,7
2017	2.729.406	153.539	94,67	18.729,5
2018	2.577.717	12.155	99,53	7.940,1
2019	2.334.638	13.257	99,44	8.042,9
2020	2.035.996	120.639	94,41	10.569,9
2021	1.979.945	9.527	99,52	6.511,1
2022	1.827.129	18.560	98,99	8.663,3
2023	1.636.240	89.354	94,82	9.249,8
2024	1.612.059	7.383	99,55	5.945,3
2025	1.516.311	11.588	99,24	8.067,6

Table 9. Production Losses, Efficiency, and Flared Gas for the System with Two Turbogenerators and Three Gas Turbine Driven Compressors.

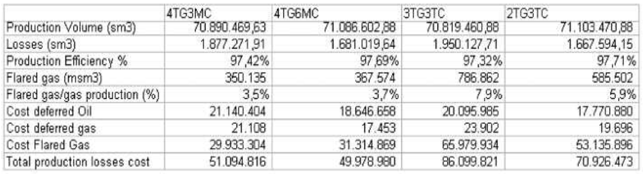


	2TG3TC			
Time	Production Volume (sm3)	Losses (sm3)	Production Efficiency %	Flared gas (msm3)
2008	7.865.542	564.824	97,03	115.151
2009	9.067.805	62.242	99,33	109.303
2010	7.899.364	72.672	99,09	118.366
2011	6.467.872	307.675	95,46	75.513
2012	5.728.507	31.094	99,47	87.201
2013	4.943.790	29.757	99,41	45.889
2014	4.003.587	192.706	95,41	26.837
2015	3.587.276	20.636	99,43	3.250
2016	3.222.353	17.535	99,46	1.468
2017	2.750.501	132.527	95,40	1.613
2018	2.576.762	13.178	99,49	298
2019	2.335.773	12.185	99,48	85
2020	2.059.371	97.316	95,49	85
2021	1.979.453	10.093	99,49	166
2022	1.836.119	9.614	99,48	58
2023	1.648.391	77.248	95,52	39
2024	1.611.012	8.410	99,48	122
2025	1.519.996	7.883	99,49	57

COST OF DEFERRED PRODUCTION AND FLARED GAS

Based on the simulation outcome it is possible to calculate present value of the production losses. According to Miranda and Brick (2004) the cost of deferred production is calculated considering that the volume not produced at a certain time will be recovered throughout the rest of the life cycle, and its value is a function of both the discount rate and average decreasing rate of oil flow. Table 10 shows the summary of the cost calculations, as well as the average volumes and efficiencies over life.

Table 10. Summary of Production Losses Cost Calculation.

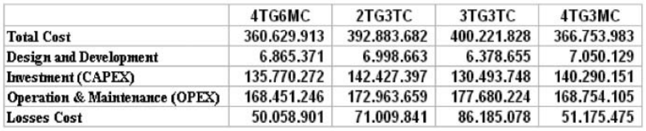


	4TG3MC	4TG6MC	3TG3TC	2TG3TC
Production Volume (sm3)	70.890.469,63	71.086.602,88	70.819.460,88	71.103.470,88
Losses (sm3)	1.877.271,91	1.681.019,64	1.950.127,71	1.667.594,15
Production Efficiency %	97,42%	97,69%	97,32%	97,71%
Flared gas (msm3)	350.135	367.574	786.862	585.502
Flared gas/gas production (%)	3,5%	3,7%	7,9%	5,9%
Cost deferred Oil	21.140.404	18.646.658	20.095.985	17.770.880
Cost deferred gas	21.108	17.453	23.902	19.696
Cost Flared Gas	29.933.304	31.314.869	65.979.934	53.135.896
Total production losses cost	51.094.816	49.978.980	86.099.821	70.926.473

LIFE CYCLE COSTS

After computing all the costs of the breakdown structure, the life cycle costs for the four studied alternatives can be calculated. Table 11 shows a summary of the results, and Figure 9 presents a graphic comparison of the cost categories for each case.

Table 11. Present Value of the Life Cycle Costs.



	4TG6MC	2TG3TC	3TG3TC	4TG3MC
Total Cost	360.629.913	392.883.682	400.221.828	366.753.983
Design and Development	6.865.371	6.998.663	6.378.655	7.050.129
Investment (CAPEX)	135.770.272	142.427.397	130.493.748	140.290.151
Operation & Maintenance (OPEX)	168.451.246	172.963.659	177.680.224	168.754.105
Losses Cost	50.058.901	71.009.841	86.185.078	51.175.475

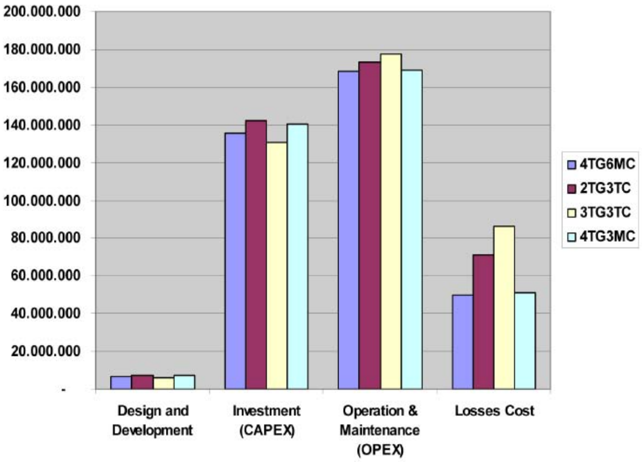


Figure 9. Life Cycle Cost Comparison.

CONCLUSION

Within the authors' company environment, for the last two years, the reputation of the all-electric solution for centrifugal compressors drives was at serious risk. It has been a challenge to overcome the image damage caused by the transformer failures. Due to their magnitude, there is no forgiveness for these failures, having caused such unacceptable downtimes. But, although these facts are still all too fresh in memory, one needs only to recall the long history of failures on the gas turbine side, also having caused significant losses and downtimes. But we are not at a new "war of technologies" nor at a "war of drives." What this paper shows is that there is no magic formula that gives the recipe to make the right decision. These are particular cases for a particular project, with local and global constraints in logistics, raw material, commodity prices, and issues regarding manufacturing quality. The models are assembled based on assumptions and premises.

Answering the question made in the introduction of this paper, the simulation demonstrates a still promising advantage for the electric drives, when taking into account the data and experience collected so far. This of course assuming right sized transformers, or fixed speed motors. The facts demonstrated that, regardless of the technology, mature or not, quality and quick response are essential, like in every business.

NOMENCLATURE

2TG3TC = Two turbogenerators and three turbocompressors
3TG3TC = Three turbogenerators and three turbocompressors
4TG3MC = Four turbogenerators and three motocompressors
4TG6MC = Four turbogenerators and six motocompressors
β = Shape factor
CAPEX = Capital expenditure or investment cost
γ = Location factor or delay (h)
η = Scale factor or characteristic life (h)
MTTF = Mean time to failure (h)
MTTR = Mean time to repair (h)
OPEX = Operational cost
R(t) = Reliability function
RBD = Reliability block diagram
TurboREM = Turbomachinery events record
VFD = Variable frequency drive

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