Optimizing Spare Parts Inventory and Logistics for Maximum Plant Uptime in the Energy Sector

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***Abstract*— Equipments play a critical role in Oil & Gas (ONG) operations. Failure of their proper and efficient functioning has direct and significant bearing on plant uptime, energy output and supply chain (SC) stability. This article delves into the mechanical failure modes and predictive maintenance techniques, to enhance spare part forecasting. It establishes the usefulness of predictive analytics in deciding optimum spare parts inventory levels necessary for ensuring cost rationalization for balancing operational cost and efficiency. The article focuses on the application of sophisticated technology for achieving maximum plant uptime.**

***Keywords*—** *Supply Chain, SCM, Spare Parts, Inventory Management, Optimization, Equipment, Mechanical Failure.*

1. Introduction

Maintenance of oil & gas operation is a complex and difficult job. The industry is dependent on a very wide and elaborate network of machinery comprising offshore drilling rigs, onshore extraction equipment as also pipelines and refineries - each and every one carrying out operations under extreme conditions. The smooth operation of equipment and machinery becomes essential to ensure unspoiled functioning of this intricate mesh of the oil and gas supply chain. The reliability of critical assets is of paramount importance in the seamless and efficient operation of the supply chain. However, unforeseen breakdowns and component failures can compromise this reliability.

Availability of right spare parts at the right time and in conformance to quality standards is indispensable in ensuring operational continuity and in maximizing uptime [1]. Since every minute of downtime is equivalent to production loss which means lower productivity, delays in projects and product deliveries, therefore, have an adverse financial impact [2]. Therefore, the article focus on ways and means to maximizing plant uptime. The article draws data and concepts from various published literary works spanning across books, articles from peer-reviewed journals as IJSCM, reports published by renowned organizations such as McKinsey, national and international newspapers, business dailies. Charts and diagrams have been used for easy illustration of statistics.

2. Literature Review

A very common incident in the oil and gas industry is mechanical failure which is the straightforward outcome of operating under harsh conditions and high pressure, regular use of corrosive substances, and employment of complex machinery in the complete process of extraction, transportation, and processing of oil and gas. This makes regular scrutiny, supervision and maintenance crucial for avoiding equipment breakdowns [3]. Spare parts inventory is maintained to help respond quickly to any mishap that is taking place or has a high probability of occurrence.

The term "spare parts", in the oil and gas industry, refers to components that are kept at hand and are readily available for quick repair or replacement of equipment that are malfunctioning at the time of a mechanical failure.

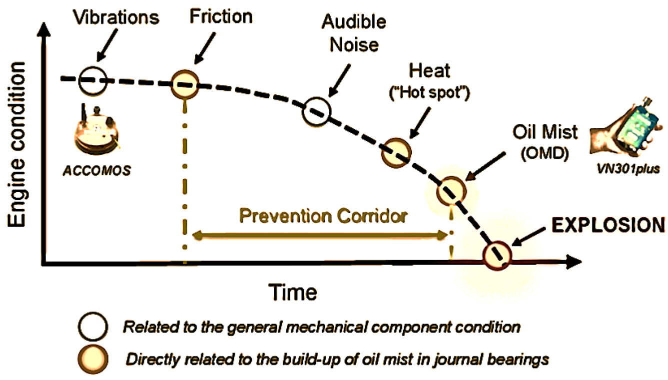


Figure 1: Sequential Development of Mechanical Failures Over Time [4]

As evident from the above figure, there occurs a sequence of events before mechanical failure reaches the stage of causing any major damage such as an explosion or any other serious accident that could cause loss of life and operations ultimately leading to mammoth financial losses. Early detection of a mechanical failure, therefore, can help to avoid such eventualities but the key concerns are proper and timely detection and the availability of appropriate spare parts necessary for repair or replacement.

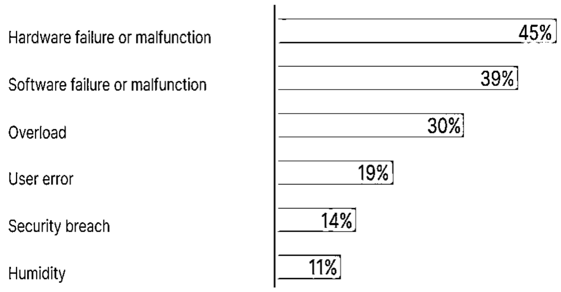


Figure 2: Causes of Unplanned Downtime [5]

Hardware failure being the key cause of mechanical failure, maintenance of an inventory of necessary spare parts assumes key importance in the smooth operations of an oil and gas business [6].

Deepwater Horizon oil spill in 2010 is a prominent real-life example of a mechanical failure. A failure of a blowout preventer (BOP) - a critical safety device designed to prevent uncontrolled oil flow in case of an emergency. Its faulty mechanism led to massive crude oil spillage into the Gulf of Mexico resulting in significant environmental damage and loss of life [7]. An early detection could have prevented it.

Other, more recent incidents of mechanical failure include

- In June 2022, a mechanical incident following an officially required water pressure test at the OMV Schwechat Refinery in Austria caused significant damage to the main crude oil distillation unit [8].
- In September 2022, a fire and explosion at the BP-Husky Toledo Refinery in Oregon, Ohio caused loss of tow lives and $597 million in property damage. Investigators identified violations of process safety rules and inadequate training of workers [9].
- In July 2023, an explosion and fire on a glycol unit occurred at Dow's Louisiana Operations' Glycol 2 plant in Plaquemine, Louisiana [10]

2.2 Criticality of Spare Parts

For an oil and gas enterprise persistently, rising oil and gas prices cannot act as a reliable source of sustainability for their on-going projects. This does not imply that profitability is not attainable. Rather it means that rising prices are not the single source of profitability and sustainability. Profitability can be boosted, at least in parts, by enhancing efficiency rather than the volume of production. Towards this end, the oil & gas players are concentrating on ways to enhance their assets efficiency and improve their operational excellence. Procedures SUH AS industrial cleaning can result in costs rationalization which helps the company to remain competitive. When it comes to enhancing efficiency, equipment maintenance is of utmost importance amongst all the projects. It is specifically important and is indispensable for a host of expensive equipment including drill pipes and elevators. Equipment maintenance also provides significant economic opportunity. When executed well, equipment maintenance helps companies obtain a level of operational efficiency that allows the company to navigate successfully through volatile oil markets through the extension of their equipment lives [11]. The repair and maintenance activities require the easy and smooth availability of spare parts. Herein lies the importance of spare parts inventory management (SPIM). It helps to rationalize costs while ensuring timely availability of the specific spare parts that conform to quality and safety standards.

Spare parts play the crucial role of assuring maintenance of efficient operational conditions at the plants and at the offshore platforms. Approximately 200K sundry items are retained in a number of inventory plants [12, 13]. The criticality of spare parts is understandable from the risk that they pose on the operation of the enterprise. The insufficient availability of spare parts or the availability of spare parts that are of inferior quality or the delay in the availability of spare parts have significant bearing on the operational aspect of a plant. It decides the reliability of the oil and gas supply chain and its sustainability. Both aspects are of crucial importance in the modern energy-hungry world. The improper or inadequate availability of spare parts also accentuates the dangers of mechanical failure causing the delay in the resumption of normal functioning. Inventory management is essential as the cost of missing a critical piece can well surpass its cost of storage. The common control tools may often turn out to be less than sufficient to control spare parts inventories [14].

2.3 Impact of Mechanical Failure

Ensuring superior operational efficiency and maximizing productivity in the dynamic and composite world of the oil and gas industry, demands effective asset management. The presence of and management of large volumes of obsolete spares often poses a significant challenge to efficient SPIM. This critical area must never be overlooked for the simple reason that the cost of overlooking can be daunting – there is significant financial loss associated due to increase in plant downtime, compromised safety, and its obvious fall out - hindered efforts towards sustainability.

2.2.1. Plant Downtime

Downtime is often considered as akin to death of the bottom line of an oil and gas company [15]. The two main causes of unplanned downtime are aging equipment and mechanical failure. In fact, the former one could be the root cause of the latter, which again highlights the need to maintain an optimum level of necessary spare parts inventory.

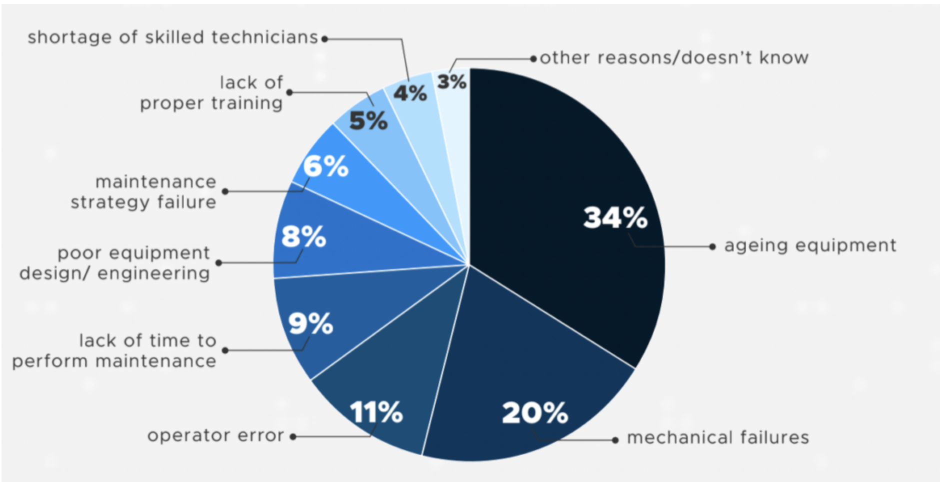


Figure 3: Key Causes of Unplanned Downtime [16]

Each year, an average oil and gas company would go through a minimum unplanned downtime of 27 days, which approximately costs the company $38mn [17].

Even when the downtime takes just about 3.65 days, the consequential losses can reach as high as $5mn [15] which proves that even a very short interval of unplanned downtime has the potential to cause significant financial damages [18]. For instance, say the rig has a yearly turnover $500 million, in that case even 1% annual downtime or simply 3.65 days of unplanned downtime per year, a statistic that is exceptional by industry standards, would result in an adverse financial impact of more than $5 million [5, 19]. By reducing unplanned downtime Malaysia-based Petroliam Nasional Berhad (PETRONAS) saved US$17.4M in a year [20].

During 2021-2022, there has been more than 76% surge in the downtime costs in the oil & gas industry with the figure touching $149 million per site during the same period [2]. To curb the devastating impact of such financial consequences, oil & gas enterprises generally follow the practice of allocating 30-40% of their annual budgets for maintenance of equipment and at strengthening reliability efforts [2]. This further substantiates the volume of investment that goes into maintenance activities and the need for efficient spare part inventory management.

22.2. Disruptions in Energy Output

In the energy business, downtime in the plants is a general occurrence because of harsh conditions in which they operate, general wear and tear, corrosion, and fatigue, that frequently impact components such as pipes, valves, pumps, and rotating machinery. This leads to mechanical failure and potential production disruptions in the absence of ready availability of necessary spare parts at the right moment.

Equipment such as gas turbines must undergo regular maintenance to ensure reliable and consistent performance. Once a problem is identified during turbine operation or inspection for maintenance, identification and implementation of an optimal and effective solution often requires significant engineering work.

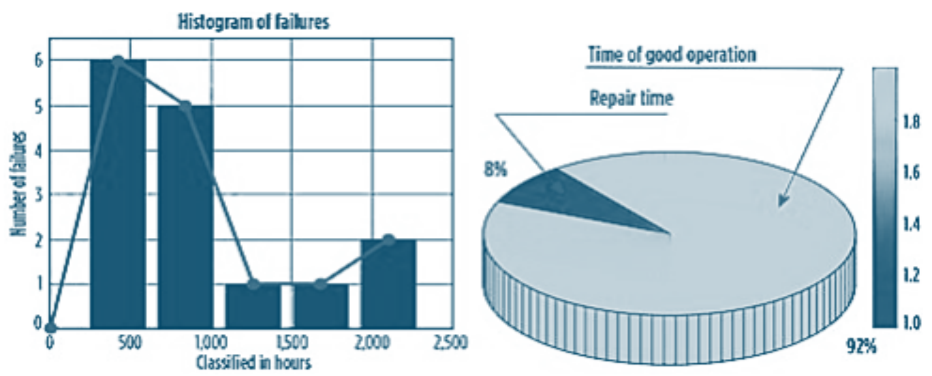


Figure 4: Failures by classes (in terms of Hours) & Uptime vs. Repair Time in General (%) [21]

A study of the history of functional failures and shutdowns of the turbine over a period of 2 years revealed that in general a gas turbine was halted 15 times within a span of 2 years for general cleaning, and the key reason behind such stoppage was exposure to harsh climatic conditions [21].

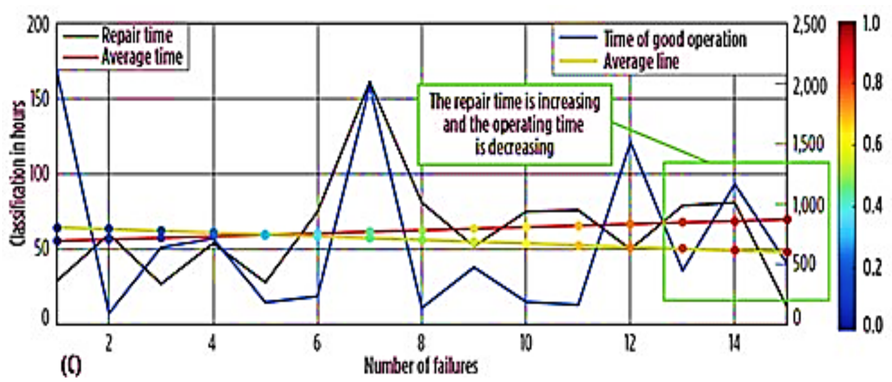


Figure 5: Statistics Study on the History of Breakdowns [21]

3. Spare Parts Inventory Management (SPIM)

As the foregoing sections suggest, management of optimum levels of spare parts at owned or occupied warehouses where they can be easily accessible without much delay is a necessity for smooth functioning of any oil and gas enterprise. The objective is to maintain a lean and economically viable supply chain, lifeline of any business, which in turn will offer competitive edge [22].

The unique nature of spare parts demand differentiates its supply chain from the supply chains of other items. Spare parts demand is not only uncertain but is extremely inconsistent along with the need for significantly high service level [23]. Additionally, spare parts management involves handling and supervision of a significantly large number of dissimilar items, with each generally having a different procurement lead time, lot size, and safety stock, making spare parts forecast and inventory management extremely difficult [24]. Companies, hence, frequently focus on identifying and maintaining the optimum inventory levels, since its maintenance leads to handling significant outlays [25]. The identification and implementation of effective inventory policies can help managers improve the SC system through reduction of both the out-of-stock and inventory levels. Companies, thus try to reach the optimum level of spare parts inventory.

3.2 Maintaining Optimum Spare Parts Inventory

In most of the manufacturing companies, SPIM is a critical process with a strategic significance, and involves handling a sizable number of very different items. The importance of maintaining an optimal level of inventory has already been elaborated in the literature review section. Maintenance spare parts shortages can cause significant problems for the firm, sometimes even leading to operational disruptions. Conversely, excess inventory generally causes enlarged storage costs and even adverse financial consequences as their monetary value diminishes over time due to both physical depreciation and financial inflation [26].

However, prediction or calculation of optimum inventory is not an easy job with a large number of variabilities involved. Efficient SPIM requires accurate demand forecasting, application of inventory optimization models, effective supply chain management (SCM) strategies, and appropriate data analysis techniques. Through their implementation a company endeavors to strike a balance between demand variability and inventory levels, thus curtailing stockouts while reducing excess inventory, and in the process optimizes financial resources. This further leads to enhanced operational efficiency, cost reductions, and superior customer satisfaction thus ensuring timely availability of accurate spare parts for maintenance.

3.3 Maintain Supply Chain (SC) Stability

Characteristics of the ONG industry is completely different from common industries since the final product of this industry is extracted from a raw material, and is not manufactured. The industry is involved in a global SC encompassing transportation (domestic and international), ordering and visibility and control of inventory, handling materials, export-import facilitation and information technology. It is a world-wide supply industry.

However, this sector’s general process chain being usually found in difficult-to-access far-flung areas, tend to get impacted by preventive or emergency maintenance problems in prospecting equipment causing interruptions in the extraction process due to the failure of parts of a specific machinery. Hence, the maintenance teams will always want that spare parts for replacement are readily available and accessible. Sometimes they demand machinery replacement parts whose quick supply is problematic and often have high manufacturing cost if conventional methods. Sometimes, replacement parts can’t be manufactured using conventional methods due to obsolesce. Their dearth invariably causes delays in both preventive and corrective equipment maintenance [27].

SPIM, therefore, becomes indispensable. It plays a critical role in maintaining supply chain stability by ensuring that necessary components are readily available to quickly repair equipment breakdowns, minimizing production downtime and disruptions to the overall operational flow, especially in industries where machinery is crucial to production processes. Speed is of essence here. Quick responses to faults / malfunctions can avoid safety protocol compromise – a key consideration in maintaining seamless supply chain. Spare parts are crucial to ensuring the safety of life and property by maintaining system integrity [28]. Spare parts inventory entails upfront investment outlay, but is a cost-effective long-run strategy that mitigates or minimizes downtime cost and emergency repairs expenses. Expedited shipping of critical components can significantly overshoot the cast of spare parts inventory maintenance.

3.4 Integration with product life cycle management

Failure modes in the oil and gas industry encompass cracking, distortion, fracture, fretting, and damage from exposure to heat and corrosive elements. Integrating SPIM with product life-cycle management allows inventory optimization that helps in efficient maintenance planning throughout the equipment's lifespan thus limiting the problems arising from obsolesce. This gives the company sufficient time to plan and execute replacement and not rush into undertaking substantial financial commitment without considering pros and cons. Failure analysis is, therefore, conducted as part of the life-cycle management of a system, structure, or component [29].

4. Discussion

4.2 Failure Analysis & Prevention

For making informed selections of repair strategies to mitigate risk of future failures it is essential to understand the genuine cause behind a failure. Success of failure analysis heightens its potential to reveal the defects in a system design or a component, assembly slipups, and production flaws. It can also reveal problems of material imperfections or its improper processing, service irregularities or maintenance predicaments as also detect unintentional or involuntary factors [29]. Reliability-based maintenance (RBM) and strategies based on failure analysis help achieve maintenance optimization. Predictive maintenance (PdM) is considered the most trusted strategy for reduction in downtime and failure probability but RBM the best in providing total equipment effectiveness [30].

The efficiency of this design has been established by means of validation, across all filling levels under North Atlantic conditions, using only standard foam reinforcement (without the requirement for high-density foam). Cost reductions and improvement in the Boil-Off-Rate (BOR) is achieved employing 100% standard foam. In addition to this, the adoption of double cargo tanks that are exactly similar contributes to cost efficiency besides streamlining operations. Similar kinds of potential have been discovered through the application of these principles in the design of novel state-of-the-art Bunker Vessels [18].

Care must also be taken for proper insulation of the tanks carrying the LNG. Use of membrane-type tanks that possess significant surface-to-volume ratio, which results in greater economic efficiency. For transporting LNG safely, these tanks are painstakingly designed to maintain the precise low temperatures and for prevention of any amount of LNG leakage [25]. Studies revealed that the most cost-effective solution, in terms of economic feasibility [26] and safety of LNG tanks, is the one in which the total use of mastic ropes was reduced by approximately 42% compared to the conventional manual design [25]. Optimization of LNG carrier allocation, LNG storage planning, and LNG transport planning, are essential for the minimization of the total cost of transport [27].

4.2.1. Use of AI-driven Predictive Analytics and Machine Learning (ML) to Anticipate Failures

Modern complex machinery and infrastructure consist of numerous components. The imperatives for swift response to equipment failures and minimization of production disruptions are ready availability of spare parts. Besides enhancing operational efficiencies, their preservation helps alleviate adverse financial consequences of unexpected maintenance activities and accidental downtime. Complete assessment of business processes and machinery assets is the foremost step of a sound condition monitoring strategy. Prevention is always better than cure for that it is best to have a proactive strategy for plant-wide condition monitoring. Quick response and downtime reduction also demand diligent equipment monitoring across locations is essential. Oil and gas transportation and refining has become more sophisticated over time and with the evolution of smart devices, generating massive volumes of machine data that can be mined for information and allowing the use of Artificial Intelligence (AI) for predictive maintenance [15].

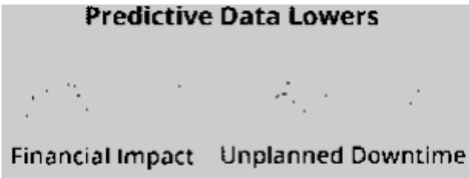
Using AI, ML, and advanced analytics, sophisticated predictive maintenance technologies can identify problems and pre-emptively alert relevant technicians to avoid equipment failure and safety risks [17]. A McKinsey report says that predictive maintenance solution has been used by an offshore oil and gas company for 20% reduction in downtime which beefed up production, annually, by over 500,000 oil barrels [31, 17]. Asset-intensive industries such as Oil & Gas are increasingly turning towards novel and sophisticated technologies in their strive to achieve greater reliability and their bid to ensure better availability of equipment and spare parts, to help rationalize and control the maintenance costs [31].

ML, natural language processing (NLP) and advanced analytics are used in ordering spare parts and its fulfilment. AI-powered image recognition systems examine spare parts photographs for their precise identification. Advanced data analytics allows efficient tracking and of spare parts inventory, enables future demand prediction allowing dynamic recovery of stocks [32].

4.2.2. *Leveraging Sensor Data to Predict Mechanical Failure*

PdM encompasses an assortment of methods that can detect early sign of any equipment problem, allowing maintenance staff and operators to take pre-emptive action. More sophisticated approaches analyze sensor data to predict failures through the identification of signs of identified failure modes. A range of advanced-analytics and machine-learning techniques are applied by the most mature of the PdM systems for identifying and categorizing issues and offering actionable insights to operations and maintenance personnel [31].

Information extracted from electrical connections of equipment, lubrication, thermography, ERP or asset management system and equipment history data, allow businesses to recognize patterns and spot likely issues. Predictive maintenance software uses this data to forecast impending failures. Rather than general statistics equipment-specific and depreciation data can help ONG companies establish equipment-based maintenance tasks [15].



As per data from U.S. Department of Energy, compared to reactive maintenance predictive maintenance saves over 40% and 8-12% compared to preventative maintenance. McKinsey's study shows that machine downtime could be reduce by 30-50% using predictive maintenance, increasing machine longevity by 20-40% [15]. Leveraging data for equipment failure forecasts, predictive analytics can optimize spare parts inventory permitting businesses to pre-emptively order essential components in anticipation, minimizing downtime. Accurate demand forecasting helps avoid maintaining unnecessarily large spare parts inventory. In essence, predictive maintenance strategies allow migration from reactive to proactive SPIM [33]. Big Data analytics unlocks patterns and associations hidden within massive raw data revealing opportunities for better outcomes [34]. Sensor data can help establish key performance indicators for critical elements and processes [35]. Regular audits, inspections, feedback, incident analysis can help evaluate performance against benchmarks which in turn can identify scope for improvement, ultimately avoiding downtime.

4.2.3. *Using Digital Twins to Predict Mechanical Failure*

A digital twin provides a dynamic, virtual representation of a system or physical object, simulating its behavior in real-time [36]. Visualization and advanced analytics aspects of this technology enables efficient operations [37]. Industry 4.0 makes virtualization of spare-parts possible which allows print directly from the platform or workstations [27]. Additionally, Digitization and 'Industrial Internet of Things' (IIoT) allows dynamic communication amongst production line layers [38]. The transformation generated applying Industry 4.0 in the oil industry reaches improves productivity [39], betters inventory control and data management thus improving overall business plan [40].

4 Recommendation: A Comprehensive Strategy is Best

Unless supervised before failure, uncollected data cannot be recreated post occurrence. All-inclusive condition monitoring strategy combines technology and domain expertise. A plant-wide strategy enables the application of the right blend of sensors, monitors, automated diagnostic software, portable, walk around solutions, service and training that best meets the corporate needs. Generally, an automated strategy is best to avoid human bias, lower overall cost and provide round-the-clock monitoring. A sensors suite can monitor different conditions and limitations of various machines. The costs are justified by the access to real-time data, and a factory-wide examination and monitoring of the healthiness of individual critical assets.

5 Conclusion

This article substantiates that maintenance is a key focus area to improve operational discipline. None can overlook the critical role played by maintenance in preventing costly disruptions, guaranteeing operational smoothness, and minimalizing unplanned downtime that can otherwise result from inaccessibility or unavailability of critical spare parts.

Real-time asset health and performance monitoring helps detect irregularities, driving action with advanced alerting. It helps to ensure safety, lowers emissions and rationalize petro-technical workflows, and extract superlative performance, thus enhancing reliability of upstream assets. AI-driven predictive analytics preempt incidents and minimize unexpected asset behavior enabling equipment operators and maintenance teams to quickly troubleshoot incidents.

This article also establishes the usefulness of predictive analytics in deciding the optimum level of spare parts inventory in order to ensure cost rationalization and in striking a balance between cost and efficiency. Maintaining spare parts inventory warehouse entails significant cost but the cost is worth bearing considering the gravity of financial consequences that would result from plant downtime, loss or property or equipment damage or loss of lives or environmental disasters that could result from mechanical failure at the plants.

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