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Design and implementation of a pulley locking tool for the air fan cooling system to enhance maintenance safety at company XYZ LNG

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Abstract

This study addressed a critical safety and efficiency challenge in the maintenance of air fan cooling systems at company XYZ Liquefied Natural Gas (LNG), where technicians traditionally relied on unsafe manual methods, using bare hands and a wooden block to stop rotating pulleys. These practices, observed over a decade of operations, were identified as a leading cause of near-miss incidents, exposing operators to crush injuries, entanglement, and amputations. Motivated by the need for a safer, engineered solution, this research designed, fabricated, and implemented a specialized pulley locking tool. Developed through a structured engineering design process, the tool prevents direct human contact with moving components while aligning with modern safety management principles and human factors engineering. Field trials demonstrated a reduction in braking time from 20–30 minutes to only 4 minutes, along with significant ergonomic and psychological benefits reported by operators. The tool not only improved efficiency but also strengthened confidence in maintenance procedures. This work represents a practical intervention that transforms safety theory into application, providing a replicable model for other LNG facilities and industries with rotating equipment. The results highlight how engineered tools can simultaneously mitigate risks and improve productivity in high-risk environments.

Keywords:
Maintenance safety improvement; safety tools; workplace accident prevention

1 Introduction

Natural gas is recognized as a major clean energy source, with global consumption recorded at 3840 billion cubic meters (*bcm*) in 2020 and projected to reach 5625 bcm by 2050. To enable more efficient storage and transportation, natural gas is typically converted into Liquefied Natural Gas (LNG), which undergoes significant volumetric reduction when cooled to −160 °C [1]–[4].

Due to their large-scale operations, LNG plants consume substantial energy, making efficiency improvements crucial for reducing both natural gas usage and CO_2 emissions. Studies have shown that low-grade energy can effectively support absorption refrigeration under air-cooled conditions [5]–[8].

The production of LNG from natural gas involves multiple interdependent stages. One of the essential supporting processes is the cooling system. During the maintenance of the air fan cooler, a recurring issue observed is the windmill effect, characterized by reverse rotation of the fan pulley. Mechanical faults or brake system failures can lead to unintended reverse rotation, significantly increasing the risk of accidents for maintenance users.

In industrial environments, ergonomics and safety are interrelated factors essential to workplace health. Ergonomics focuses on designing tools and tasks to reduce physical strain, while safety targets hazard prevention. Integrating ergonomic principles into safety practices helps to prevent injuries and supports a more effective and holistic occupational health and safety system [9]–[11].

The creation of a safe work environment is consistently recognized as a persistent challenge in the industrial environment, as emphasized by the International Labor Organization (ILO). Although numerous studies have assessed workplace hazards, a comprehensive definition of safety applicable across all work environments is still lacking. Ongoing research continues to uncover a wide spectrum of risk factors, from visible physical dangers to less apparent but potentially more serious psychological threats [12], [13].

Proper maintenance planning plays a crucial role in ensuring equipment reliability by determining the most effective timing and frequency for preventive actions. Despite thorough planning, human error remains a significant challenge, often leading to flawed execution and increased operational costs. To address this, Human Error Probability (HEP) is used as a quantitative approach to evaluate the likelihood of errors occurring in specific maintenance tasks or systems [14], [15].

The evolution of safety management theories has significantly enhanced our understanding of workplace accident causation, particularly through the lens of systems thinking and human factors engineering. Heinrich's Domino Theory laid the foundation by emphasizing the sequential nature of accidents, where unsafe acts and conditions lead to injuries. However, modern reinterpretations of this theory have shifted focus toward systemic interactions, recognizing that accidents are not caused by singular events but rather by the dynamic interplay between people, machines, and organizational systems. This systems-based perspective is further supported by researchers, according to [16], who argue that understanding the complex relationships among system components such as human behavior, technology, operational processes, and organizational culture is critical for effective accident prevention.

Similar to the conveyor pulley shaft failure documented by [17], which arose from fatigue and inadequate maintenance, rotating components in LNG air fan systems pose significant mechanical hazards under improper operational conditions.

While previous frameworks emphasize the interplay between human behavior, technology, and organizational processes, the contribution of this study lies in its translation of those theoretical insights into a tangible engineering solution. By implementing an additional pulley locking tool in the air fan cooling system at company XYZ LNG, the research addresses a critical interface between human interaction and machine operation. Unlike purely analytical models, this tool mitigates risk by physically preventing unsafe manual engagement during maintenance tasks. This approach reinforces modern human factors engineering principles by not only considering operator behavior but also reshaping the task environment to guide safer actions, thereby operationalizing systems thinking into a practical safety enhancement in the LNG sector.

The effectiveness and optimization of safety practices in industrial environments are profoundly influenced by human factors, encompassing both behavioral and psychological dimensions. According to recent findings in [18]. The Behavior-Based Safety (BBS) approach highlights the importance of individual behavior in accident prevention, suggesting that an employee's perception of risk and adherence to safety procedures directly impact safety performance on-site. In the context of the company, where maintenance procedures involve high-risk activities, such as halting rotating equipment, these human factors become especially critical. Unsafe actions such as manually stopping the air fan cooler pulley exemplify how inadequate behavioral safety measures can escalate risks. Therefore, integrating behavioral safety principles with engineered safety solutions, such as the additional pulley stopping tool, can substantially reduce incidents caused by human error and promote a safer maintenance environment.

This research addresses a critical gap in mechanical safety practices by developing and implementing an additional pulley locking tool specifically for air fan cooling systems in LNG facilities. Its importance lies in providing a practical engineering solution to prevent unsafe manual intervention during maintenance, a common cause of operator injury. By translating safety management principles and human factors engineering into a tangible, task-level intervention, the study contributes to the advancement of applied safety engineering. It not only enhances operational safety but also supports the integration of mechanical design with system-based safety approaches, thereby offering a replicable model for risk mitigation in other high-risk industrial environments.

2 Research methodology

In relation to the previously discussed issues, a specific challenge in maintaining the air fan cooler system is the occurrence of windmilling, or the reverse rotation of the fan pulley. Initially, technicians attempted to halt this rotation using improvised methods, such as manually applying force by hand, as shown in Fig. 1 or using wooden blocks as shown in Fig. 2, which posed significant safety risks and lacked reliability.

Fig. 1. Stopping the pulley using the hand

Fig. 2. Stopping the pulley using a wood block

During the maintenance of the air fan cooler system, a critical safety issue was identified involving the use of improvised tools to stop the reverse rotation (windmilling) of the fan pulley. Technicians relied on non-standard methods, such as applying force manually or using wooden blocks, to stop the system. These tools were not intended for such purposes, resulting in extended maintenance times and creating significant safety hazards. From a safety standpoint, this practice clearly falls under both unsafe actions, defined as human behaviors that violate standard safety procedures, and unsafe conditions, which refer to the use of inappropriate tools and exposure to hazardous environments. According to standard industrial safety principles, workplace accidents are predominantly caused by these two factors. The use of inadequate tools not only compromised the effectiveness of the maintenance process but also exposed workers to an elevated risk of injury, highlighting the urgent need for a dedicated braking mechanism as part of a preventive safety strategy. Moreover, such conditions reflect broader systemic issues commonly encountered in industrial operations, where failures stem not only from human error but also from equipment malfunctions, harsh environmental conditions, disorganized procedures, and deficiencies in management systems. These factors often interact and compound, creating hidden, overlapping risks. As these hazards become interconnected, they can trigger a chain reaction of failures, amplifying small issues into more serious events through what is known as the butterfly effect. This emphasizes the importance of addressing root causes and implementing proactive safety interventions to break the chain of risk escalation [19].

From a time-efficiency standpoint, the maintenance of the air fan cooler at the company currently requires approximately 20 to 30 minutes solely for the braking process. This duration is considered inefficient; therefore, the integration of additional equipment is necessary to enhance the overall maintenance procedure. These findings are based on data collected through direct industrial observation conducted during routine maintenance activities.

2.1 Research methodology flow

The research workflow undertaken for the design and development of the additional tool for the air fan cooler is outlined as shown in Fig. 3.

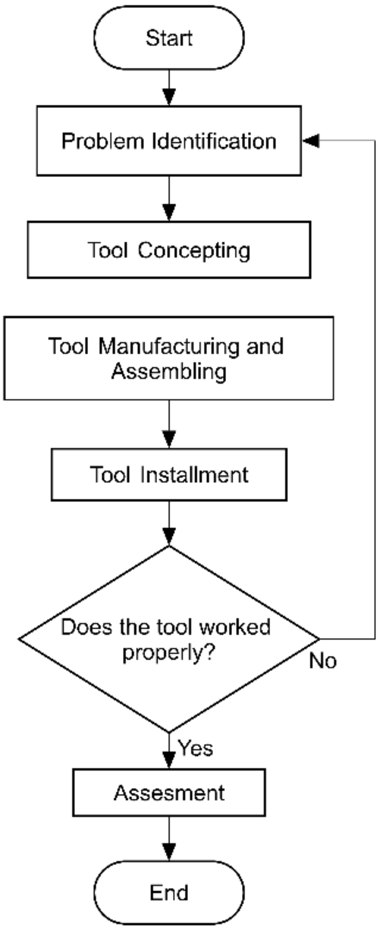

Fig. 3. Flowchart of research

The research process followed a systematic approach as outlined in the flowchart. It began with Problem Identification, where the specific challenge to be addressed by the tool was clearly defined. Next, the Tool Concepting stage involved generating and evaluating ideas to solve the identified problem. Once a viable concept was selected, the Tool Manufacturing and Assembling phase was initiated, involving the production and integration of components. The Tool Installation step ensured the tool was correctly positioned and ready for operational testing. The functionality of the tool was then verified through the decision point: Does the tool work properly? If the tool failed to function as intended, the process looped back to the Problem Identification stage for re-evaluation and redesign. If the tool operated successfully, the process advanced to the Assessment phase, where performance and objectives are thoroughly reviewed. The evaluation utilized time-based parameters, comparing the duration required to stop the air fan pulley without the additional tool against the time recorded when the tool was implemented. The process concluded at the end stage once all evaluation criteria, including the efficiency improvements, were indicated by the time reduction. The process concluded at the end stage once all evaluation criteria were satisfied.

2.2 Problem analysis

The braking process using a manual hand-operated system and wooden blocks, as illustrated in Figures 1 and 2, is highly time-consuming, typically taking between 20-30 minutes depending on the reverse rotation (windmilling) of the air fan cooler. Additionally, from a safety perspective, this braking method poses significant hazards. Therefore, this study aims to analyze and develop a solution that reduces the risk of accidents or injuries resulting from unsafe and inefficient working conditions.

Based on direct observations and data collected by site mechanics during routine operations and maintenance of the air fan cooler system over the past ten years, a Pareto diagram of accident risks was constructed, as shown in Fig. 4, to support and guide the subsequent analysis process.

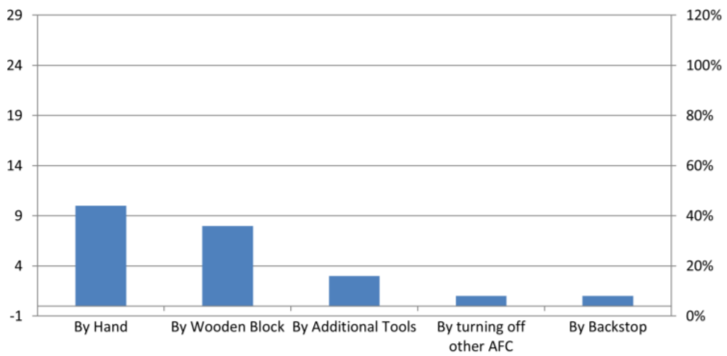

Fig. 4. Pareto diagram of accident risk

Stopping the pulley using bare hands poses the highest risk of injury, as human hands have limited strength and endurance to withstand the force of rotating equipment. Similarly, the use of wooden blocks introduces an unsafe condition, as the block can be dislodged or ejected unexpectedly, potentially leading to hazardous incidents.

In the absence of appropriate mechanical safety tools, operators working near rotating components such as air fan pulleys are at risk of severe injuries, including crush injuries, entanglement, impact trauma, lacerations, and even amputations. Additional risks, such as musculoskeletal strain and friction burns, may also occur due to manual intervention during maintenance, especially when safety protocols or lockout mechanisms are bypassed [20].

The systematic identification of the contributing factors leading to the risk of working accidents during the air fan cooler braking process, a fishbone diagram was employed as shown in Fig. 5.

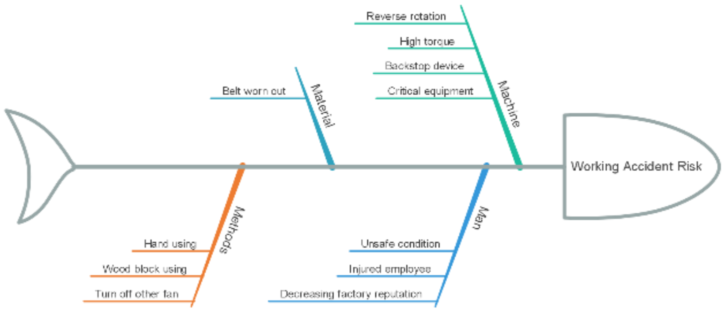

Fig. 5. Fishbone diagram of a working accident

Machine-related factors include reverse rotation, high torque conditions, lack of a backstop device, and the designation of the equipment as critical, all of which heighten operational hazards. Material issues were identified, such as worn-out belts that may compromise the braking system's effectiveness. Method factors encompass manual and unsafe braking practices, including hand use, wooden block application, and the need to shut down adjacent fan systems-actions that are both inefficient and hazardous. Man-related elements reflect human factors such as unsafe work behavior, the risk of injury, and the broader impact on organizational reputation due to workplace incidents.

3 Results and discussion

The human factor is the most important aspect concerning when the accident might happen. A study about statistics on the prevention of major industrial accidents showed that 15% of human injuries were caused while in the maintenance process [21]. Maintenance quality and effectiveness depend on worker competence, which supports better risk management. Improved communication also enhances risk management outcomes [22]. A preventive action to reduce the risk of injury during the maintenance process on the air fan cooler is designing an additional tool that is supposed to ensure there is no component still working, especially in the rotary part.

The implementation of the additional pulley locking tool in the air fan cooling system at the company represents a practical advancement in operational safety within the LNG industry. While prior studies such as [23], which applied TSA-GEO and ANFIS methodologies have focused on probabilistic modelling and system-level risk assessments, the present study introduces a novel intervention at the task-specific level. The designed tool directly addresses one of the most frequent and hazardous maintenance behaviors: manual pulley handling during shutdown procedures.

Experimental observations demonstrated a clear reduction in risk exposure during maintenance activities. The integration of the locking mechanism not only eliminated the need for direct manual contact with the rotating component but also ensured compliance with procedural safety protocols. This contrasts with the findings of James and Renjith, where the emphasis lies on forecasting and categorizing potential risks. In contrast, this study contributes a tangible, mechanical solution that prevents the occurrence of unsafe acts at the source.

3.1 Additional tool design concept

In mechanical drive systems, pulleys are essential components for transmitting motion and power. However, unintended pulley movement or slippage can occur during operation, potentially leading to decreased system efficiency and posing safety risks to both the machinery and operators. To mitigate these issues, an auxiliary pulley stop mechanism is proposed. This section discusses the conceptual design of the device, focusing on enhancing operational stability, improving energy transmission efficiency, and ensuring a safer working environment. The concept design is shown in Fig. 6.

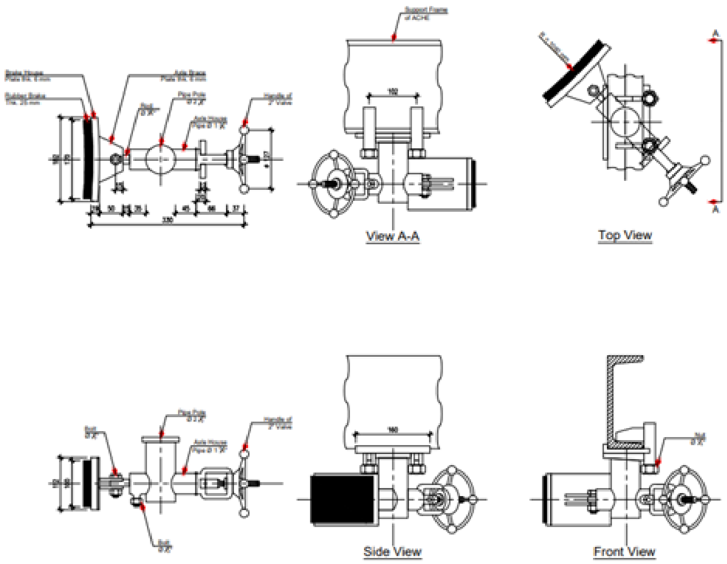

Fig. 6. Additional tool's concept

The auxiliary mechanism employs a brake pad as the contact interface to arrest the rotational motion of the pulley in the air fan cooler system. The braking torque is modulated through a rotary handle mechanically coupled to an adjustment shaft, enabling fine-tuning of the normal force applied to the brake pad and thereby optimizing both braking efficiency and operational safety. The tool would be installed as illustrated in Fig. 7.

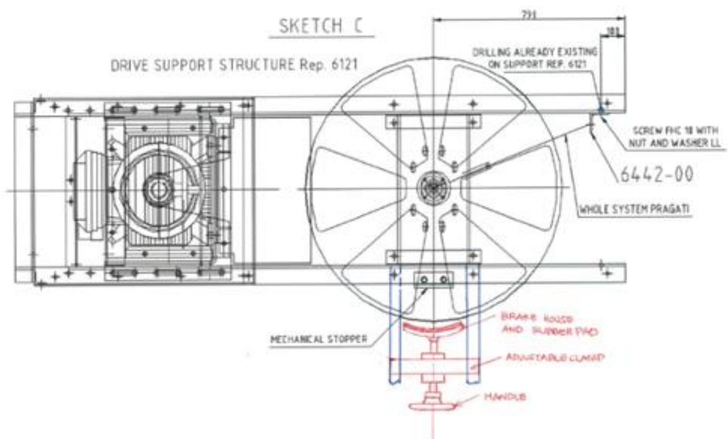

Fig. 7. Applicated tool concept

The materials needed for the manufacturing process are defined based on the parameters outlined in Table 1, which include material type, technical specifications, cost estimation, and descriptions relevant to the application.

Table 1. Bill of materials of pulley stopper

No.	Type	Specification	Price (rupiah)	Description
1	Round pipe	CS, Dim. 2 ½”	-	Stock
2	Round pipe	CS, Dim. 1 ½”	-	Stock
3	Sheet metal	CS, t=6mm	-	Stock
4	Handle	Gal. Dim. 6”	-	Stock
5	Threaded shaft	CS, M16	-	Stock
6	Rubber	EPDM, t=25mm	-	Stock
7	Bolts and nuts	M12x100	-	Stock
8	Welding wire	RD 260	100000	Purchase
9	Glue	SC 2000 + hardener	900000	Purchase
	Total		1000000	

3.2 Additional tool manufacturing and assembly

At the company, surplus materials from completed projects or construction activities are stored in a dedicated warehouse, despite remaining in good and usable condition. In support of material reuse and cost efficiency, technicians identified and repurposed suitable components from this inventory to fabricate the additional air fan cooler tool, following the bill of materials specified in the finalized design. The additional tool has been manufactured and assembled shown in Fig. 8.

Fig. 8. Manufactured and assembled the tool

3.3 Installment and observation

Upon completion of the manufacturing and assembling processes, the tool was installed on the air fan cooling system, as illustrated in Fig. 9.

Fig. 9. Installed tool

Following several maintenance activities on the air fan cooler, the researchers observed that, in the absence of a dedicated braking device, technicians resorted to manually arresting the pulley's rotation using a wooden block, a practice that, although functional, exposes operators to significant safety hazards. The company has cultivated a robust safety culture in line with international best practices, wherein near-miss incidents are rigorously analyzed and addressed before they result in harm. Although near-misses do not cause immediate injury, their systematic investigation enables the implementation of targeted corrective measures, thereby reducing the likelihood of future accidents, lowering accident-related costs, and improving overall worker productivity [9].

The researcher subsequently developed the following Standard Operating Procedure (SOP) to ensure safe and effective use of the additional tool:

1. Verify that the work area is secure and compliant with safety regulations.
2. Confirm that the pulley guard has been fully disengaged before installation.
3. Utilize appropriate installation tools, specifically a torque wrench or spanner, to ensure proper bolt tightening during special tool assembly.
4. During the braking process, rotate the handwheel gradually and continuously to prevent potential damage to the belt and pulley interface.
5. Once the pulley has reached a complete stop, promptly disassemble and remove the special tool to restore the system to its original state.

3.4 Trial and assessment

A trial phase is conducted to verify its proper fitment and operational readiness. This phase also includes a time study to quantify the duration required for the installation process, ensuring the tool meets functional and efficiency requirements for practical application.

During the trial phase, the researcher directly observed aspects requiring improvement. Notably, the braking process operated smoothly, quickly, and safely. The installation of the tool took 3 minutes, while the braking process lasted 1 minute. One key finding was the excessive weight of the tool, indicating the need for design modification. The result that has been collected and can be compared to the previous condition, while the pulley was braked manually, as shown in Table 2.

Table 2. Braking time comparison

No.	Braking medium	Time (min)
1	Human handling equipment	20
2	Additional tool	4

The application of an additional tool is five times faster than the previous method used. An additional tool also gave a safety guarantee to the technician during the maintenance process. The following points highlight the observed improvements resulting from the installation of the additional tool.

Despite the positive outcomes demonstrated by the implementation of the additional pulley locking tool, this study has several limitations that may influence the generalization and integration of the results. First, the tool was tested and evaluated exclusively within the specific operational and environmental conditions of the air fan cooling system at the company. As such, variations in system configurations, equipment design, or maintenance procedures at other facilities may limit the direct applicability of the results without appropriate adjustments. Second, the analysis primarily focused on qualitative risk reduction and time-based operational efficiency, while quantitative data on long-term failure rates, tool wear, or ergonomics under repeated use were not extensively captured. Furthermore, the study did not incorporate simulation-based modeling (e.g., finite element analysis) to assess stress concentrations or mechanical limits of the tool under abnormal loading conditions.

These limitations highlight several opportunities for future research. It is recommended that subsequent studies explore the adaptability of tool design across different types of rotating machinery and industrial sectors. Additionally, integrating computational analysis to simulate tool behavior under various load cases could strengthen mechanical reliability validation. Further investigation into the ergonomic and human factors performance of the tool, including operator usability, fatigue reduction, and behavioral compliance, would also contribute valuable insights. Finally, a cost-benefit analysis considering production scalability and lifecycle maintenance costs should be conducted to evaluate the broader industrial feasibility of the design.

4 Conclusion

This study developed and implemented an additional pulley locking tool to address critical safety risks and inefficiencies in the maintenance of air fan cooling systems at the company. The intervention effectively replaced hazardous manual practices with a reliable, engineered braking mechanism.

There are several key outcomes. The first is safety improvement, which eliminates reliance on bare hands and wooden blocks, significantly reducing the risk of entanglement, crush injuries, and amputations. The Second is time efficiency, reduced pulley braking time from 20–30 minutes using manual methods to only 4 minutes, thereby shortening overall maintenance duration. The third benefit is ergonomic and psychological, as operators reported greater comfort, reduced stress, and improved confidence during maintenance tasks. The fourth is to design refinement needs, although effective, the tool's weight requires optimization. Splitting the device into two parts is recommended to improve handling. The fifth is institutionalization to integrate the tool into the SOP to ensure consistent application and compliance with industrial safety standards.

Overall, the pulley locking tool demonstrates how task-specific engineering solutions can operationalize safety management principles while improving productivity.

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