

	TÉCNICAS DE COSTES DEL CICLO DE VIDA PARA LA TOMA DE DECISIONES EN LA OPTIMIZACIÓN DEL MANTENIMIENTO. CASO DE ESTUDIO: INDUSTRIA DEL PETRÓLEO Y GAS	INDUSTRIA TECHNOLOGY
RESEARCH ARTICLE	Carlos Parra M., Pablo Viveros G., Fredy Kristjanpoller, Adolfo Crespo M., Vicente González-Prida	Maintenance Engineering

LIFE CYCLE COST TECHNIQUES FOR DECISION MAKING IN MAINTENANCE OPTIMIZATION. CASE STUDY: OIL AND GAS INDUSTRY

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ABSTRACT:

Life Cycle Cost Analysis (LCCA) is a methodology developed to evaluate the variation in the costs of assets during their useful life. This paper explores aspects related to the impact of reliability on total life cycle costs and describes the basic model of constant failure rate (Woodward's model). This model includes within its evaluation process, the estimation of the consequences (low-reliability costs) that could be caused by the various failure events of an asset within a production system. The research considers the presentation of a case study for the application of the Woodward's model in the selection and replacement of a compression system in an oil and gas industry company, which allows contrasting the performance of a traditional system versus a system based on technology and tools of industry 4.0, analyzing in a real case the strengths, limitations, realities, and myths of the application of this type of technology in the case under study. As a final point, this work concludes by presenting some recommendations aimed at consolidating the LCCA methodology within a process of Asset Management.

Key Words: Life Cycle Costs, Reliability, Industry 4.0, Asset Management.

RESUMEN:

El análisis del Coste del Ciclo de Vida (LCCA) es una metodología desarrollada para evaluar la variación en los costes de los activos durante su vida útil. Este documento explora aspectos relacionados con el impacto de la fiabilidad en los costes totales del ciclo de vida y describe el modelo básico de tasa de fallo constante (modelo de Woodward). Este modelo incluye dentro de su proceso de evaluación, la estimación de las consecuencias (costes de baja fiabilidad) que podrían ser causados por los diversos eventos de fallo de un activo dentro de un sistema de producción. La investigación considera la presentación de un estudio de caso para la aplicación del modelo de Woodward en la selección y reemplazo de un sistema de compresión en una empresa de la industria del petróleo y gas, el cual permite contrastar el desempeño de un sistema tradicional versus un sistema basado en tecnología y herramientas de la industria 4.0, analizando en un caso real las fortalezas, limitaciones, realidades y mitos de la aplicación de este tipo de tecnología en el caso en estudio. Como punto final, este trabajo concluye presentando algunas recomendaciones destinadas a consolidar la metodología LCCA dentro de un proceso de Gestión de Activos.

Palabras Clave: Costes del Ciclo de Vida, Fiabilidad, Industria 4.0, Gestión de Activos.

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1. INTRODUCTION

1.1 INTRODUCTION TO LIFE CYCLE COST ANALYSIS (LCCA) PROCESS

In the maintenance management context, it is essential to determine the process or course of action that determines the proper execution of associated activities. For this, it is necessary to consider a model for maintenance management, which is presented in Figure 1, synthesizing the information provided by other models developed in the literature [9]. Each of the phases described is related to a key decision area within asset management, and for each of them, there are relating methodologies and techniques that allow them to be carried out.

In this process, Phase 7 corresponds to the analysis of the life cycle of assets and the optimization of replacement, a stage in which all costs associated with the useful life of an asset are calculated and considered from research, design, and acquisition, through the operation phase until its elimination and replacement. Although some costs are evident, the correct analysis of the life cycle of an asset depends in turn on the information of the asset's reliability analysis, related to aspects such as the failure rate, spare parts to consider for its maintenance, and repair times and costs, aspects that are not trivial nor negligible [9]. Associated with this phase of the model, the Asset Life Cycle Cost Analysis (LCCA) is found as the main support tool, and also an essential technique for the research developed.

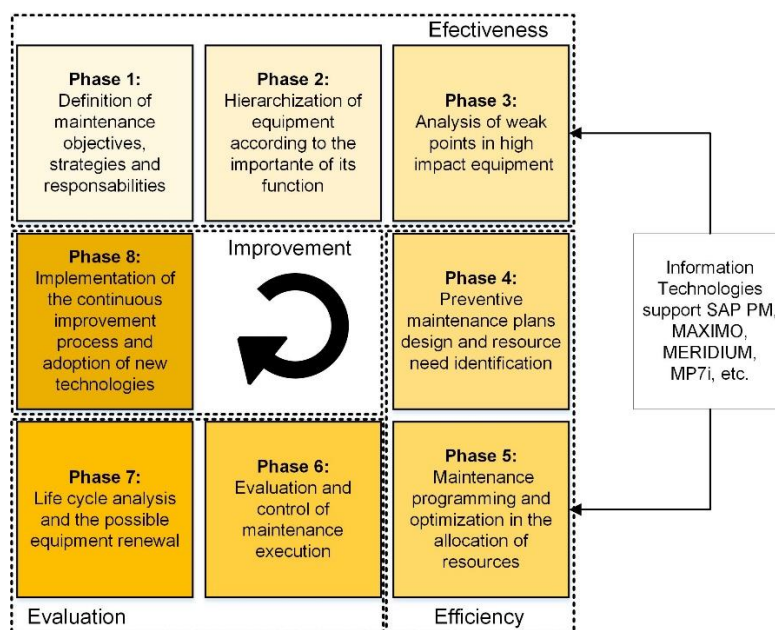


Figure 1. An integrated model of the maintenance management process (MMM). Source: (Parra and Crespo, 2015) [23]

The concept of life cycle cost analysis began to be applied in a structured manner from the 70s, specifically in the US Department of Defense (DoD), in the area of military aviation [2]. However, most of the methodologies developed in this stage by the DoD were oriented toward processes of procurement and logistics and did not include the design and production phase.

Once the need to apply LCCA methodologies in the design, planning and control of production processes was recognized, the US National Science Foundation sponsored a conference in 1984, where the main academies and industrial organizations participated [16], 34 research areas were identified in this conference, receiving the highest priorities the areas of economic evaluation in the design phase, life cycle analysis and computer-assisted design (CAD - CAE: computer-aided estimating) [2].

In an attempt to improve the design of the assets and reduce the changes in time in concurrent engineering, Life cycle engineering has emerged as an effective technique within the process of cost optimization [7]. Life cycle engineering considers that the initial phase of asset development begins with the identification of its need, and later other phases such as design (conceptual,

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preliminary, in detail), production (manufacturing), use (operations, maintenance), support (logistics) and disincorporation (replacement), will be generated.

Kirt and Dellisola [19] define the LCCA as an economic calculation technique that allows optimizing decision making associated with the design, selection, development, and replacement processes of the assets that make up a production system. This technique proposes to quantitatively assess all costs associated with the economic life period expected, expressed in annual equivalent monetary units (dollars/year, Euros/year, pesos/year). Alting [1] distinguishes 6 phases in the life cycle of an asset: recognition of necessity, design development, production, distribution, use, and disincorporation. The life cycle process begins with the definition of the different production tasks for preliminary design. Then activities such as production plan, plant layout, equipment selection, definition of manufacturing processes, and other similar activities are developed. Later, the logistic before the design phase is considered. This phase surrounds the development of the necessary support for the design and the different stages of production support for possible users, the maintenance plan provided for the use of the assets (see Figure 1), and the process for disincorporation of the assets [8]. Alting [1] suggests that the following aspects must be evaluated: agile manufacturing, environmental protection, working conditions, maintenance processes, and human and economic resources optimization.

In the last few years, Value Engineering, Design, and Production Organization field specialists have improved the quantification of the costs assessment process, including the use of techniques that quantify the reliability factor and the impact of the failure events on the total costs of a production system throughout its life cycle [28]. These improvements have allowed decreasing uncertainty in the decision-making process of areas of vital importance such as design, development, substitution, and acquisition of production assets. It is important to clarify that in all the LCCA process there are many decisions, both technical and non-technical actions, which must be adopted throughout the use of an industrial asset. Markeset and Kumar [22] raise that most of these actions; particularly those that correspond to the design phase of the production system have a high impact on the asset life cycle and greatly influence the production total costs. There are particular interests to the decisions related to the process of improving the “reliability” factor (design quality, technology used, technical complexity, failure frequency, corrective/preventive maintenance costs, maintainability levels, and accessibility) since these aspects have a great influence on the asset life cycle total cost, and greatly influence the expectations to extend the life of production systems to reasonable costs (see details in [4], [22], [13]).

1.2 RECENT RESEARCH

The recent research expands and extends the application of life cycle cost analysis, both in considerations concerning failure and maintenance process considerations, as well as in the application of this technique in new research fields. To diagnose possible system failures to carry out timely maintenance while minimizing system maintenance costs, Yoon, Yoon, Yoo, Kim, and Kim [32] propose considering in the framework of analysis of life cycle costs the incorporation of both false and lost alarms in the context of fault diagnosis, carrying out a stochastic simulation method for estimating maintenance costs in the life cycle. For its part, the research carried out by Liu, Zhao, Liu, and Liu [21] presents a model for the cost of the life cycle considering that the system under study is subject to multiple degradation processes or dependent failure modes, which they are modeled through a copula function to establish this stochastic dependency; the environmental influence on its part affects the degradation processes. These considerations are subsequently included in the analysis of the system life cycle, considering a finite evaluation horizon. Other research seeks to include recovery processes in the life cycle cost analysis, such as reuse and recycling once the useful life of the assets has ended [17]. In this context, Hasegawa, Kinoshita, Yamada, and Bracke [18] propose a review of the different options in the life cycle to select parts from disassembly processes for reuse, recycling or disposal, in different countries and therefore to different market values, to obtain a savings rate of CO₂ and a recovery cost from said pieces. To address the problem of global warming and compliance with regulations associated with atmospheric carbon levels, Li and Wright [20] elaborate a review of available negative emission technologies (NET), comparing the different results both for their emission of greenhouse gases, as well as the costs, using techno-economic analysis and a life cycle analysis respectively.

1.3 BASIC THEORETICAL ASPECTS OF COSTS

The total costs of an asset from its conceptualization to its withdrawal will be supported by the user and will have a direct impact on the marketing of the asset [27]. As buyers, we will pay for the resources required to design and market the asset, and as asset users we will pay for the resources required to use, operate, and disincorporate the asset. The total life cycle costs can be decomposed in different categories as shown in Figure 2. This decomposition is known as cost breakdown structure (CBS). This structure breaks down the costs according to the organizational activities that give rise to the productive system [14]. The CBS represents in general

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terms the main types of costs associated with the processes of design, production, marketing, use, and disincorporation, although it must be taken in account that the level of breakdown and the different categories of costs will depend on different factors such as: the nature of the asset to develop, the type of information available, the process of design and manufacturing, the economic variables, the human resource, the existing technology, among others.

Another aspect of interest is related to the difference in importance between the different types of costs. For example, while the organization wants to know the total costs of the asset to develop, the designer is only interested in the costs that he/she can control. Some of the costs incurred in the life of the equipment are difficult to visualize in the design phase, these costs are related to the way the organization will develop the product. In such a way that the definition of the asset life cycle total costs should be classified in the costs related to the global process of development, and in the costs related to the asset design process. Some aspects that the designer does not generally consider in this process are related to the production and construction costs of the asset, a fact that is detrimental to reducing costs in this phase of the life cycle. In the design phase, these costs are not relevant to the designer, which does not mean that the organization should be obviated these types of costs since later these costs should be considered by the people in charge of producing and manufacturing the asset [15].

The costs related to this stage are linked to the initial phases of the development of the system (project visualization, basic, conceptual, and detail engineering). It is important to mention that the results obtained in a cost analysis process achieve its maximum effectiveness just during this initiation phase. As presented in Figure 3, once the design has been completed, it is difficult to substantially modify the economic results [24]. It is more, the economic considerations related to the life cycle should be specifically proposed during the phases mentioned above to exploit the possibilities of effective economic engineering. It must be taken into account that almost two-thirds of the asset or system life cycle costs are already determined in the conceptual and preliminary design phase (65-85% of opportunities for the creation of value and costs reduction) ([12], cited in [24]).

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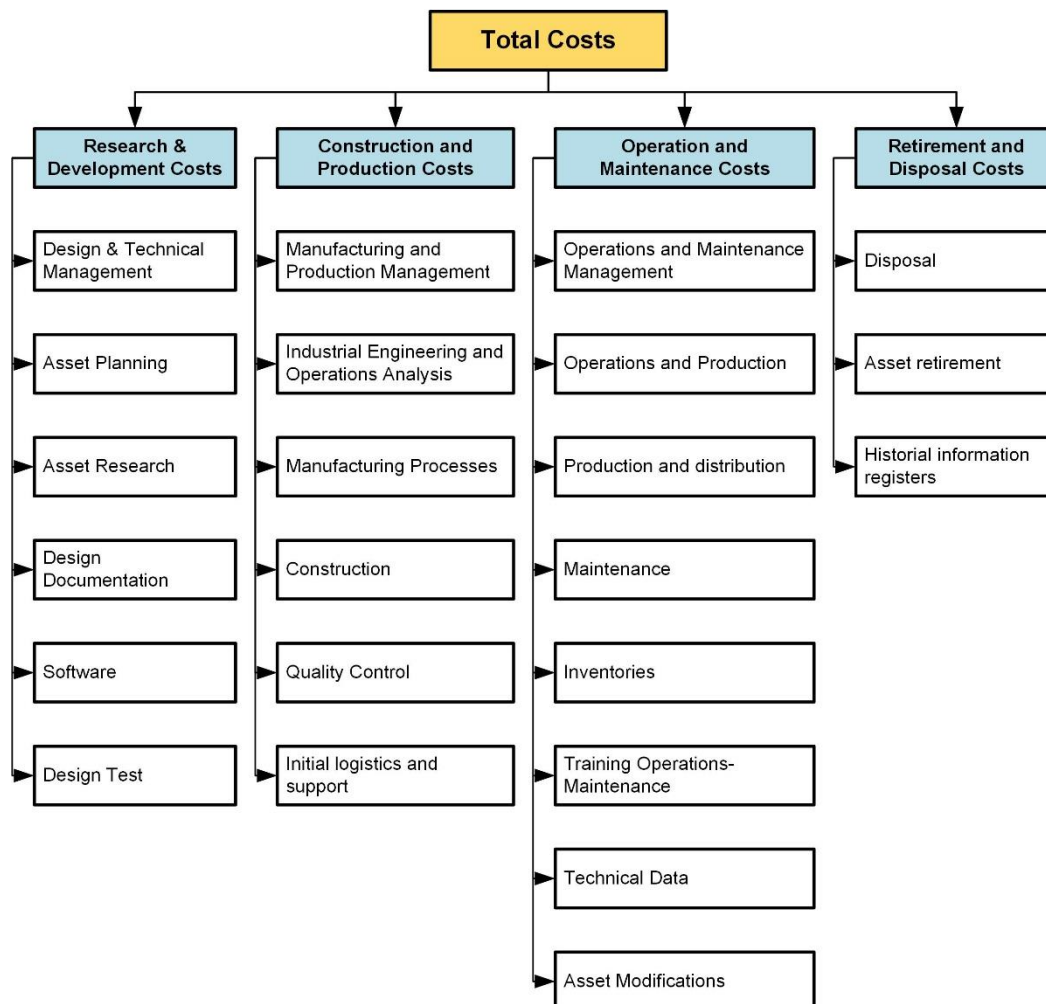


Figure 2. Cost Breakdown Structure (CBS) Source: (Fabrycky and Blanchard, 1991)

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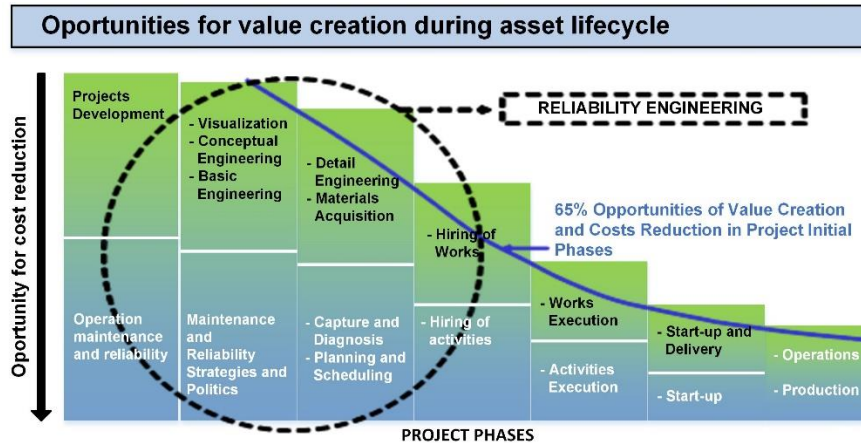


Figure 3. Opportunities for costs reduction. Source: (Parra and Crespo, 2015) [23]

1.4 IMPACT OF RELIABILITY IN LCCA MODELS ASSESSMENT

Woodhouse [29] poses that in order to design an efficient and competitive productive system in the current industrial field it is necessary to evaluate and quantify the economic impact of the reliability factor throughout the life cycle of an industrial asset. The quantification of reliability factor allows, first of all, predict how production processes may lose their operational continuity due to unforeseen failure events (behavior of the failure frequency), and second, analyze and evaluate the economic impact (costs) that failures cause to safety, environment, operations, and production.

The key aspect of the term Reliability is related to operational continuity. In other words, it can be affirmed that a production system is "reliable" when it is capable of fulfilling its function safely and efficiently through its life cycle. Now, when the production process begins to be affected by a large number of unforeseen failure events (low reliability), this scenario causes high costs mainly associated with function recovery (direct costs) and impact on the production process (penalty costs).

Reliability total costs (caused by unforeseen failures), can be characterized in the following form ([3], [25], [28]):

- Penalty costs:
 - ✓ Downtime (production unavailability), marketing opportunity loss, deferred production, operational losses, product quality impact, safety, and environmental impact.
- Direct corrective maintenance costs:
 - ✓ Labor: direct costs related to labor (own or hired) in case of an unplanned action.
 - ✓ Materials and spare parts: direct costs related to consumables and spare parts used in case of an unplanned action.

The reliability and maintainability of an asset have a considerable impact on costs during the operation phase of the life cycle. These two characteristics are directly associated with the behavior of the following two indicators:

- Mean Time Between Failures (MTBF):

$$MTBF = \text{operational times} / \text{amount of failures} \quad (1)$$

Systems with small MTBF figures reflect low-reliability values and high amount of failures

- Mean Time to Repair (MTTR):

$$MTTR = \text{repair times} / \text{amount of failures} \quad (2)$$

High MTTR systems reflect low maintainability values (systems in which they need a lot of time to be able to recover their function).

According to Woodhouse [29], an important factor in the increase in costs throughout the life cycle is caused in many opportunities due to the lack of forecasting before the unexpected appearance of failure events, scenario provoked by ignorance, and the lack of

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analysis in the design phase of aspects related to the reliability factor. This situation results in an increase in operating costs (costs that were not considered in the project initial stages) affecting the profitability of the production process in this way. In the next section will be explained the details of a basic model, that allows evaluating the economic impact of reliability throughout the life cycle of an industrial asset.

The main contribution of this research is based on the practical application of techniques of the life cycle cost of assets in a real problem, which allows supporting the decision-making process in an electrical company industry. The case study also considers the comparison of two alternatives for the replacement of an essential asset in the production process, including as one of the alternatives an industry 4.0 component-based system, which allows measuring the impact economic of the eventual incorporation of this technology in the electrical industry.

The research is structured as follows: in section 2, the fundamental aspects of the Woodward model and its application to the case study for the selection of a compression system are established, thus obtaining the results of the application; In section 3, the discussion from the obtained results is developed; and in section 4, the conclusions and final considerations are established, as well as future work areas that extend from the research topic presented.

2. METHODS AND RESULTS

2.1 MATERIALS, OPERATIONAL CONTEXT, AND ASPECTS OF INTEREST OF THE SELECTED LCCA MODEL

In the following paragraphs a practical case of application of the Life Cycle Cost Analysis (LCCA) technique was developed to identify the best option, between two different types of motor-compressor, to be selected within the installation project of the PTS1 gas compression station, for the gas transport company T-ENERGY. The technical management of the T-ENERGY organization, selected the Woodward LCCA model [23, 30], to carry out the technical-economic comparison of scenarios between the two motor-compressor options, listed below:

- Option 1: CA / AR (traditional motor-compressor station)
- Option 2: MOP (motor-compressor station that includes industry 4.0 technologies)

The selection of the Woodward model by the T-Energy organization was justified by the effectiveness and ease of implementation of this technique in the selection process of new equipment with limited information on failure data. The Woodward Model, allows to quickly calculate cost estimates for failures with a little complex mathematical level, which can help guide the selection process (purchase) of different alternatives and/or assets replacement. The main limitation of Woodward's model is associated with the calculation economic impact of reliability since this model proposes a constant failure frequency to be considered along the life cycle of the asset to be evaluated; in which reality does not occur in this manner, since normally the failure frequency changes as the years go by due to the influence of different factors (operations, maintenance, materials quality, among others). It is important to mention that the T-Energy organization understands and recognizes the technical limitations of Woodward's LCCA model and its impact on the final results of the case study presented in this report (in particular, the technical management of the T-Energy organization, considers that the ease of implementation of the Woodward model is the most important criterion for its application in this phase of equipment selection) [17], [23, [30].

For the application of the Woodward's LCCA model, the organization formed a working group made up of the following people (4 people) :

- A leader of the LCCA Model application (Reliability Engineering, 1 person).
- Two experts in the types of equipment to be evaluated (CA/AR (traditional motor-compressor station) & MOP (motor-compressor station that includes industry 4.0 technologies)
- An expert in industry 4.0 (Automation and Control Engineering)

The application of the Woodward's LCCA Model, was planned to be executed in 4 months from April to July 2019. In addition to the 4 people who make up the main group, interviews were conducted with different specialists related to the areas to be evaluated in the process of applying Woodward's LCCA methodology.

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2.2 WOODWARD'S LCCA MODEL

In general terms, the Woodward LCCA model [30] proposes the following scheme to calculate the impact of failure costs in the life cycle of an industrial asset:

1. Establish the system operational conditions. Describe system operational modes (full load, half load, without load) and the production capabilities to satisfy.
2. Establish the factors of use. These factors must indicate the operating status within each operation mode.
3. Identify the different options to be evaluated. Select the existing alternatives that can meet the requested production needs.
4. Identify for each alternative all basic costs categories: initial investment, development, acquisition, planned maintenance, replacement.
5. Determine for each alternative the reliability total costs (*RTC*). Identify the main types of failures and frequency, which will be a constant value throughout the asset life cycle (this aspect is detailed below).
6. Determine critical costs. Identify the cost categories of greater impact and analyze the factors that promote high costs (propose control strategies).
7. Calculate all costs in present value (*P*) for each alternative. Define the discount rate and the expected life period and estimate and estimate the total costs in the present value for each alternative.
8. Select the winning alternative. Compare the total costs of evaluated alternatives and select the option that generates lower costs for the expected life period.

About the previous scheme, the Woodward model proposes the following equation to calculate the different costs that an industrial asset generates throughout its life cycle.

$$LCTC(P) = \sum_{T=1}^T IC + OC + PMC + RTC + MMC \quad (3)$$

Where:

(*P*) = Present Value.

LCTC(P) = Life cycle total costs in present value (*P*), considering a discount rate (*i*) and an expected useful life (*T*).

IC = Acquisition and installation costs, normally given in present value.

OC = Operating costs, normally given as an annualized value(**)¹.

PMC = Preventive maintenance costs, normally given as an annualized value(**).

RTC = Reliability Total Costs (failure costs), normally given as an annualized value. In this case, it is considered a constant failure rate, so the impact on costs is the same in all the years(**).

MMC = Major – Specials Maintenance Costs, normally given as a future value(**).

In relation to the quantification of reliability costs (*RTC*), Woodward model proposes to evaluate the impact of the main failures on the production system cost structure, from a simple process which is summarized below:

First, the most important failure types are determined, then it is assigned to each failure type a constant value of failure frequency (constant likelihood of failure, this value will not change throughout the expected life). Subsequently, it is estimated the impact on costs per year generated by the failures in production, operations, environment, and safety; and finally, it is estimated in present value at a specific discount rate. This value represents the total impact of failure costs for the expected life years.

Below are the steps to be followed to estimate the costs by failures according to the Woodward model:

1. Define failure types (*f*), where $f = 1 \dots F$ for Failure types.

¹ (**): All costs categories will be converted to present value (*P*) at an interest rate (*i*) and an expected life period (*T*).

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- Define annual expected failure frequency δ_f . It is expressed as failures by year. This frequency is considered to be an annual constant value for the expected useful life cycle. It is estimated as:

$$\delta_f = \frac{N}{T} \quad (4)$$

Where:

N = total amount of failures

T = years of expected useful life.

- Estimate costs related to each failure type C_f (US\$/failure). These costs include spare parts costs, labor, the production losses penalties, and operational impact.

$$C_f = \sum_{f=1}^F MTTR_f \times C_{pe_f} \quad (5)$$

Where:

$MTTR$ = mean time to repair

C_{pe} = hourly penalty costs (production, labor, spare parts), measured in (US\$/hour).

- Estimate annual failure total costs RTC_f (US\$/year):

$$RTC_f = \sum_{f=1}^F C_f \times \delta_f \quad (6)$$

- Calculate the costs by failure in present value $PRTC_f$ (US\$). Given an annualized value RTC_f , its monetary value is estimated according to the number of years of expected useful life (T), for a discount rate (i). The equation to estimate the $PRTC_f$ in present value is:

$$PRTC_f = RTC_f \times \frac{(1+i)^T - 1}{i \times (1+i)^T} \quad (7)$$

Subsequently, the costs calculated by reliability are added to the rest of the costs evaluated (investment, planned maintenance, operations, etc.). The total cost is estimated in present value for the selected interest rate and expected years of useful life; and it is compared to the result obtained with the total costs of the other options evaluated. The diagram presented in Figure 4 summarizes roughly the essential aspects of the described methodology.

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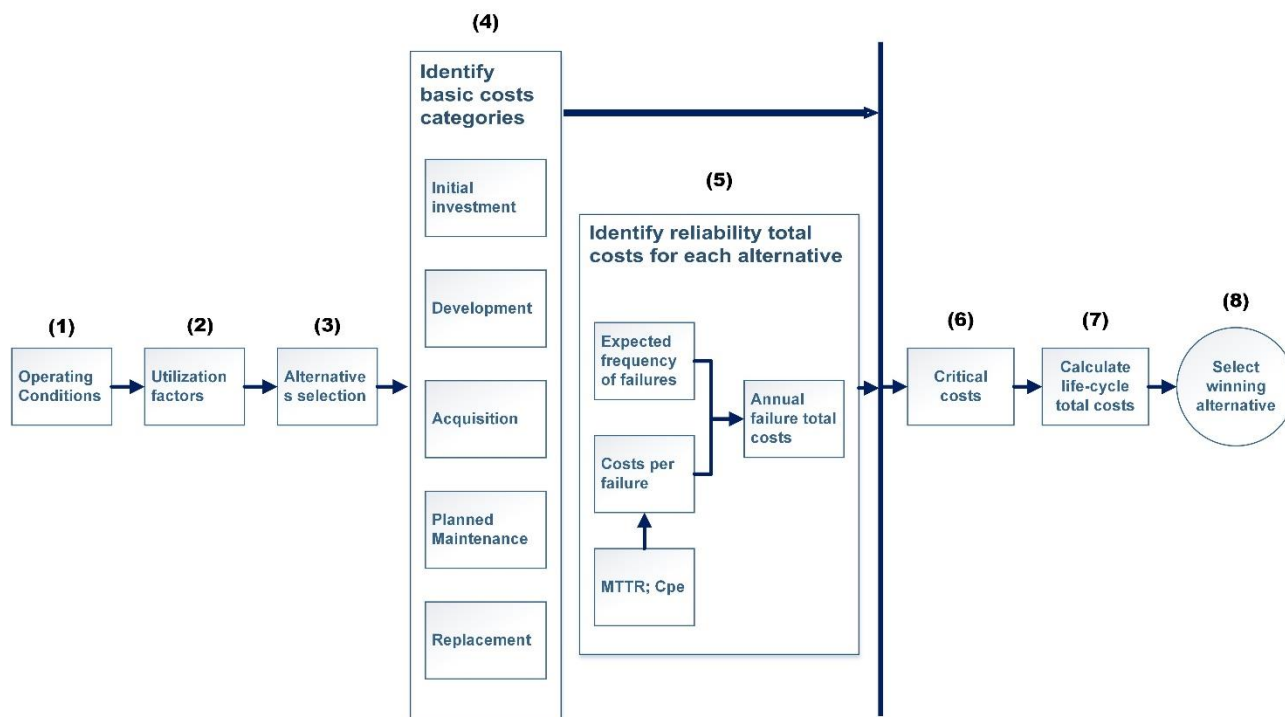


Figure 4. Woodward and LCCA model methodology diagram. Source: Own elaboration.

2.3 LCCA WOODWARD MODEL APPLIED TO T-ENERGY. CASE STUDY

2.3.1 Case study. selection of best compression system for the new compression station pts1

The following application of the Woodward LCCA model was developed to identify the best technical – economical option, between different motor-compressor options, CA/AR versus MOP, to be selected within the installation project of the PTS1 gas compression station, for the gas transport company T-ENERGY. A possible scenario was evaluated.

- **Scenario 1:** With production penalty. It is estimated demand for gas transportation in the new PTS1 Compression station of 270 MMCFD, which would be covered with the following alternatives:
 - ✓ **Option 1:** Three CA/AR motor-compressors (3 of 3 configuration) to cover the demand for gas transport. Include basic online monitoring systems (PAS: Portable Analyzer System) for more important operating variables. The PAS measure dynamic data relative to crank position and then apply the principles of thermodynamics and science to precisely assess machinery condition and performance. The portable analyzer utilizes multiple sensor technologies to collect data degree-by-degree with respect to crank angle. Measurement points include in-cylinder pressure, vibration on the frame, crosshead and cylinder, ultrasonic on the valves and injectors, proximity of rod movement and angular velocity of the crankshaft. Using gas laws, equations of state and proprietary diagnostics, the PAS and software are able to assess the mechanical condition, performance and economic return of reciprocating compressors and engines. The portable analyzer also incorporate tools to evaluate rotating equipment. In additional to the crank-angle-based vibration necessary for reciprocating machinery evaluation, analyzers incorporate the time waveform and FFT tools for evaluation of rotating machinery such as pumps, fans and motors. Advanced features are included to analyze the condition of turbomachinery, either directly or connecting to existing protection systems.

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- ✓ Option 2: Two MOP rotary compressors (2 of 2 configuration) to cover the demand for gas transport. Include an Industry 4.0 integral system, digitization, and total monitoring. The integral monitoring system (4.0) includes some peripheral universal connection (PUC) modules to each compressor unit. Some PUCs can monitor high-speed rotating components and characteristics that include rotor, impellers, valve train, electrical motor health, main bearings and frame vibration. In this case in point is an array of Industrial Internet of Things (IIoT), services and software online to monitor, manage and optimize rotary compressors. Analyzing data using 'learning' algorithms helps the system to build an understanding of each customers normal operating conditions. In the event of any unusual activity or significant variation, a specialist engineer is alerted. They will then review the data and decide if there is a problem. The customer is then contacted, and corrective actions are undertaken. If the change observed is considered unusual but acceptable, the system can be taught to ignore any recurrence of it. The monitoring undertaken is a two-way process, as the algorithm understanding deepens, it can update parameters within a machine's own controller. The machine can then alert on-site staff directly to any indication that a problem is developing. The use of augmented reality can also provide maintenance staff with virtual support from remote experts who can view what the maintenance staff are seeing in real time, which adds extra guidance and support for a machine. The monitoring system works as follows:
- Sensing capabilities are retrofitted by attaching what are described as peripheral universal connection (PUC) modules to the compressors unit.
 - PUC modules can monitor high-speed engine components and characteristics that include rotating parts, valve train, electrical interface, main bearings and frame vibration. On a compressor, monitoring can pressure, suction temperature and vibrations (vibration bias voltage and vibration raw time).
 - Fleetwide reports compare high-level KPIs, including a heat map of highest and lowest performing units. A health report might cause a customer to shut down two under-performing units and start-up another that is operating closer to peak performance. Automatically generated daily reports address component issues such as magnetic pickup stability, transducer calibration, bias voltage, and hardware communication issues.
 - Data analysis uses the calculated trend data to compile a daily health report.

Finally, all the capabilities of the portable analyzers, as well as online systems, come together in a software that allows to analyze and correlate in an integral way all the variables of the rotating equipment. This application automatically makes performance calculations, provides plotting tools, runs what-if scenarios, automates reporting and gives automatic diagnostics to help the analyst. It also allows users to easily transfer data among colleagues and industry experts for remote analysis, offering the possibility of developing a Digital Twins (DT) application.

In both options, when losing a unit, it will generate a penalty for lack of gas transportation. **Scenario 1. Analysis (With production penalty):**

Option 1: Production loses 18.750 US\$/hour

Option 2: Production loses 28.125 US\$/hour

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Table 1. Case Study. Economic Data Scenario 1 (With production penalty)

Data	Option 1 CA/AR	Option 2 MOP
IC: initial cost (investment)	52.656.000 US\$	57.086.400 US\$** ** (4.000.000 US\$ Approx., Industry 4.0 technologies)
OC: operational costs (annual)		
Operations	1.704.594 US\$/year	848.500 US\$/year
Lubes	131.701 US\$/year	0 US\$/year
Consumables	459.680 US\$/year	89.334 US\$/year
Energy	3.898.383 US\$/year	2.524.000 US\$/year
PMC: preventive maintenance costs (annual)	643.850 US\$/year	343.650 US\$/year
MMC: overhaul (major maintenance) costs (failure)	2.162.162 US\$, year 5 2.270.270 US\$, year 10 2.383.784 US\$, year 15 2.502.973 US\$, year 20	450.000 US\$, year 5 472.500 US\$, year 10 496.125 US\$, year 15 520.931 US\$, year 20
i: interest rate	16%	16%
T: expected useful life period	20 years	20 years

The following is shown the economic evaluation of the two alternatives presented above, including the economic impact of failure events. For the estimate of the costs generated by the failure events, the procedure proposed by the Woodward LCCA model will be used. The failure data of the CA / AR system was supplied by the users who use this equipment in gas production areas in Colombia and Argentina. The failure data of the MOP system was given by the manufacturer of this equipment, taking as a reference user of equipment that work in conditions similar to those analyzed in this case study. The data of failure frequency (δ_f), MTTR and failure-related penalty costs (Cpe) are shown in the following table

Table 2. Failure costs, reliability, and maintainability. Case Study, Scenario 1

Data	Option 1 CA/AR	Data	Option 2 MOP
Failure Modes		Failure Modes	
1. Compressor		1. Motor	
1.1 Cylinder		1.1 Magnetic Bearings	
δ_f : failure frequency	0,2 failures/year	δ_f : failure frequency	0,1 failures/year
MTTR (hours/failure)	1.440 hours	MTTR (hours/failure)	72 hours
Cpe1 (by production)	18.750 US\$/hour	Cpe1 (by production)	28.125 US\$/hour
Cpe2 (by materials, labor)	35,57 US\$/hour	Cpe2 (by materials, labor)	2.291,66 US\$/hour
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.785,57 US\$/hour	Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	30.416,66 US\$/hour
1.2 Valves		1.2 Control System (AMB System)	

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Data	Option 1 CA/AR	Data	Option 2 MOP
δ_f : failure frequency	5 failures/year	δ_f : failure frequency	0,2 failures/year
MTTR (hours/failure)	9 hours	MTTR (hours/failure)	9 hours
Cpe1 (by production)	18.750 US\$/hour	Cpe1 (by production)	28.125 US\$/hour
Cpe2 (by materials, labor)	100,84 US\$/hour	Cpe2 (by materials, labor)	1.666,66 US\$/hour
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.850,84 US\$/hour	Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	29.791,66 US\$/hour
1.3 Gas Packing		1.3 Accessories and electrical wiring	
δ_f : failure frequency	1 failure/year	δ_f : failure frequency	0,1 failures/year
MTTR (hours/failure)	11 hours	MTTR (hours/failure)	11 hours
Cpe1 (by production)	18.750 US\$/hour	Cpe1 (by production)	28.125 US\$/hour
Cpe2 (by materials, labor)	74,46 US\$/hour	Cpe2 (by materials, labor)	545,45 US\$/hour
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.824,46 US\$/hour	Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	28.670,45 US\$/hour
1.4 Bars		1.4 Motor cooling filters	
δ_f : failure frequency	0,2 failures/year	δ_f : failure frequency	0,33 failures/year
MTTR (hours/failure)	1440 hours	MTTR (hours/failure)	24 hours
Cpe1 (by production)	18.750 US\$/hour	Cpe1 (by production)	28.125 US\$/hour
Cpe2 (by materials, labor)	2,46 US\$/hour	Cpe2 (by materials, labor)	125,00 US\$/hour
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.752,46 US\$/hour	Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	28.250,00 US\$/hour

Table 2. Failure costs, reliability, and maintainability. Case Study, Scenario 1. (Continuation)

Data	Option 1 CA/AR	Data	Option 2 MOP
Failure Modes		Failure Modes	
1. Compressor		1. Motor	
1.5. Auxiliary Equipment		1.5. ABB-AC S-5000 Control System	
δ_f : failure frequency	0,33 failures/year	δ_f : failure frequency	1 failure/year
MTTR (hours/failure)	720 hours	MTTR (hours/failure)	24 hours
Cpe1 (by production)	18.750 US\$/hours	Cpe1 (by production)	28.125 US\$/hour
Cpe2 (by materials, labor)	2,78 US\$/hour	Cpe2 (by materials, labor)	83,33 US\$/hour
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.752,78 US\$/hour	Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	28.208,33 US\$/hour
1.6 Compressor Bench		2. Compressor	

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Data	Option 1 CA/AR	Data	Option 2 MOP
δ_f: failure frequency	0,5 failures/year	2.1 Turbine-Compressor	
MTTR (hours/failure)	72 hours	δ_f: failure frequency	0,1 failures/year
Cpe1 (by production)	18.750 US\$/hour	MTTR (hours/failure)	120 hours
Cpe2 (by materials, labor)	20,29 US\$/hour	Cpe1 (by production)	28.125 US\$/hour
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.870,29 US\$/hour	Cpe2 (by materials, labor)	1.125,00 US\$/hour
		Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	29.250,00 US\$/hour
1.7 Structural			
δ_f: failure frequency	2 failures/year	2.2 Electric Motor	
MTTR (hours/failure)	1 hour	δ_f: failure frequency	0,1 failures/year
Cpe1 (by production)	18.750 US\$/hour	MTTR (hours/failure)	120 hours
Cpe2 (by materials, labor)	40,00 US\$/hour	Cpe1 (by production)	28.125 US\$/hour
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.790,00 US\$/hour	Cpe2 (by materials, labor)	958,33 US\$/hour
		Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	29.083,33 US\$/hour
1.8 Crossheads			
δ_f: failure frequency	0,2 failures/year		
MTTR (hours/failure)	1440 hours		
Cpe1 (by production)	18.750 US\$/hour		
Cpe2 (by materials, labor)	3,08 US\$/hour		
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.753,08 US\$/hour		
2. Motor			
2.1 Cylinder Head			
δ_f: failure frequency	0,33 failures/year		
MTTR (hours/failure)	72 hours		
Cpe1 (by production)	18.750 US\$/hour		
Cpe2 (by materials, labor)	141,91 US\$/hour		
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.891,91 US\$/hour		

Table 2. Failure costs, reliability, and maintainability. Case Study, Scenario 1. (Continuation)

Data	Option 1 CA/AR	Data	Option 2 MOP
Failure Modes			
2. Motor			
2.2 Cylinders			

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Data	Option 1 CA/AR	Data	Option 2 MOP
δ_f: failure frequency MTTR (hours/failure) Cpe1 (by production) Cpe2 (by materials, labor) Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	0,33 failures/year 72 hours 18.750 US\$/hours 47,75 US\$/hour 18.797,75 US\$/hour		
2.3 Compressor Bench			
δ_f: failure frequency MTTR (hours/failure) Cpe1 (by production) Cpe2 (by materials, labor) Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	0,2 failures/year 48 hours 18.750 US\$/hour 35,16 US\$/hour 18.785,16 US\$/hour		
2.4 Journal Bearings			
δ_f: failure frequency MTTR (hours/failure) Cpe1 (by production) Cpe2 (by materials, labor) Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	2 failures/year 24 hours 18.750 US\$/hour 56,32 US\$/hour 18.806,32 US\$/hour		
2.5 Turbochargers			
δ_f: failure frequency MTTR (hours/failure) Cpe1 (by production) Cpe2 (by materials, labor) Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	0,33 failures/year 24 hours 18.750 US\$/hour 17,23 US\$/hour 18.767,23 US\$/hour		
2.6 Accessories			
δ_f: failure frequency MTTR (hours/failure) Cpe1 (by production) Cpe2 (by materials, labor) Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	0,2 failures/year 24 hours 18.750 US\$/hour 115,48 US\$/hour 18.865,48 US\$/hour		
2.7 Structural			

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Data	Option 1 CA/AR	Data	Option 2 MOP
δ_f : failure frequency	2 failures/year		
MTTR (hours/failure)	1 hour		
Cpe1 (by production)	18.750 US\$/hour		
Cpe2 (by materials, labor)	40,00 US\$/hour		
Cpe (Cpe1+Cpe2): penalty costs (US\$/hour)	18.790,00 US\$/hour		

From the information shown in Table 2 the total costs by failures ($PRTC_f$) are calculated in present value. The total cost due to failures per year (RTC_f) is calculated from the equations (5) and (6); the total costs by failures (RTC_f) are calculated with equation (7). Below are presented the results of the total costs by failures of the two evaluated options.

Table 3. Results of the Failure Costs Case Study, Scenario 1

Results	Option 1 CA/AR	Option 2 MOP
RTC_f : total costs due to failures by year (US\$/year)	24.619.807,3 US\$/year	2.031.052,5 US\$/year
$PRTC_f$: total costs in present value (US\$) for (i=16%, T =20 years)	145.966.960,5 US\$	12.041.787,1 US\$

Following are presented the LCCA total results in present value.

Table 4. LCCA Total Results Case Study, Scenario 1 (With production penalty)

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Results	Option 1 CA/AR	Option 2 MOP
IC: initial cost (investment)	52.656.000 US\$	57.086.400 US\$ <i>**(4.000.000 US\$ Approx., Industry 4.0 technologies)</i>
OC: operational costs (present value)		
Operations	10.106.266,62 US\$	5.030.621.5 US\$
Lubes	780.834,27 US\$	0 US\$/year
Consumables	2.725.369,58 US\$	529.647,07 US\$
Energy	23.112.892,57 US\$	14.964.394,4 US\$
PMC: preventive maintenance costs (present value)	3.817.284,21 US\$	2.037.446,18 US\$
MMC: overhaul costs (major maintenance) (present value)	1.029.433,47 US\$, year 5 514.632,98 US\$, year 10 257.274,68 US\$, year 15 128.616,40 US\$, year 20	214.250,85 US\$, year 5 107.108,00 US\$, year 10 53.545,28 US\$, year 15 26.768,27 US\$, year 20
i: interest rate	16%	16%
T: expected useful life period	20 years	20 years
PRTCf (P) total costs by failures in present value	145.966.960,5 US\$	12.041.787,1 US\$
LCTC(P) Life Cycle Total Costs in present value, i: 16%, T: 20 years	241.095.525,4 US\$	92.091.968,74 US\$
PRTCf (P) / LCTC(P) = % (total costs by failures/life cycle total costs, both in present value)	61%	13%

Table 5. Summary of Results Case Study, scenario 1

Results	Option 1 CA/AR	Option 2 MOP Best option
IC: initial cost (investment)	52.656.000 US\$	57.086.400 US\$ <i>**(4.000.000 US\$ Approx., Industry 4.0 technologies)</i>
PRTCf (P) total costs by failures in present value	145.966.960,5 US\$	12.041.787,1 US\$
LCTC(P) Life Cycle Total Costs in present value, i: 16%, T: 20 years	241.095.525,4 US\$	92.091.968,74 US\$
PRTCf (P) / LCTC(P) = % (total costs by failures/life cycle total costs, both in present value)	61%	13%

3. DISCUSSION

Analyzing the economic results obtained in the LCCA (Tables 4 and 5), the option 2 MOPIC compression system that includes integral diagnostic and analysis tools from Industry 4.0, becomes the best economic alternative, compared to option 1, CA/AR compression system. The percentage of additional costs by adding intelligent digitization and monitoring tools is 14.2 % of the total initial investment of the MOP compression system. The economic difference between the two options is approximately 149 MMUS\$ (this amount represents the potential savings by selecting this option). A valid appearance to be considered in this analysis is related to the evaluation of total costs due to failures ($PRTC_f$). Including this category of costs in the economic evaluation process, it becomes the economic greater weight in the comparison process of the two alternatives evaluated (the possible minimization of total costs due to failures are largely related for the efficient use that must be given to the monitoring and intelligent diagnostic tools proposed by Industry 4.0, including in MOP compression system). In summary, option 2 (MOP compression system) was the winner in the LCCA and its category of failure costs ($PRTC_f$) only represents 13% of the total life cycle costs, compared to the option 1,

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CA/AR compression system, in which the category of failure costs represents 61% of the total life cycle costs. The winning option, the MOP compression system, includes a series of Industry 4.0 tools that will allow [10]:

- Complex aggregation analysis: To process information obtained on different dates or in different locations.
- Multi-dimensional query and analysis: To analyze and extract asset data from different viewpoints.
- Log data analysis: To control the asset health during its operation.
- Time-window-based stream data analysis: To detect trends in operation.
- Complex event processing: To detect failures before they occur.
- Baseline Analytics is used to detect anomalies, and the data used is usually local to the asset itself when it operates under normal operating conditions.
- Diagnostic analytics provide very fast results and identify the root cause of the failure, so it requires a prior study of the different states of the failure.
- Prognostic analytics is generally used to calculate the remaining useful life of a component, requiring a multitude of input data and is not as fast as diagnostic analytics

Another attribute presented by the 4.0 maintenance tools included in the MOP Compression system are the reports that can be obtained from the analysis of the maintenance and operations data. The analysis of the information in the reports to be developed will help to [10]:

1. Identify the requirements of all key stakeholders to the provision of information.
2. Identify the most critical assets and then select the information that must be taken into account that will lead to effective decision making. Finally, it is necessary to determine what data is needed to get this information. The necessary data could take many different forms, including:
 - Data about the compression assets (themselves, current condition, the current level of performance).
 - Data relating to the activities that have been performed on the assets (operational activities, maintenance activities and modifications, upgrades, or replacements).
 - Data about the financial or other impacts if the assets underperform or fail to perform at all; data relating to safety, environmental or other incidents; data relating to expected future asset performance, costs, and risks; etc.
3. Identifying the types of decisions that will have the greatest potential impact on the achievement of asset management (and organizational) objectives. The decisions can be made at many different organizational levels, including:
 - Strategic Decisions—potentially those with the greatest potential business impact, capital investment, and allocation of operating expenditure decisions. Moreover, those decisions for which objective data is most likely to be difficult to obtain and analyze.
 - Management Decisions—such as to replace or upgrade an asset to meet specific business needs, about the timing of these major events, also those related to the allocation of working capital (such as for spare parts holdings), decisions relating to whether to insource or outsource particular activities.
 - Operational Decisions—involved with short-term control of maintenance and operational activities, these are technical decisions relating to day-to-day operations.

Considering the relevance of the costs related to the failure presented by the case study analyzed, it is relevant to point out that the Woodward model considers a constant failure rate, that is, that the impact of the failures to costs will remain constant at all years through the entire planning horizon. This reveals a limitation of the model since this assumption is not usually the norm for the random behavior of failures in the equipment. Therefore, it is important to emphasize that the costs associated with the occurrence of failures can be imprecise by demonstrating high levels of uncertainty in the estimation. The model can underestimate or overestimate this cost item if the result is compared with the modeling of the failures using, e. g., a Weibull distribution, a result that in turn will depend on the estimation process and the values of the parameters obtained. In this sense, Woodward's model should be used to guide the process of selecting replacement alternatives, but it should not be used to make conclusive decisions [9].

In summary, the results of the LCCA process of Case Study, in the scenario evaluated (with penalty), resulted in the best option for the MOP compression system compared to CA/AR compression system. It is recommended to make a much more detailed LCCA of

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the last case presented, to evaluate the renewal of current compression systems CA/AR, by the technology of rotary compressors MOP, since, depending on technical-economic information taken as reference, the results obtained at the level of total life cycle costs of the MOP compression system is more profitable than traditional technology of CA/AR reciprocating compressors.

4. FINAL CONSIDERATIONS AND FUTURE WORKS AREAS

From the results obtained in this assessment, it is very easy to understand the true economic impact that can bring with them the failures of a production system, which is why it is very important, the process of evaluating reliability (failures behavior) proposed by the Woodward model and integrate it with the economic evaluation process (economic impact of the failure events). All of this in order to optimize decision making (decrease uncertainty) within the required processes (evaluation, selection, and justification) for purchase and replacement of assets in T-ENERGY organization.

The orientation of this report towards the study and analysis of the reliability factor and its impact on costs is due that much of the increase in total costs during the expected life cycle of a production system, is mostly caused by the lack of forecasting before the unexpected appearance of failure events, scenario caused by ignorance and for the absence of technical evaluation in the design phase of the aspects related to reliability. This situation brings as a result in an increase of the total operational costs (costs that were not considered in the initial phases of the project) and affecting in this way the profitability of the production process.

In the process of analysis of costs throughout the life cycle of an asset, there are many decisions and actions which must be taken, being of particular interest for this work those aspects related to the process of improving reliability (design quality, the technology used, technical complexity, failures frequency, costs of preventive/corrective maintenance, levels of maintainability and accessibility); since these have a great impact on the total cost of the life cycle of the asset, and greatly influence the expectations to extend the life of assets at reasonable costs.

As a closing discussion, important efforts must be developed to reach analytic models providing value by improving asset performance. In most of today's complex engineering assets, despite the existence of well-developed physical models for a component of a system, the complexity that arises from the combination of elements, and often the changes in environmental and operational conditions, make it impractical to characterize a complete system through closed mathematical expressions [10]. The application tools of Industry 4.0: Artificial Intelligence (AI), Machine Learning (ML), Digital Twins (DT), Neural Networks (NN), Internet of Things (IOT), etc., provide intelligence and flexibility to predictive models and are very valuable for discovering patterns of behavior in the presence of randomness. Both reasons make these techniques increasingly important [10]. In diagnostic analytics, data must be examined to answer the question "Why did it happen?"; techniques such as drill-down, data discovery, data mining, and correlations are used to take a deeper look at data to try to understand the causes of failures and behaviors. In prognostic analytics, data-based approaches are gaining ground, especially when the system is extraordinarily complex and the development of a model with more accuracy is prohibitive in economic terms. The disadvantages of this approach are that it has a wider confidence interval than other approaches and needs a high amount of data to train the model. Data-based approaches can be divided into fleet-based statistics and sensor-based conditioning. Both include modeling the accumulated damage (or, equivalently, health) and then extrapolating to a threshold of damage (or health), or directly calculating the remaining useful life and its impact on total life cycle costs [10]. The objective application of the LCCA techniques will allow organizations to efficiently select their physical assets with a lower level of uncertainty, contributing to not to fall into the simplicity of selecting their assets taking into account only current trends "fashion of the moment", a scenario that today is it repeatedly, especially in the process of justification of the various tools proposed by the so-called Industry 4.0.

For these reasons, it is of the utmost importance within the process of analysis of life cycle costs of the assets evaluate and analyze in detail all aspects related to the economic impact of reliability and maintainability factors. In the near future, it is believed that the new evaluation proposals for reliability costs in LCCAs will take advantage of development in the field of mathematics and it will be used methods such as:

- Industry 4.0 Techniques: digitalization, internet of things, intelligent monitoring, etc.), see [8], [10], [11], [17], [26].
- Advanced techniques of statistical analysis of Reliability: see [5], [10], [23], [31], [6].

Finally, these methods will have their particular characteristics, since it is not feasible to develop a single LCCA methodology that covers all the specifications and technical requirements. However, it is necessary to include within the current methodologies of LCCA models that allow estimating the impact of reliability, being able to reduce the level of uncertainty in the process of evaluating total expected costs in the useful lifetime cycle of a production asset.

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