LIFE CYCLE COST ASSESSMENT OF TURBOMACHINERY FOR OFFSHORE APPLICATIONS

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ABSTRACT

This paper describes a comprehensive life cycle cost (LCC) analysis procedure, regarding turbomachinery systems for offshore oil and gas production platforms. The LCC analysis includes the development of a cost breakdown structure, the selection of costs models, data gathering and treatment, model allocation and development of the life cycle costs profile, and, finally, the life cycle cost assessment. An important step is the analysis of the reliability, availability, and maintainability of the plant, which quantifies the potential production losses relative to the plant availability.

A dilemma that, very often, challenges rotating machinery engineers is how to make a decision between mechanical and electric drives for the main platform compressors. Usually, about 50 percent of the power requirement of a platform is used for gas compressing. A case study is conducted to evaluate among different driving solutions and also to demonstrate the cost reduction and optimization potential. It can be observed that the production losses are critical for the overall outcome.

INTRODUCTION

The implementation of new projects for offshore oil and gas production rigs has been substantially accelerated during the last decade in the Brazilian State of Rio de Janeiro. The design and construction of offshore production systems require huge sums of capital investment, which can reach, or even exceed, one billion dollars. The turbomachinery equipment that is used for power generation and gas handling is critical and essential to oil and gas production. The oil platforms need self-sufficiency in the production of the necessary energy to perform its operations, given the technical limitations and economic unfeasibility to connect to the continental electrical system. Moreover, natural gas is found in abundance on the platform, being produced along with the oil extracted from the underground reservoirs. The power generated by gas turbines can be consumed in the productive process in two distinct forms. The turbines can be used for direct mechanical drives, for equipment such as pumps and compressors, and for the production of electric energy in electric alternators. On smaller platforms, internal combustion engines are likely to be more cost effective.

The decision between mechanical and electrical drives for the main platform compressors will be made during the conceptual phase of the platform design because changes of configuration can be very costly, if not impossible, at later stages of the design phase. Therefore, there is a need to perform a comprehensive technical and economical evaluation taking into account all phases of the system life cycle. The life cycle cost analysis process and trade off studies can lead to optimum configuration for critical equipment, such as gas turbines and centrifugal compressors. As stated previously a key step is the reliability, availability, and maintainability analysis, which relates productive capacity to the system and its component availability. The system productive capacity calculations are performed with the aid of a model based on the Markov model. In order to reduce the complexity of the Markov chain, due to the number of equipment and subsystems, the model is applied only to smaller subsystems. The results for each set of two subsystems are merged. The merged subsystems are merged again, and so on, up to the top-level system. The main advantage of the model is to allow evaluation of the productive capacity, which can be used to assess the associated production losses, along with the remaining costs categories. The case study demonstrates that the production losses can be critical for the overall outcome.

SYSTEM MISSION AND REQUIREMENTS

The purpose of the turbomachinery system considered in this paper is to generate and provide the energy needed for the platform operations and, also, to provide the pressurized gas used by platform processes. The system will provide three types of energy: mechanical, electrical, and thermal. Figure 1 shows the top-level functional diagram for the required energy system. For each of these there is a demand profile during the life cycle of the system.

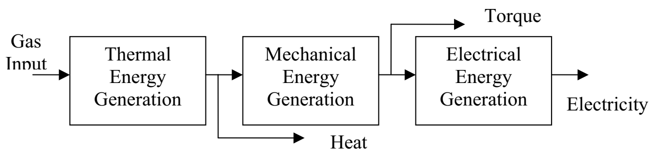

Figure 1. Top-Level Functional Diagram for Platform Energy System.

The demand profile for each type of energy is a function of the platform liquid and gas production profile. Figure 2 illustrates both the oil production and the electrical energy demand profiles. The gas and water handled by the platform have similar profiles. The platform's fluid handling systems account for the majority of the required power, they include the injection pumps, gas lift and export compressors, crude oil export pumps, and so on. Based on the system purpose and requirements, the power generation system and major drivers can be configured. Alternative solutions to achieve the same result are then considered. There are a great number of possible solutions, considering the possible choices, i.e., the number of units in parallel, the level of redundancy, mechanical or electrical drives, gas turbines, steam turbines, internal combustion engines, variable speed drives, or fixed speed drives.

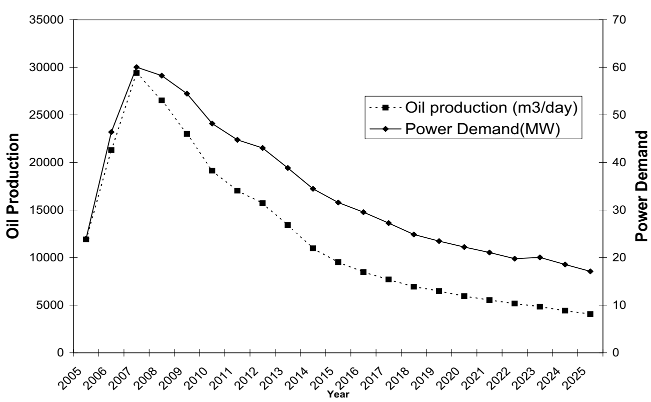

Figure 2. Oil Production and Power Demand Profiles.

SYSTEM COST BREAKDOWN STRUCTURE

The life cycle cost (LCC) analysis of a system is conducted considering all the costs from the conception of the system up to its retirement including the development, construction, commissioning, testing, and operation. The LCC analysis is a part of the systems engineering process, with its holistic approach. According to Kawauchi and Rausand (2002), it is necessary to apply a specific approach to the evaluation of the productive capacity for petrochemical and petroleum plants.

The cost breakdown structure will define the cost categories for each phase of life cycle. Starting from a generic model, the structure will be developed with cost categories that are applicable to power systems and offshore platforms. The following cost items will take part of the structure: research and development costs, acquisition costs, construction and production costs, operation costs, maintenance costs, losses due to deferred production and accidents, and system and parts disposition. In Figure 3 the proposed cost breakdown structure for the power system is shown.

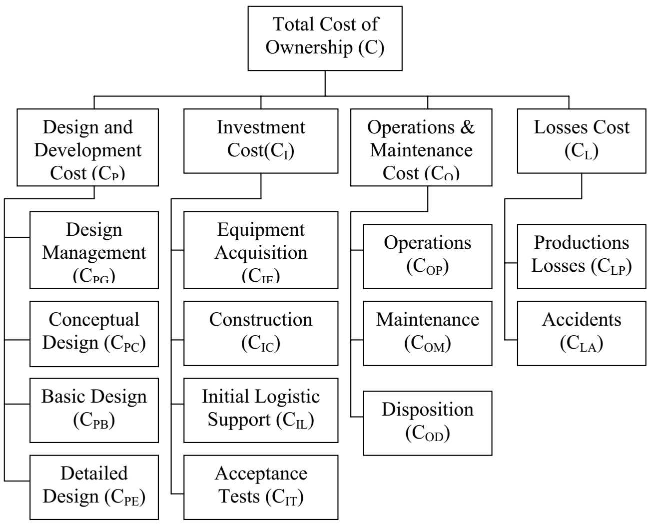

Figure 3. Cost Breakdown Structure.

The life cycle cost model can be implemented with the aid of a spreadsheet software. The proposed cost item deployment, which is applicable for turbomachinery, is outlined in APPENDIX B.

RELIABILITY, AVAILABILITY, AND MAINTAINABILITY MODEL

The oil and gas production systems for offshore platforms are complex systems, composed of several components combined into subsystems. The subsystems and components are displayed in series and parallel arrangements. In order to estimate the overall productive capacity of the system an analytical method was developed, combining the Markov model with *merging rules* developed by Kawauchi and Rausand (2002). The modeling process is developed in steps. The first one is to develop a reliability block diagram of the system. Next, attributes such as failure and repair rates, schedule maintenance frequency, and mean time are assigned to each block. The Markov method is utilized to calculate the productive capacity probability distribution (PCPD) for each parallel block, considering the cold and hot standby redundancies, if there are any. The Markov modeling becomes too complex when the number of components increases. In order to deal with the number of components, every set of two subsystems is merged utilizing the *merging rules* (Kawauchi and Rausand, 2002). The merged subsystems are merged again up to the top-level system, and then the overall plant productive capacity probability distribution can be calculated. Refer to APPENDIX A for the Markov model for redundant systems and the merging rules. Figure 4 illustrates the reliability block diagram for an oil production platform, deployed in three levels.

The PCPD, associated to the oil field potential production at a given time, can be used to calculate the expected values for the platform effective production at that time.

Example: The productive capacity probability distribution and the effective production probability distribution for the system are given in Table 1. The table represents the situation at the tenth year of the life cycle, when the potential oil production is 65 percent of the maximum field production, or 117,000 bbl/day.

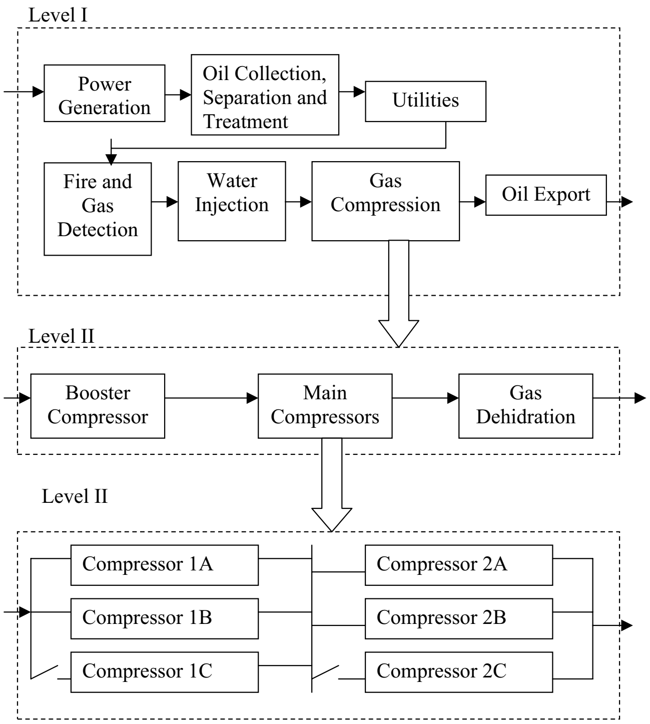

Figure 4. Reliability Block Diagram.

Table 1. Productive Capacity Probabilty Distribution and Effective Production Probability Distribution.

Probability	Productive Capacity		Effective Production (Bbl/day)
	%	Bbl/day	
95 %	100	180,000	117,000
4.5 %	50	90,000	90,000
0.5 %	0	0	0

Equation (1) is used to calculate the expected production for the tenth year.

$$P_R = \sum_{N=0}^{100\%} A_N \times P_N \tag{1}$$

where:
A_N = Probability of a productive capacity of N percent
P_N = Effective oil production achieved with a productive capacity of N percent

The expected effective oil production for the tenth year will then be 0.95 × 117,000 + 0.045 × 90,000 + 0.005 × 0 = 115,200.

FUEL CONSUMPTION MODEL

Among the operations cost one of the most relevant items is the platform fuel consumption. In order to calculate the fuel consumption (F), the energy consumption profile of the platform will be determined. The fuel consumption is also a function of the thermal efficiency of the system and the low heat value (LHV) of the fuel. For each year of the system life cycle, the fuel consumption is calculated by Equation (2), for a given annual average power (kW) demand:

$$F = \frac{kW \times 3600 \times 24 \times 365}{\eta_{th} \times LHV} \tag{2}$$

The thermal efficiency of the power system depends on the type and model of the generator driver. The efficiency varies also as a function of the power factor (PF) and the local temperature. Power systems manufacturers provide the efficiency curves. For a given ambient temperature the efficiency of a gas turbine can be calculated by an adjusted curve represented by Equation (3).

$$\eta_{th} = a \times PF^b \tag{3}$$

The parameters *a* and *b* depend on the type and model of the gas turbine. The adjusted equation is useful in the LCC model because a spreadsheet can be used to calculate the fuel consumption for different conditions along the life cycle.

DEFERRED PRODUCTION MODEL

The loss of availability of system components and its influence on the overall system productive capacity are determined based on the reliability, availability, and maintainability (RAM) model. The next step is to calculate the revenue losses that are caused by the deferred production due to capacity reduction. The production downtime in oil fields does not necessarily become production loss directly. Instead, they represent delays in the revenues and an economic impact that is a function of the interest rate adopted as a reference for the investment. During the oil field declining phase it is necessary to consider that the delayed production will be recovered along all the remaining years of the life cycle. Therefore, it is also important to consider the shape of the production profile. In order to simplify the calculations it is possible to consider the production curve with a constant decreasing rate, adopting the mean rate (D) of the profile.

Let *La* be the total delayed production due to a certain system productive capacity reduction during a certain period of time; and let us call it "apparent loss." It is named an apparent loss because, as already mentioned, it is not exactly a production loss, but a production delay instead. Let *Lr* be the real loss, i.e., *Lr* is the equivalent volume of product that can be considered as a production loss, considering the economic effect of the delay. The following Equation (4) applies (Paiva, 1997), considering a constant production decreasing rate (D) and the investment discount rate (r):

$$Lr = \frac{La}{\left[1 + \frac{D}{\ln(1+r)}\right]} \tag{4}$$

The revenue loss is calculated just by multiplying the real loss in volume (barrels) by the expected price of the product.

$$\text{Revenue Loss}(\$) = Lr(barrels) \times \text{Price}(\$ / barrel) \tag{5}$$

EXAMPLE

In order to demonstrate the application of the LCC model, a case study is presented of a real 180,000 barrels a day offshore platform. The analysis was conducted for different possible configurations for the power generation system combined with the main gas compression system. There are a number of possible combinations, with different levels of redundancy. The following example compares four of these configurations. Figures 5 and 6 show two examples of configurations. The description and labeling of the four cases are given below:

- *2TG3TC*—Two gas turbine-driven AC generators, each with 100 percent of the required capacity, and three gas turbine-driven compressor trains, each with 50 percent of the required capacity;
- *3TG3TC*—Three gas turbine-driven AC generators, each with 50 percent of the required capacity, and three gas turbine-driven compressor trains, each with 50 percent of the required capacity;

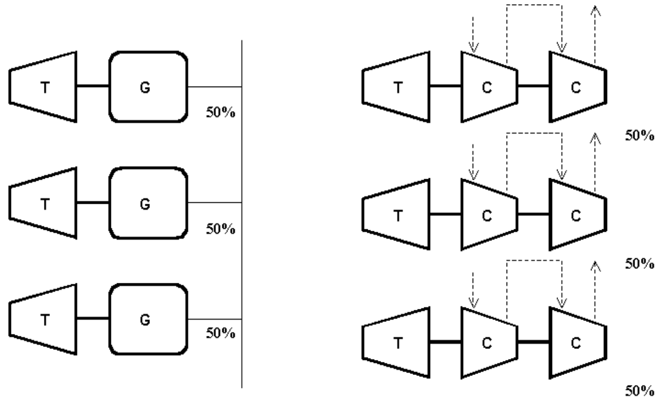

Figure 5. Configuration with Three Turbo Generators and Three Turbo Compressors.

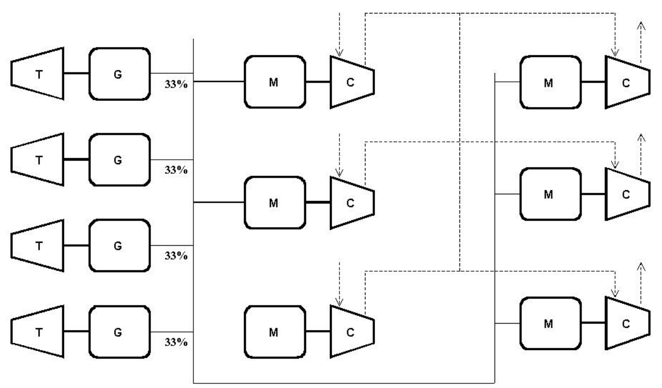

Figure 6. Four Turbo Generators and Electric-Driven Compressors in Series/Parallel Configurations.

- *4TG3MC*—Four gas turbine-driven AC generators, each with 33 percent of the required capacity, and three electric-driven, variable speed compressor trains, each with 50 percent of the required capacity;
- *4TG6MC*—Four gas turbine-driven AC generators, each with 33 percent of the required capacity, and six fixed speed electric-driven compressors in series/parallel. It is equivalent to three compression trains, with 50 percent of the required capacity each, with two compressors in series for each train. In this case the first stage has one driver and the second/third stage are driven by a second.

The life cycle cost analysis for each case was done with the aid of a set of spreadsheets. The first type of spreadsheet is used to calculate the productive capacity probability distribution and the production losses as well. Another model was developed to compute the remaining life cycle costs and to summarize the overall results, allowing the comparison of the alternatives.

Most of the input data utilized, such as mean time to repair (MTTR) and mean time to failure (MTTF), were obtained from historical data. For some equipment, the OREDA (1997) database was also used. Some of the unitary costs were based on previous projects and others were estimated by personal judgment.

One of the major requirements to be met by the system was to guarantee the regularity of the production. The production regularity is defined as the ratio between the actual production and the potential production, at a given time. The case study considered the target regularity of 90 percent as a minimum for the entire topside of the platform, including all production facilities. This means that the average oil production will be at least 90 percent of the maximum possible production, considering 100 percent availability of all systems. After running the model the regularity profile was determined and it is shown in Figure 7. It is possible to observe that two out of four alternatives can fully meet the regularity requirement along the life cycle, whereas the cases 2TG3TC and 3TG3TC show availabilities slightly lower than the target for the years 2006 to 2008, exactly those when the potential production reaches its peak. It can also be observed that the production regularity curve, although above the minimum requirement of 90 percent, has a dip, for the four cases, between 2013 and 2015. This is a consequence of the substantial increase in the water production of the reservoir that leads to a reduction in redundancy in the water treatment system.

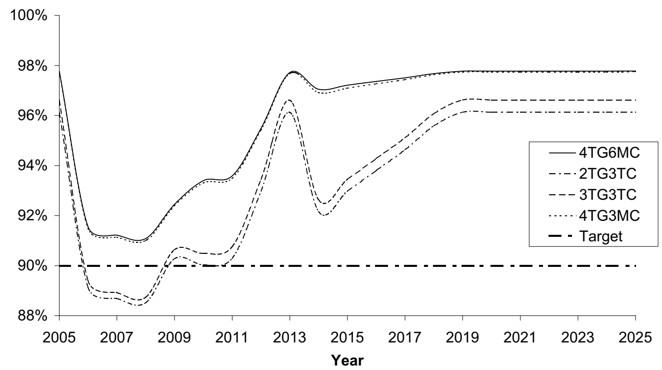

Figure 7. Production Regularity Comparison.

The life cycle cost profiles for each alternative configuration are shown in Figure 8. Figure 9 shows the cumulative costs in present value, discounted by the interest rate of the project. It can be seen that two alternatives are far more cost effective. The reason for the advantage is the highest availability, particularly during the peak production years.

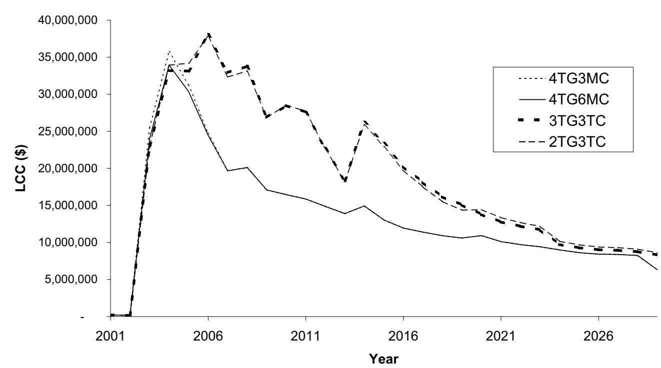

Figure 8. Life Cycle Costs Comparison for Four Alternatives.

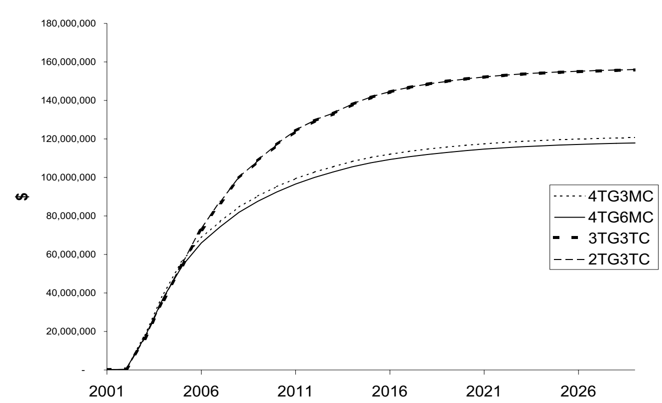

Figure 9. Cumulative Discounted Costs Comparison.

CONCLUSIONS

This paper has presented a comprehensive life cycle cost analysis procedure that was developed as a decision tool for assessing the alternative configurations of the design of turbomachinery subsystems for offshore platforms. The steps of the procedure include the definition of the system mission and requirements, development of a cost breakdown structure, and development of the mathematical models for each cost element. The models are run on a set of electronic spreadsheets. In order to consider and assess the system availability and its impact on the overall platform productivity, an auxiliary model was developed for the RAM calculations, based on the Markov chains theory.

The proposed procedure allows the comparison among several alternative configurations for the system, taking into account the number of trains, redundancies, and types of drivers for the main equipment. The results of the case study demonstrate that the potential cost reduction can achieve figures as high as 25 percent of the overall life cycle costs. It is important to notice that the cost reduction was obtained without significant increase in capital costs. The case study also shows that the system average availability has strong influence on the total cost of ownership. However, the right choice cannot be generalized and will depend on each specific production profile and its derived load profiles.

There are a number of RAM and LCC software packages available on the market. However, none of them are able to perform a life cycle cost analysis including the impact of the availability on the production. The proposed model was developed with the use of a commercial electronic spreadsheet. The main advantage of the model is to allow the simultaneous evaluation of the system productive capacity and associated oil production losses, along with the remaining costs categories.

Further development of the model is intended in order to allow risk analysis by Monte Carlo simulation and the development of a friendly interface for the spreadsheets.

APPENDIX A— PRODUCTIVE CAPACITY PROBABILITY DISTRIBUTION MODEL

Markov Model

A system reliability block diagram (RBD) is composed of a combination of several subsystems in series/parallel configuration. Usually the redundancy is found at the lower levels of the RBD. At the lowest level of the RBD a Markov model is used to represent the different states the system can assume during the life cycle. The transition from one state to another occurs according to rates that are a function of reliability and maintainability attributes of the components of the subsystem under analysis.

Let us take as an example a system with two machines in parallel, in which one of them is supposed to run continuously and the other remains in cold standby, illustrated by Figure A-1. The system can assume the following states:

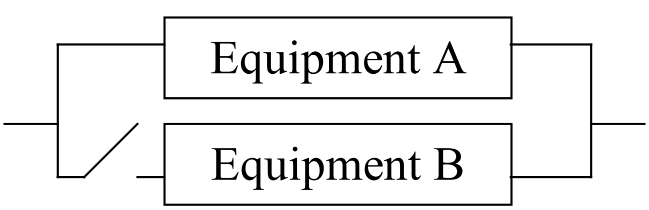

Figure A-1. System with Two Components, with Cold Standby.

- *State Zero*—When one component runs and the other remains in cold standby;
- *State One*—When the running component fails and the other has not yet started, due to a certain startup delay;
- *State Two*—When the redundant component has already started up and the failed component is being repaired;
- *State Three*—When the second component fails and the first component repair process is not yet concluded.

Each state is related to a certain system productive capacity. Table A-1 summarizes each state, the associated component conditions, as well as the productive capacity of the system. The Markov model that represents these states is shown in Figure A-2.

Table A-1. System States and Capacities.

	Number of Components			
State	Running	Failed	Cold Stand by	System Productive Capacity
0	1	0	1	100 %
1	0	1	1	0 %
2	1	1	0	100 %
3	0	2	0	0 %

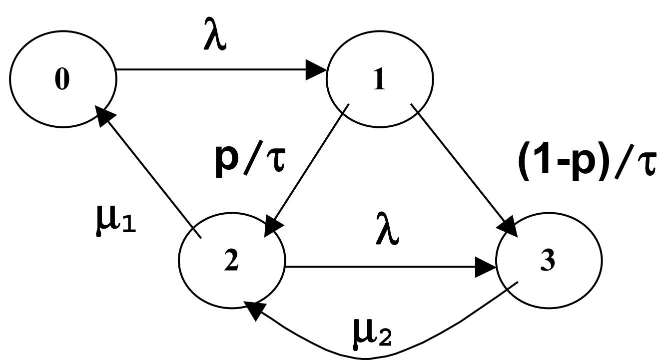

Figure A-2. Markov Model for Two Components, with Cold Standby.

The transition rate from State Zero to State One is given by the failure rate λ for either component A or B, considering that both components are identical. The transition rate from State One to State Two is a function of two parameters: the starting success probability, or starting reliability p, and the mean time to start τ. The transition rate, given that there is a successful start, will then be $1/\tau$, considering that the time to start is an exponential random variable with mean equal to τ. The transition from State One to Three is given by the complement of the 1 to 2 rate, or $(1-p)/\tau$, because in this case the component fails to start. The transition from State Two to the initial State Zero occurs according to a repair rate of μ_1. The transition rate from State Two to State Three is also λ given that both components are identical. The repair rate μ_2, for the transition from State Three to Two, depends on the number of maintenance teams and other resources available in the plant. Therefore, if there is just one team available, the repair rate μ_2 is equal to μ_1. If there are no limitations on resources the repair rate μ_2 is equal to $2\mu_1$.

In order to calculate the probabilities for each state, it is necessary to solve the Markov model system of equilibrium equations. Given the parameters λ, μ_1, μ_2, p, and τ, it is possible to calculate P_0, P_1, P_2, and P_3, which are the steady-state probabilities for each of the possible states. The following system of Equations (A-1) to (A-4) is based in the Markov model steady-state properties:

$$0 = -\lambda P_0 + \mu_1 P_2 \qquad \text{(A-1)}$$

$$0 = \lambda P_0 - \frac{1}{\tau} P_1 \qquad \text{(A-2)}$$

$$0 = \frac{P}{\tau} P_1 - (\lambda + \mu_1) P_2 + \mu_2 P_3 \qquad \text{(A-3)}$$

$$0 = \frac{(1-p)}{\tau} P_1 + \lambda P_2 - \mu_2 P_3 \qquad \text{(A-4)}$$

The above system of equations is undetermined. An additional equation is necessary. Given that all four states are mutually exclusive, Equation (A-5) also applies to the steady-state probabilities:

$$P_0 + P_1 + P_2 + P_3 = 1 \qquad \text{(A-5)}$$

The following matrix can then be used to calculate the state probabilities:

$$\begin{vmatrix} -\lambda & 0 & \mu_1 & 0 \\ \lambda & -\frac{1}{\tau} & 0 & 0 \\ 0 & \frac{p}{\tau} & -(\lambda + \mu_1) & \mu_2 \\ 1 & 1 & 1 & 1 \end{vmatrix} \times \begin{vmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 1 \end{vmatrix} \qquad \text{(A-6)}$$

The solution is given by multiplying the inverse matrix of the coefficients by the vector on the right side of Equation (A-6):

$$\begin{vmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{vmatrix} = \begin{vmatrix} -\lambda & 0 & \mu_1 & 0 \\ \lambda & -\frac{1}{\tau} & 0 & 0 \\ 0 & \frac{p}{\tau} & -(\lambda + \mu_1) & \mu_2 \\ 1 & 1 & 1 & 1 \end{vmatrix}^{-1} \times \begin{vmatrix} 0 \\ 0 \\ 0 \\ 1 \end{vmatrix} \qquad \text{(A-7)}$$

The calculations can be made with a Microsoft® Excel spreadsheet. Once the values of P_N are determined, the steady-state probabilities A_N for each system productive capacity N, are obtained (refer to Table A-1). Then:

$$A_{100} = A(100\%) = P_0 + P_2 \qquad \text{(A-8)}$$

$$A_0 = A(0\%) = P_1 + P_3 \qquad \text{(A-9)}$$

Merging Rules

The Markov model for each subsystem is used to determine the productive capacity probability distribution. Figure A-3 shows an example of a PCPD.

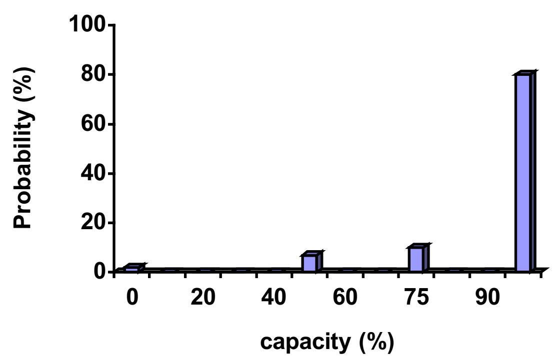

Figure A-3. Production Capacity Distribution.

In order to merge two subsystems, Kawauchi and Rausand (2002) proposed the following method, for discrete distributions:

• *Merging systems in series*—Let X and Y be the values of the productive capacities for the subsystems A and B, respectively. It is assumed that X has n + 1 values, varying from x_0 to x_n, and Y has m + 1 values, from y_0 to y_m. Z denotes the capacity for the merged system C. The productive capacity of the merged system will be the lowest between the values of X and Y, and has the value Z = z, only if one out of the following conditions is fulfilled:

• *Condition 1*—The productive capacity of the system A is z, and the productive capacity of the system B is higher or equal to z.

• *Condition 2*—The productive capacity of the system B is z, and the productive capacity of the system A is higher than z.

Taking the subsystems A and B as independent ones, the probability of system C having the value z for the productive capacity Z is given by Equation (A-10):

$$\Pr(Z = z) = \Pr(X = z)\Pr(Y \geq z) + \Pr(Y = z)\Pr(X > z) \qquad \text{(A-10)}$$

Figure A-4 shows the merging process of two subsystems in series into one sole system.

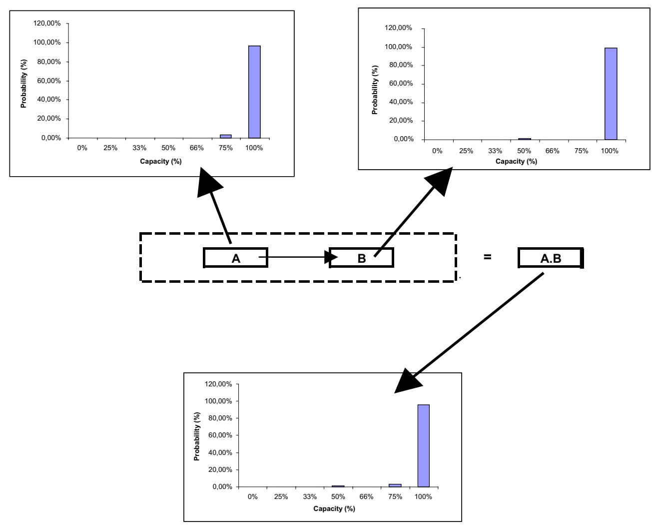

Figure A-4. Capacity Distribution Merging Process.

APPENDIX B—
COST ITEM BREAKDOWN TABLE

Table B-1. Cost Item Breakdown.

Total Cost of Ownership(C)	$C = [C_P + C_I + C_O + C_L]$ C_P = Design Cost C_I = Investment Cost C_O = Operations & Maint. Cost C_L = Losses Cost
Design Cost (C_P)	$C_P = [C_{PG} + C_{PC} + C_{PB} + C_{PE}]$ C_{PG} = Design Management Cost C_{PC} = Conceptual Design Cost C_{PB} = Basic Design Cost C_{PE} = Detailed Design Cost
Investiment Cost (C_I)	$C_I = [C_{IE} + C_{IC} + C_{IL} + C_{IT}]$ C_{IE} = Equipment Acquisition Cost C_{IC} = Construction Cost C_{IL} =Initial Logistic Support Cost C_{IT} = Acceptance Tests Cost
Construction Cost (C_{IC})	$C_{IC} = [C_{ICI} + C_{ICF} + C_{ICT}]$ C_{ICI} = Construction Facilities Cost C_{ICF} = Module Construction Cost C_{ICT} = Modules Transportation to Integration Shipyard Cost.
Initial Logistic Support Cost (C_{IL})	$C_{IL} = [C_{ILS} + C_{ILT} + C_{ILF} + C_{ILI} + C_{ILD}]$ C_{ILS} = Initial Inventory Cost C_{ILT} = Initial Training Cost C_{ILF} = Special Tooling Cost C_{ILI} = Maintenance Workshop Cost C_{ILD} = Technical Documentation Cost
Acceptance Tests Cost (C_{IT})	$C_{IT} = [C_{ITF} + C_{ITO} + C_{ITC}]$ C_{ITF} = Vendor Shop Tests Cost C_{ITO} = Shipyard Test Cost C_{ITC} = Offshore Acceptance Test Cost.
Operations & Maintenance Cost (C_O)	$C_O = [C_{OP} + C_{OM} + C_{OA} + C_{OD}]$ C_{OP} = Operations Cost C_{OM} = Maintenance Cost C_{OA} = Revamps & Upgrades Cost C_{OD} = Disposition Cost
Operations Cost (C_{OP})	$C_{OP} = [C_{OPC} + C_{OPO} + C_{OPT} + C_{OPL}]$ C_{OPC} = Fuel Cost C_{OPO} = Operators Cost C_{OPT} = Operators Training Cost C_{OPL} = Lube Oil & Chemicals Cost
Maintenance Cost (C_{OM})	$C_{OM} = C_{OMB} + C_{OMO} + C_{OMR}$ C_{OMB} = Offshore Maintenance Cost C_{OMO} = Onshore Maintenance Cost C_{OMR}= Contractor Maintenance Cost
Offshore Maintenance Cost (C_{OMB})	$C_{OMB} = C_{MBP} + C_{MBS} + C_{MBT}$ C_{MBP} = Offshore Maintenance Man-hours Cost C_{MBS} = Offshore Replaceable and Non Repairable Parts Cost C_{MBT} = Maintenance Training Cost
Offshore Maintenance Man-hours Cost (C_{MBP})	$C_{MBP} = C_{MBPC} + C_{MBPP}$ C_{MBPC} = Offshore Unscheduled Maintenance Men-hours Cost C_{MBPP} = Offshore Scheduled Maintenance Man-hours Cost
Offshore Unscheduled Maintenance Men-hours Cost (C_{MBPC})	$C_{MBPC} = \sum_{i=1}^{n} Q_{CAi} \times HH_{MCi} \times C_{HHC}$ Q_{CAi} = Unscheduled maintenance action i $Q_{CAi} = h\lambda_i$ h = System running hours λ_i = failure rate for mode i HH_{MCi} = Men-hours for Unscheduled maintenance mode i C_{HHC} = Man-hour Cost ($\$/HH_{MC}$)
Offshore Scheduled Maintenance Men-hours Cost (C_{MBPC})	$C_{MBPP} = \sum_{i=1}^{k} Q_{PAi} \times HH_{MPi} \times C_{HHP}$ Q_{PAi} = Scheduled maintenance action i. Q_{PAi} = ($fpti$) (h) h = System running hours $fpti$ =Scheduled maintenance action i frequency HH_{MPi} = Men-hours for Scheduled maintenance action i. C_{HHP} = Man-hour Cost ($\$/HH_{MPi}$)
Offshore Replaceable and Non Repairable Parts Cost (C_{MBS})	$C_{MBS} = \sum_{i=1}^{n} Q_{CAi} \times C_{SMCi} + \sum_{i=1}^{k} Q_{PAi} \times C_{SMPi}$ C_{SMCi} = Non Repairable Items for Unscheduled Maintenance i. C_{SMPi} = Non Repairable Items for Scheduled Maintenance i. C_{MBSA} = Offshore inventory Cost Note: Repairable parts are included in onshore and contractor costs.
Onshore Maintenance Cost (C_{OMO})	$C_{OMO} = C_{MOP} + C_{MOS} + C_{MOF} + C_{MOT} + C_{MOO} + C_{MOD}$ C_{MOP} = Onshore Men-hours Cost C_{MOS} = Onshore Replaceable Non repairable Parts Cost C_{MOF} = Support Equipment and Tools Cost C_{MOT} = Qualified Training Cost C_{MOO} = Work Shop Real Estate Cost C_{MOD} = Technical Documents Cost
Onshore Men-hours Cost (C_{MOP})	$C_{MOP} = \sum_{i=1}^{n} Q_{OAi} \times HH_{Oi} \times C_{HHO}$ Q_{OAi} = Onshore Maintenance Actions type i $Q_{CAi} = (h)(f_{Oi})$ h = System running hours f_{Oi} =Onshore Maintenance Actions type i frequency $f_{Oi} = \frac{1}{MTBO}$ for Overhauls or $f_{Oi} = \lambda$ for onshore repairable parts HH_{Oi} = Men-hours for Onshore Action i C_{HHO} = Onshore Man-hour Cost ($\$/HH_O$)
Onshore Replaceable and Non Repairable Parts Cost (C_{MOS})	$C_{MOS} = \sum_{i=1}^{n} Q_{OAi} \times C_{SOi} + C_{OA}$ C_{SOi} = Non repairable parts for action i. C_{OA} = Onshore Inventory Cost
Contractor Maintenance Cost (C_{MOR})	$C_{MOR} = \sum_{i=1}^{n} Q_{RAi} \times (C_{Ri} + C_{TRi})$ Q_{RAi} = Number of Repairable Items Type i. C_{Ri} = Repair Cost for Item i. C_{TRi} = Shipment Cost for item i.
Disposition Cost (C_{OD})	$C_{OD} = F_C \times Q_{CA} \times (C_{DIS} - V_{RES})$ F_C = Condemnation factor. C_{DIS} = Disposition Cost per item V_{RES} = Residual Value
Losses Cost (C_L)	$C_L = C_{LP} + C_{LA}$ C_{LP} = Production Losses C_{LA} = Accidents Losses.
Production Losses (C_{LP})	$C_{LP} = C_{LPO} + C_{LPG} + C_{LQG}$ C_{LPO} = Oil Deferred Production Cost C_{LPG} = Gas Deferred Production Cost C_{LQG} = Flared Gas Cost
Oil Deferred Production Cost (C_{LPO})	$C_{LPO} = (P_P - P_R) \times fa \times C_{oil}$ P_P = Maximum Possible Oil Production P_R = Achieved Oil Production $P_R = \sum_{N=0}^{100\%} A_N \times P_N$ A_N = Availability of system for capacity of N %. P_N = Oil Production with capacity of N %. fa = Loss factor $fa = \frac{1}{1 + \frac{D}{(LN(1+r))}}$ D = Production average decreasing rate (%/year) r = interest rate (%/year) C_{oil} = Oil Price ($/bbl)
Gas Deferred Production Cost (C_{LPG})	$C_{LPG} = (P_{PG} - P_{RG}) \times fa \times C_{gas}$ P_{PG} = Maximum Possible Gas Production P_{RG} = Achieved Gas Production C_{gas} = Gas Price ($\$/m^3$)
Flared Gas Cost (C_{LQG})	$C_{LPG} = Q_{gas} \times C_{gas}$ Q_{gas} = Flared Gas C_{gas} = Gas Price Note: Maximum allowed gas flaring is limited by local government regulations.
Accident Cost (C_{LA})	$C_{LA} = TFA \times C_{AC}$ TFA = Accident rate(1/y) C_{AC} = Cost per Accident

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