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Performance Optimization of Crude Oil Barging Transportation

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***Abstract* - The effectiveness and safety of crude oil barging transportation is largely dependent on inland waterway transportation and the engaged mechanical systems. Mechanical systems breakdowns and logistical delays deter performance of tugboat propulsion systems. To improve the efficiency of crude oil barging operations, this study explored reliability analysis of tugboat propulsion components. Predictive maintenance methods, reliability engineering tools, and failure data analytics were jointly considered in a quantitative, exploratory-descriptive research approach. In this study, critical failure modes spanning shaft lines, couplings, and gear assemblies were identified and ranked using Failure Modes and Effects Analysis (FMEA). While, most parameters used for reliability measures such as Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and system availability were analyzed using ReliaSoftBlockSim and Weibull analysis, the correlation and root cause analysis approach were applied in the determination of the connections between component failures and important operational variables involving barge turnaround time, tug availability, fuel consumption, and mission delays.**

The key results of the study showed that failure of mechanical components leads to unscheduled operations downtime. The research offers a strong and significant performance improvement using redundancy and managing maintenance interval, in providing a data-driven roadmap for incorporating Reliability-Centered Maintenance (RCM) into marine logistics, especially in inland crude oil transportation operations. In addition, .a predictive maintenance framework based on vibration analysis, oil debris detection, and infrared thermography were handled using condition monitoring data.

Keywords: Optimization, Maintenance, Propulsion system, Reliability analysis, Barging operations, Tugboat failure.

I. INTRODUCTION

Transportation of crude oil from offshore production locations to refineries, storage facilities, and export destinations, mostly depends on a complex web of maritime logistics involving tugboat. Tugboats are essential parts of marine support activities that enhance smooth maneuverability of floating vessels. In narrow, crowded, or shallow waterways where the agility of larger vessels is limited, they offer vital services including towing, pushing, positioning, mooring assistance, and escorting huge oil barges and tankers (Drewry Maritime Research, 2020). These operations are particularly common in inland waterways, coastal terminals, and offshore platforms where careful vessel handling is necessary to prevent spills, collisions, and groundings.

Tugboats are usually assigned the duty of enabling the smooth movement of oil from offshore fields to terminals or refineries, either directly or through lightering operations, in crude oil barging operations. Thus, their performance and dependability are essential to maintaining the integrity of oil transport schedules and guaranteeing continuous logistics chains. Serious downstream repercussions, such as berth congestion, demurrage expenses, environmental risks, and supply chain operating bottlenecks, might result from a tugboat operation failure or inefficiency (Sambracos & Maniati, 2012).Inherently, tugboats operate in a tough and challenging maritime environment with frequent exposure to strong currents, wind shear, varying wave dynamics, huge tow loads. Overtime, the presence of wear and tear brought on by frequent engine restarts, high load cycles, and quick maneuvers remains part of the operational challenges (Sambracos & Maniati, 2012). Additional consideration is that tugboats usually run on strict schedules, they may have extended service periods with little time off for preventive maintenance. If these operational pressures are not proactively handled, failures of the tugboat propulsion, steering, hydraulic systems, towlines, and engine components become frequent (Almeida *et al*., 2015).

Tugboat failure can be caused by communication devices. These devices are susceptible to interference and exposure from the environment. Also, the failures are as a result of fatigue, corrosion, overheating, and lubricant degradation. Failure of these systems can lead to either a partial or total loss of maneuverability, endangering operational continuity, equipment safety and reliability. According to Modarres *et al*. (2017), that equipment requires to operate as intended under specific circumstances and for a predetermined amount of

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time without malfunctioning. Given the foregoing, the interdisciplinary relevance of reliability study on floating system is important to analyze in order to minimize failure and mitigate failures throughout the entire system lifecycle. Beyond analysis, Smith & Hinchcliffe, (2004), stated that reliability-centered frameworks like Total Productive Maintenance (TPM) and Reliability-Centered Maintenance (RCM) offer structured approaches to improve crew performance through standardization and training, maximize maintenance resources, and increase operational availability. For high-availability settings like the transportation of crude oil, these frameworks promote proactive maintenance planning, condition-based monitoring (CBM), and cycles of continuous improvement.

To forecast, avoid, and mitigate failures throughout the entire system lifecycle, marine operations employ quantitative tools including Weibull analysis, Failure Mode and Effects Analysis (FMEA), Mean Time Between Failures (MTBF), and Fault Tree Analysis (FTA).

The significance of tugboat dependability is further increased by the growing regulatory demands and environmental factors. Operators must make sure that their fleets are not just effective but also in compliance with the strict safety and environmental standards enforced by organizations like the International Maritime Organization (IMO). Unexpected mistakes that cause dangerous emissions or oil spills can lead to expensive fines, insurance claims, and harm to one's reputation (IMO, 2021).

The financial ramifications of tugboat performance issues are substantial from an economic standpoint. A single malfunction may cause crude supplies to be delayed, vessel turnaround times to increase, bunker fuel consumption to increase, and demurrage charges to be imposed by charterers or terminal operators. Reliability is no longer simply an operational issue but also a strategic necessity as marine logistics becomes more and more linked with just-in-time (JIT) supply principles (Chopra & Meindl, 2019).

The need for data-driven reliability models and performance optimization tools specifically designed for the maritime service industry is rising as a result of these dynamics. More sophisticated condition-based and predictive maintenance techniques are being made possible by the use of predictive analytics, Internet of things (IoT) sensors, and marine-specific Enterprise Asset Management (EAM) systems. However, foundational research that identifies baseline reliability criteria and performance indicators unique to tugboat operations is necessary before these technologies can be adopted.

Given the foregoing, the purpose of this study is to evaluate the dependability of tugboats involved in crude oil barging operations, with a focus on the Nigerian maritime oil logistics chain. By using quantitative dependability techniques to actual operational data, identifying failure patterns, and suggesting technical and financial viable strategic solutions. The gap between theories and practical was reduced drastically. With the ultimate goal of improving both dependability and efficiency in crude oil transportation logistics, the study also evaluated the suitability of modern performance improvement frameworks within this particular operational setting.

II. CRITICAL REVIEW OF CRUDE OIL BARGING OPERATIONS

Crude oil barging operations has been described as a very efficient and reliable way of crude oil transportation to the vessels, particularly using tugboats (Wang, T., & Meng, Q. 2012).These vessels perform critical functions such as towing, positioning, berthing, and providing emergency assistance especially in narrow, shallow, or environmentally sensitive waterways (Stopford, 2009; Drewry Maritime Research, 2020). As global energy demand increases, and operational environments become more complex, ensuring the dependable performance of tugboat systems especially propulsion components become a significant concern (Wang, T., & Meng, Q. 2012).

The tugboat propulsion system as a central performance aspect of the system where failures also occurs due to wear, shaft misalignment, lubrication issues, or thermal stress are among the most common causes of vessel downtime and failure rates has been handled in the literature (Willsky *et al.*, 2019; Almeida *et al.*, 2015). Scholar like Sanchez *et al.*, (2020), worked on mechanical diagnostics, and emphasized on the use of methods such as Failure Mode and Effects Analysis (FMEA), Root Cause Analysis (RCA), and condition monitoring techniques, including vibration analysis and infrared thermography for solutions.

Several other scholars carried out studies on Diesel engines, and found out that they are susceptible to tugboat overheating, component fatigue, and improper fuel-air mixing, leading to reduced power output and increased fuel consumption (Zio, E. 2009). The studies on challenges of Propellers and thrusters exposed to cavitation, fouling, and corrosion, which diminished hydrodynamic efficiency and compromised maneuverability were carried out (Zhang *et al.*, 2018), while Shaft and coupling components results in fatigue or structural failures in barging operation has been successfully investigated and root causes ascertained (Tung *et al.*, 2021). Recently, Smith & Hinchcliffe, (2004), researched

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on the shift from reactive to, preventive and reliability-centered maintenance (RCM) in the maritime for enhancing asset life, reducing costs, and minimizing unplanned downtimes. Also, Modern maritime practice to incorporate advanced technologies such as digital twins, Internet of Things sensors, and artificial intelligence for anomaly detection and real-time condition monitoring for informed decision making to improved operational metrics, including availability, turnaround time, and fuel consumption was addressed by Tao *et al*., (2019), without analyzing engine failures and its possible effects on marine engines. Effective failure pattern analysis on marine engines components for adequate maintenance management and optimization were studied (Al-Subaie. *et al* 2019).

III. RESEARCH METHODOLOGY AND MATERIALS

3.1 Research Framework

This research focused on minimizing tugboat subsystems failure rate, and improve the reliability for optimal crude oil barging performance operation. It employed the use of reliability software (ReliaSoft) as a computing tool for quantitative analysis in the reliability engineering to describe the data sources, and analyze the marine engine subsystem,

3.2 Research Design

This research was designed to tackle the operational and technological intricacies of tugboat reliability in crude oil barging operations by employing a quantitative, exploratory-descriptive design. The research emphasized appropriate systemic data collection and detailed analysis of reliability improvement on tugboat. Empirical failure data and system analysis were all integrated into a logical analytical framework in support of the research design, through interdependent phases. These phases comprise Failure Mode Evaluation and Reliability Assessment, Reliability Analysis Using Engineering Tools, Root Cause and Operational Impact Analysis, and Performance Optimization.

Using quantifiable engineering data, the quantitative component enabled objective study of downtime statistics, mechanical failure trends, and system dependability indicators. Where reliability studies were rare or unrecorded, like the Nigerian maritime industry, the exploratory-descriptive component facilitates the thorough characterization of failure mechanisms, underlying causes, and system behavior under actual operating settings. The study design is summarized in Table 3.1.

Table 3.1: Summary of Research Design Alignment

Research Objective	Research Design Strategy
Evaluate failure modes and reliability of propulsion components	Failure data collection, FMEA, downtime logging
Develop and apply reliability models using FMEA and ReliaSoft	Weibull++ life data analysis, BlockSim simulations, MTBF/MTTR estimations
Identify root causes of inefficiencies and their operational impact	Root Cause Analysis, correlation with performance metrics, downtime analytics
Propose optimized maintenance and performance strategies	

3.3 Materials and Methods

The materials used in this study include:

Data from the Company (Historical Maintenance Records), ReliaSoft, Failure Modes and Effects Analysis (FMEA), Microsoft Excel, and Weibull++.

3.4 Data Collection

This research gathered primary and secondary data that was specifically focused on tugboat engine mechanical subsystems (propulsion and steering) for its results and analysis.

The Primary data was collected through direct observation, interview with key personnel, and review of Maintenance and operation logs from selected tugboat operators in Nigeria’s inland and coastal terminals. Also, from equipment failure reports and downtime logs, fuel consumption and barge turnaround records.

The Secondary data was gathered by extensive review of existing literature in the subject area, industry reports and accessing academic journals.

3.5 Reliability Model

Considering that the study is focused on tugboat engine subsystems, the subsystem reliability were gotten from equation (3.1)

$$R_s = \prod_{i=1}^{n}\left(1 - \prod_{k=1}^{n}(1 - R_{ki})\right) \qquad (3.1)$$

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Where: R_{ki} is the reliability of the system k, R_s is the system reliability, and $R_{sub,j}$ is the reliability of subsystem j.

To actualize the subsystem's reliability, we applied equation (3.2)

$$R_{sub,j} = 1 - \prod_{k=1}^{n_i} (1 - R_k) \qquad (3.2)$$

Where n_i is the subsystem in parallel Considering identical component of the subsystem is obtained using equation (3.3)

$$R_{sub,j} = 1 - (1 - R_{ki})^{ni} \qquad (3.3)$$

Using ReliaSoft, Weibull++ and BlockSim method for the system reliability assessment and tugboat subsystem propulsion performance with Failure matrix, Mean Time Between Failures (MTBF), and system availability as various reliability measures. The components with higher failure rate were less reliable in accordance with the historical failure data as shown in Tables 3.2 and 3.3 respectively.

Table 3.2: Failure Data for Reliability Analysis

Component	Operating Hours Before Failure	Repair Duration Hours	Failure Mode	Failure Severity	Maintenance Type
Coupling 1	621.8	10.3	Misalignment	High	Corrective
Gearbox 1	143.4	5.8	Overheating	Medium	Corrective
Coupling 2	937.3	12.0	Misalignment	Medium	Corrective
Gearbox 2	1178.1	9.4	Overheating	High	Corrective
Propeller Shaft	1076.1	11.0	Fatigue Crack	Low	Corrective

Table 3.3: Reliability Indices of Tugboat Components

Component	Life (Hours)	Repair (Hours)	Availability (%)
Coupling 1	620	10	98.41269841
Gearbox 1	150	12	92.59259259
Coupling 2	930	9	99.04153355
Gearbox 2	1180	11	99.07640638
Propeller Shaft	1080	8	99.26470588

IV. RESULTS AND DISCUSSIONS

4.1 Failure and Repair Duration of Tugboat Components

The below figure presents component failure and the repair duration according to historical failure data. The gearboxes and couplings were likely to fail, with their repair times to exceed nine hours due to coupling misalignment and gearbox overheating. Both the frequency and the severity of these components were high. It presents the failure intervals (hours before failure) and repair durations of key tugboat propulsion components. The Figure highlights differences in reliability performance across components such as couplings, gearboxes, and the propeller shaft. By comparing the hours before failure with the time required for repairs, provides insights into both durability and maintainability of the propulsion system.

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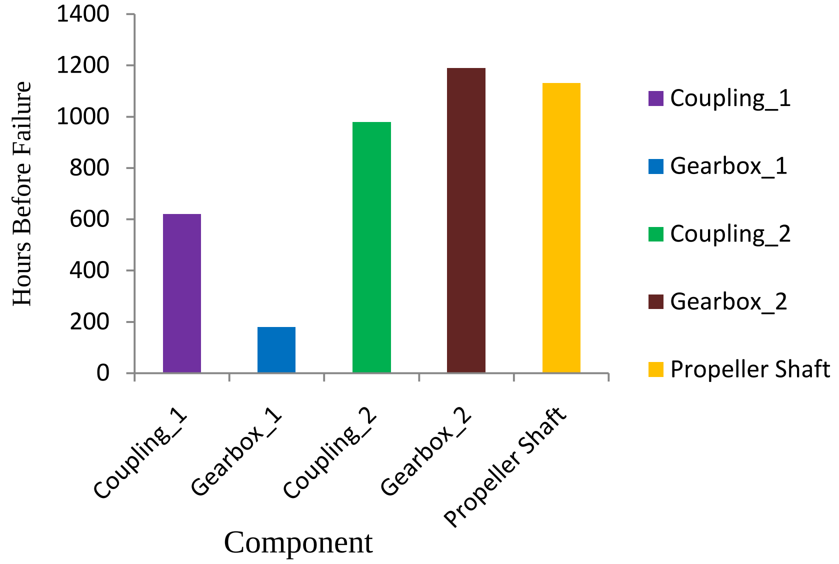

Figure 4.1: Failure and Repair Duration of Tugboat Components

Gearbox_2 and the Propeller Shaft demonstrated the longest operating intervals before failure, each exceeding 1100 hours, indicating strong reliability within the system. Coupling_2 also performed well, lasting nearly 950 hours before failure. In contrast, Coupling_1 showed moderate reliability, failing after about 620 hours, while Gearbox_1 link was the weakest. Failing in just ~150 hours to indicate that Gearbox_1 component poses a major concern for overall propulsion reliability. The repair durations for all the components were averaged between5 to 15 hours, except Gearbox_1, with very minimal repair time. Implying that Gearbox_1 poor performance was as a result of frequent failures, and not due to repair processes. Gearbox_2, the Propeller Shaft, and Coupling_2 are comparatively robust components with long service lives and quick repair times, making them reliable for continuous operations.

4.2 Component Life Duration (Operating Hours)

Figure 4.2 indicates critical tugboat propulsion components life duration, comparing total successful operating hours of each components prior to failure.

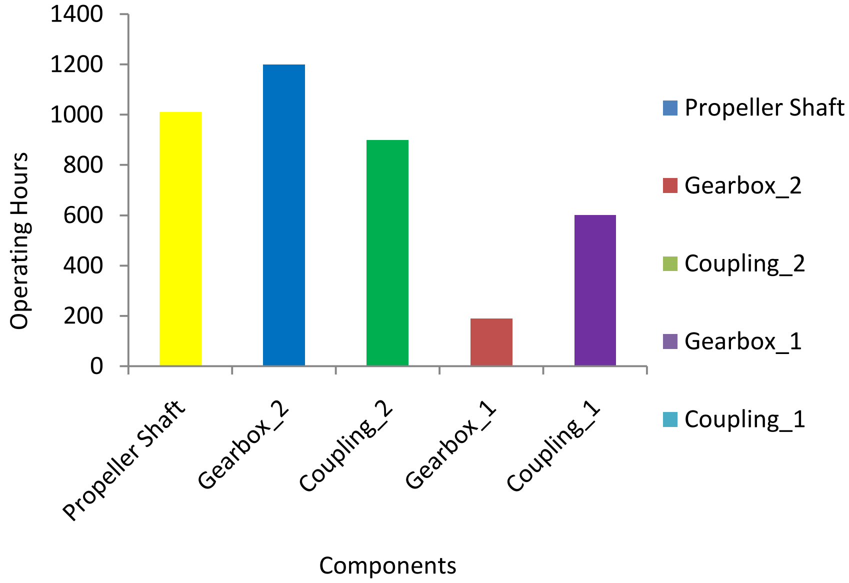

Figure 4.2: Component Life Duration (Operating Hours)

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Based on the result, the most reliable components of the tugboat propulsion system were Gearbox_2, Propeller Shaft and Coupling_2 with approximately 1300, 1,080 and 930 hours of operations. While Coupling_1 operated at around 620 hours, placing it in the mid-range of component performance, Gearbox_1 was the most unreliable component, operating for only ~150 hours before failure.

From a reliability standpoint, the result showed clear disparity between high-performing components such as Gearbox_2 and the Propeller Shaft and underperforming ones like Gearbox_1. Therefore, failure frequency and component life duration are strongly linked to system availability and overall propulsion efficiency. These findings support targeted interventions, such as prioritizing predictive maintenance and component redesign for Gearbox_1, while maintaining condition-based monitoring for other components with longer life spans.

This analysis supports strategic maintenance interventions and justifies redundancy for components with shorter life cycles. Refer to Table 3.3 with performance and availability of tugboat propulsion components data.Gearbox_2 and the Propeller Shaft achieved the highest reliability performance, with MTBF values of 930 hours and 1,080 hours, respectively. Their availability percentages, 99.08% and 99.26%, confirm their robustness and minimal disruption to tugboat operations. Coupling_2 also performed strongly, with 930 hours MTBF and 99.04% availability, making it a dependable component under operational conditions.

Subsequently, Coupling_1 demonstrated moderate reliability, operating for 620 hours before failure with an availability of 98.41%. In addition, it suggests that the component requires closer monitoring compared to the higher-performing Gearbox_2 and Propeller Shaft. The most critical finding is that Gearbox_1 emerged as the weakest component, with a significantly lower MTBF of 150 hours and an availability of 92.6%. Despite its relatively short repair time of 12 hours, the frequency of its failures makes it the primary source of downtime risk in the propulsion system.

Table 4.1: Operational Performance Data

Tug ID	Average Turnaround Time (hrs.)	Tug Availability (%)	Delayed Missions	Fuel Consumption (LPH)	Failures Per Month
TG-001	41.6	82.5	5	108.0	2
TG-002	34.5	87.7	2	117.2	3
TG-003	40.1	90.9	4	124.2	3
TG-004	33.8	75.9	5	111.7	0
TG-005	35.0	89.8	0	122.1	5

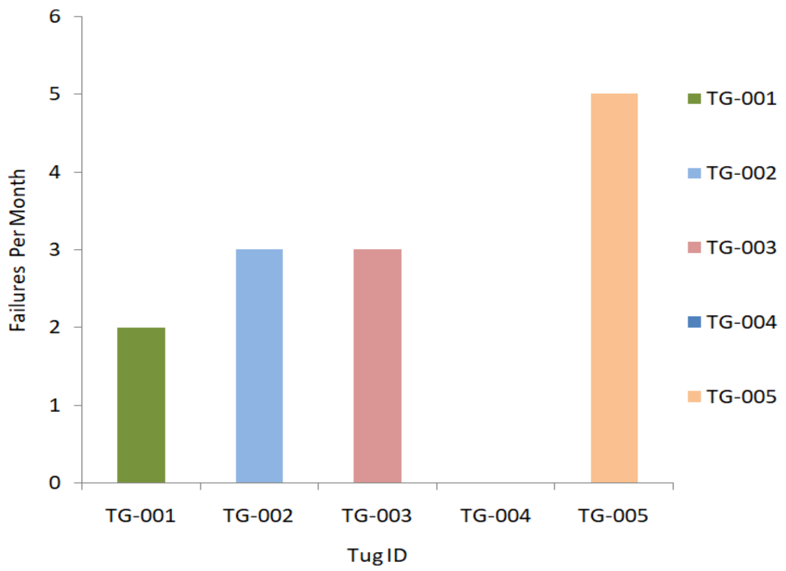

Figure 4.3: Monthly Failures per Tugboat

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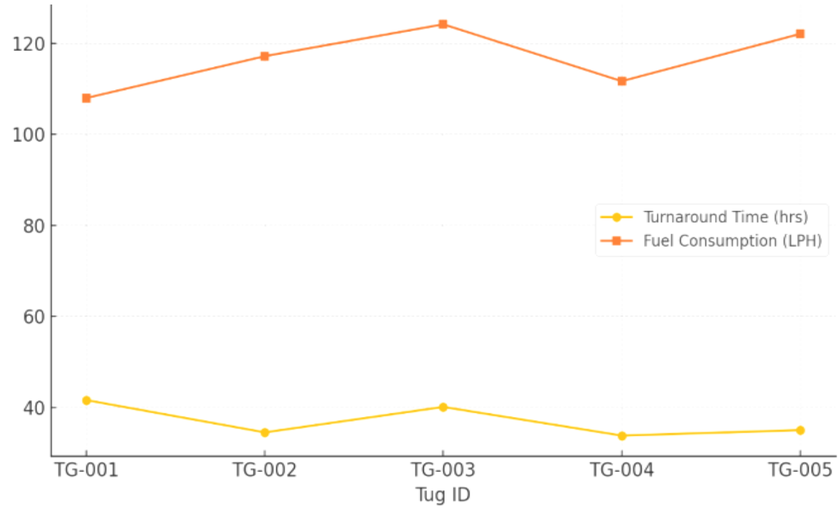

Figure 4.4: Turnaround Time and Fuel Consumption by Tug

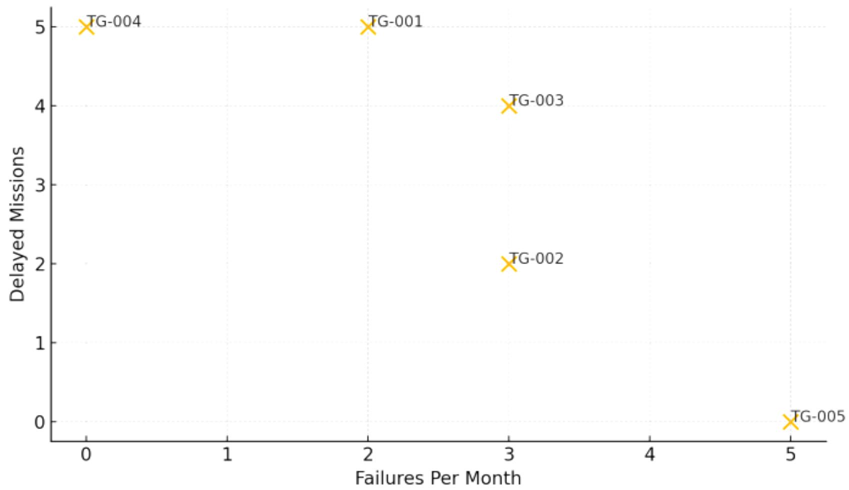

Figure 4.5: Correlation: Failures versus Delayed Missions

Figure 4.3, Considered Failure frequency and delayed missions for a substantial correlation (r = 0.68), according to correlation analysis. Frequent of breakdowns were also associated with longer turnaround times and increased fuel usage for tugboats.

The results from Figures 4.3, 4.4, and 4.5 collectively highlight the multifaceted operational impact of tugboat failures, efficiency gaps, and mission delays.

Failure Frequency (Figure 4.3) showed clear variability across the fleet, with TG-005 recording the highest monthly failure rate, while TG-004 recorded no failures. Intermediate performers such as TG-002 and TG-003 recorded three failures each, while TG-001 had two failures. These uneven distributions showed that TG-005 vessel impose a disproportionate burden on maintenance teams and operational continuity.

The turnaround Time and Fuel Consumption in Figure 4.4 was obtained from Table 3.3, and it revealed operational inefficiencies of TG-003 and TG-005 with high fuel consumption rate. Also, the experienced longer turnaround times, directly translate into higher operating costs. Conversely, TG-002 and TG-004 performed more efficiently, combining shorter turnaround times with moderate fuel consumption, thereby delivering more sustainable operations. TG-001 showed low fuel consumption but longer turnaround time, reflecting trade-offs between energy use and scheduling performance.

In Figure 4.5, the Failures against Mission Delays results obtained revealed that reliability issues are not always the sole drivers of delayed operations. Please refer to Table 3.3, TG-005, despite having the highest failure rate, experienced no mission delays, suggesting effective contingency measures, rapid repairs with allocation of redundancy within operations. In contrast, TG-004 experienced no failures but recorded five

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delayed missions, pointing to operational or organizational bottlenecks unrelated to mechanical breakdowns. Similarly, TG-001 had only two failures but recorded five delayed missions, while TG-002 and TG-003 showed varying degrees of correlation between failures and delays.

Taken together, these results demonstrate that operational impact is shaped by both technical reliability and management practices. Frequent failures increase the risk of inefficiency, as shown in TG-005, but effective recovery measures can mitigate mission delays. Conversely, organizational inefficiencies, as observed in TG-004, can undermine operational readiness even in the absence of technical faults. The analysis therefore reinforces the importance of a dual strategy: First, to improve reliability performance through predictive maintenance and engineering upgrades. Secondly, to address operational inefficiencies through better scheduling, resource allocation, and logistics support. In addition, these results affirm that propulsion failures significantly affect crude oil barging efficiency and logistics planning.

V. CONCLUSION

Conclusively, the dependability of inland tugboat propulsion systems and reliability approach to enhance performance in crude oil barging operations were effectively addressed, through combination of failure analysis, engineering reliability tools to achieve the project deliverables. Failure Mode Evaluation revealed significant level of susceptibility associated with tugboat sub-systems with respect to recurrent failures such as overheating and misalignment resulting in operational downtime and system unavailability. While relevant applied reliability analysis tools improved system reliability, the operational Impact Analysis demonstrated strong correlation between tugboat failures and performance inefficiencies, including increased barge turnaround times, mission delays, and high fuel consumption.

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