Review

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Enhancing Turnaround Maintenance in Process Plants through On-Stream Phased Array Corrosion Mapping: A Review

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Abstract: This review paper aims to understand the current processing plant maintenance systems and further identify on-stream phased array corrosion mapping (PACM) to reduce turnaround maintenance (TAM) activity during plant operations. Reducing the TAM duration and extending the TAM interval are common goals of most researchers. Thus, a detailed review was performed to understand the maintenance systems and the problems faced. Furthermore, a review of the current PACM application and the possibility of applying it during on-stream inspection was also performed. PACM has better detectability for localized corrosion, and the results can be obtained for a range of thicknesses, which is the main advantage of this method. The challenge is to apply it to a surface with high temperatures, owing to the greater probe contact and the limitation of ultrasonic properties. This literature review provides a more precise direction for future research to evaluate PACM on piping that can be utilized in inspection during plant operation at elevated temperatures. Detecting and monitoring corrosion growth without shutdown.

Keywords: Non-Destructive Testing (NDT); Phased array ultrasonic testing (PAUT); Risk-based Inspection (RBI); Turnaround maintenance (TAM)

1. Introduction

Process plants are one of the topics that many researchers have devoted their time to exploring, with process plants covering a wide range of industries, such as petrochemicals, oil and gas, power plants, and food production. These studies address vital areas, such as the design, fabrication, and material selection of plant equipment, as well as construction procedures, testing requirements, safe operating practices, maintenance strategies, and overall operational efficiency [1–5].

This review explores the potential application of phased-array corrosion mapping (PACM) during plant operations to restrain the total turnaround maintenance (TAM) duration. By redistributing the inspection workload during TAM and ensuring the availability of spare parts prior to scheduled maintenance, the goal is to reduce downtime. This review was structured into two

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categories to provide a holistic perspective. The first category elucidates the diverse traditional maintenance strategies prevalent in process plants, thereby enhancing the understanding of maintenance terminology. This section also encapsulates the challenges researchers face in TAM and introduces diverse methodologies for enhancing TAM systems. Techniques such as assessment tools for optimization [6,7], questionnaire surveys [8,9], software aid development, and Risk-based Inspection methods [10,11] have emerged as effective approaches in this context.

The second focus area of the review deals with PACM, which is currently applied in plant inspection and maintenance. It also addressed the advantages and limitations of the proposed method.

An important insight from the reviewed literature is that researchers mainly share the common goal of minimizing TAM duration and extending TAM intervals, thus reducing TAM costs. A common solution that has attracted considerable attention is strategically shifting the TAM activity to on-stream inspections.

The PACM is gaining prominence because it can swiftly detect localized corrosion and cover larger scan areas in less time. However, it is challenging to apply this technique during on-stream inspections where elevated temperatures often exceed the recommended ultrasonic testing (UT) temperature limit of 52 °C [12]. Although success articles related to PACM applications exist [13–15], they mainly pertain to ambient temperature. An exception is the work of Turcu et al. [16], who introduced the use of a dual linear probe to conduct PACM experiments at temperatures of up to 150 °C.

This review underlines the growing inclination toward integrating on-stream inspections with normal plant operations to curtail the overall TAM duration. The efficacy of PACM in swiftly detecting localized corrosion reinforces its potential and underscores the need for further investigation.

Future research aims to evaluate phased-array corrosion mapping on piping typically joined by multi-bolt systems [17–19] that can perform inspection during the plant's operation (on-stream) up to 400 °C to effectively detect general and localized corrosion in the most common materials. Furthermore, it reduces TAM duration and extends TAM interval.

2. The Process Plant Inspection and Maintenance System

The world relies heavily on operational processing plants, encompassing vital sectors, such as petrochemicals and refineries, which provide essential petroleum derivatives for modern society. These plants form the backbone of many economies and serve as strategic reserves for certain nations, underlining their significance [20].

Optimizing efficiency, augmenting output, and mitigating power disruptions in refineries have been focal points of discussion among researchers. Maintenance is a critical factor for ensuring the seamless functionality of these plants. Various maintenance strategies can be deployed within petrochemical plants and refineries to improve equipment performance. These strategies encompass diverse methodologies, including preventive, predictive, condition-based, and proactive maintenance. Each strategy presents a distinct approach to equipment upkeep, encompassing regular maintenance routines, condition monitoring, and targeted interventions. Table 1 shows the interrelationships between the different maintenance strategies applied in the TAM. The selection of a maintenance strategy depends on the specific demands and prerequisites of a given plant or refinery. A judicious evaluation of the array of maintenance options is pivotal for determining the most optimal and resource-efficient path for maintaining equipment in its prime operational state.

Table 1. Description of maintenance strategies applied in TAM.

	TAM
RCM	Integration: TAM employs Reliability-centered maintenance (RCM) principles during turnarounds to optimize maintenance strategies. RCM identifies essential assets and failure modes, which subsequently impact the planning and execution of TAM tasks.

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CBM	Strategic Use: Condition-based maintenance (CBM) is implemented at TAM to evaluate the current status of critical assets in real time. The information derived from CBM is utilized to make informed decisions and perform maintenance actions that are precisely targeted.
TPM	Efficiency Goals: Total productive maintenance (TPM) principles are applied within TAM to maximize equipment efficiency during production. Turnarounds allow the implementation of TPM strategies, contributing to overall plant productivity.
PM	Scheduled Tasks: Preventive maintenance (PM) tasks are scheduled during TAM to prevent potential failures. The integration ensures that planned maintenance is executed efficiently, minimizing disruptions during production.
CM	Unplanned Maintenance: While TAM primarily focuses on planned maintenance, Corrective maintenance (CM) is included to address unforeseen issues discovered during the turnaround. CM tasks are executed efficiently to minimize downtime.
PdM	Predictive Insights: Predictive maintenance (PdM) techniques are employed within TAM to predict potential issues before they become critical. Predictive insights guide the planning of maintenance tasks, which optimizes resource allocation.
RBM	Risk Assessment: Risk-based maintenance (RBM) principles are crucial in TAM for prioritizing maintenance tasks based on risk assessments. Identifying high-risk components ensures that resources are allocated to address critical areas during turnarounds.

2.1. Clasification of Current Plant Maintenance Strategies

The criticality of operational efficiency and reliability cannot be overstated in the realm of processing plants encompassing domains such as petrochemicals and refineries. Maintaining the functionality of these plants is a pivotal challenge due to their role as economic pillars and strategic reservoirs. Researchers have delved into diverse facets of this landscape, exploring maintenance strategies, equipment optimization, and the intricate dynamics of operations [20].

A pivotal aspect of plant management is the maintenance strategy that is employed. Aghaee et al. [21] conducted a comprehensive study using fuzzy decision-making trial evaluation and laboratory (DEMATEL), dissecting various maintenance strategies. They identified corrective maintenance (CM), synonymous with breakdown maintenance, as an approach to address equipment failures. In contrast, preventive maintenance (PM) has emerged as a cornerstone strategy aimed at forestalling equipment malfunctions and forming a cornerstone of enhancement in maintenance endeavors [22]. Total productive maintenance (TPM) strategy has garnered considerable attention within this spectrum. It extends beyond equipment to encompass assets and personnel, thus portraying the evolution of PM [23]. TPM's core thrust lies in waste reduction, in alignment with the insights of Bataineh et al. and Chaabane et al. [24,25] Sahoo [26] explored the fusion of TPM and total quality management (TQM), and Kundu et al. [27] highlighted TPM's role in achieving world-class manufacturing objectives.

In the realm of strategy frameworks, reliability-centered maintenance (RCM) is a tried-and-true plan analysis approach. It establishes equipment requirements aligned with design and inherent reliability factors [28]. Risk-based maintenance (RBM) and condition-based maintenance (CBM) strategies are nested within the RCM [29]. CBM based on real-time condition monitoring has emerged as a linchpin approach for averting breakdown and preserving equipment integrity [30,31].

By seamlessly interweaving with various maintenance strategies, RCM demonstrates robust compatibility. Table 2 elucidates the nuanced interactions of the RCM with different maintenance strategies, whereas Figure 1 visually articulates the relationships between this methodology and renowned maintenance strategies.

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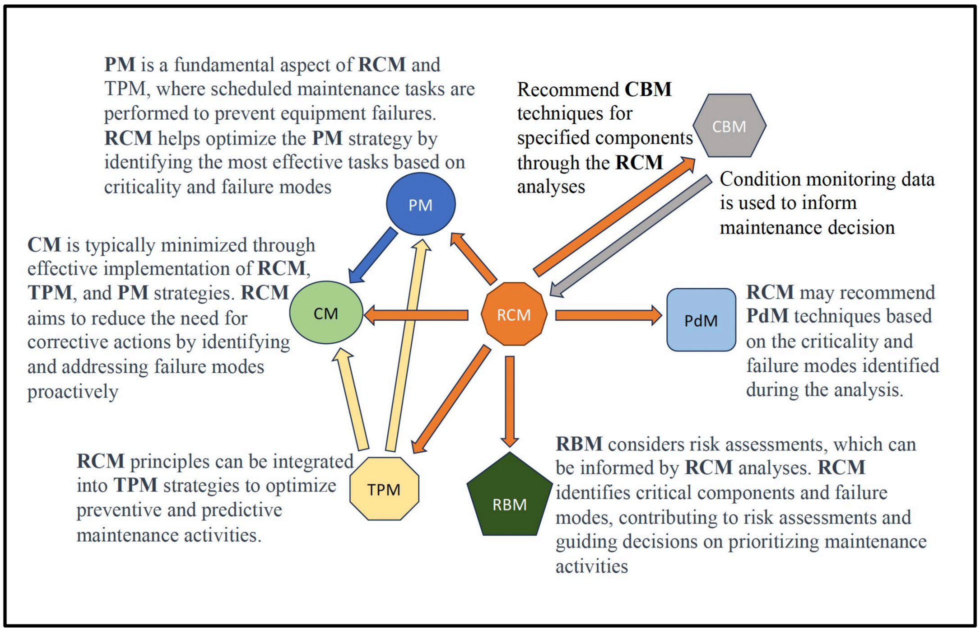

Figure 1. Visualization of interaction between RCM and maintenance strategies.

Table 2. Interaction of RCM with different maintenance strategies.

	RCM
CBM	Data Synergy: CBM data can complement RCM analyses by providing real-time condition data for assets identified as critical through RCM. This synergy enhances the precision of maintenance decision-making.
TPM	Optimizing Strategies: RCM principles optimize TPM strategies by identifying the most effective maintenance tasks for enhancing equipment reliability. The collaboration ensures a proactive approach to asset management.
PM	Task Optimization: RCM influences the optimization of PM tasks during both routine operations and turnarounds. PM tasks are selected based on RCM analyses, ensuring a targeted preventive approach.
CM	Reducing Unplanned Downtime: RCM aims to reduce the need for CM by proactively addressing potential failure modes. CM tasks become more focused and efficient, minimizing unplanned downtime.

Predictive maintenance (PdM) is an essential component of plant operation. This is an effective preemptive measure in the manufacturing industry, where operational failures can lead to market exit. Aghaee et al. [21] underscore its strategic value, positioned ahead of RCM, CBM, TPM, PM, and CM. This sentiment resonates with Tiddens et al. [32], who posited PdM as a preemptive replacement operation to thwart unforeseen breakdowns.

PdM, a form of CBM, tackles aging equipment before failure using sophisticated methods such as vibration analysis [33]. This approach curbs failure probabilities and minimizes inspection and repair costs by eliminating redundant maintenance. Although PM, PdM, and CM present opportunities for many processes, the complex nature of TAM occasionally necessitates comprehensive shutdowns [34].

Among these strategies, effective communication is crucial for orchestrating successful plant turnarounds. Ensuring clear and consistent information exchange across stakeholders (management, maintenance teams, suppliers, and contractors) guards against misunderstandings, enables timely equipment delivery, and ensures coordinated execution [35].

Considering the realm of condition monitoring, Dhandha [36] underscored the value of non-destructive testing (NDT) methods in assessing petrochemical equipment, accounting for damage type, defect size, location, and inspection method sensitivity. Meanwhile, Laza [37] drew attention to the underemphasized significance of piping systems. These systems, which are often overlooked, can yield catastrophic disruptions if left unchecked, thus necessitating a nuanced understanding of their complexities, inspection frequencies, and vulnerabilities.

Essentially, the intricate landscape of processing plants has been unraveled through these studies, spanning maintenance strategies, condition monitoring, and the imperative role of communication. As researchers have shed light on these domains, a holistic perspective emerges, guiding the path toward optimized, reliable, and efficient plant operations.

2.2. Improve TAM Efficiency by Conducting a Survey Questionnaire

TAM is a pivotal endeavor in the operation of diverse industries involving the convergence of resources, skills, and planning for repairs, inspections, and equipment enhancements [6]. Al-Turki et al. [20] explored over 80 pieces of literature comprehensively, aimed at unraveling trends and optimizing TAM strategies to curtail duration, human resources, and costs. Their study mapped out the four stages of TAM—initiation, preparation, execution, and termination–illustrating its complex and resource-intensive nature. In petrochemical plants, an eight-week process involving up to 4000 workers during peak periods is typical, whereas refinery TAM span 40 days every four years, requiring approximately 300,000 man-hours. Efficient planning, scheduling, and adept coordination have emerged as linchpin factors for this intricate landscape [20].

Scheduled shutdowns are paramount for mitigating the risks of unplanned plant mishaps. The ability to accomplish turnaround activities within predetermined timelines is pivotal because of the potential for significant financial ramifications in cases of delays. Hlophe et al. [38] probed the role of risk management in ensuring the success of plant turnarounds using a questionnaire-based approach. The study’s insights underline the direct link between effective shutdown risk management and the avoidance of considerable cost and time overruns. Project risk management is a widely acknowledged success factor for orchestrating turnaround shutdowns.

Delving into core challenges and crucial maintenance activities, Iheukwumere-Esotu et al. [39] conducted interviews and frequency analyses across diverse industries. Their findings illuminated the recurrent nature of labor-intensive and capital-demanding shutdowns, which often lead to delayed cost overruns and unfulfilled objectives. The demographic mappings of inspections, overhauls, replacements, and repairs complemented these observations.

Within petrochemical plants, the significance of turnaround activities is undeniable and is driven by the need for improvement, modification, repair, and maintenance. However, a sobering statistic reveals that a staggering 80% of turnaround endeavors fail to meet performance indicators encompassing time, cost, safety, quality, and environment. Akbar et al. [40] elucidate the intricacies of these situations, wherein a dense workforce environment can cause conflicts, accidents, confusion, and errors. Their study underscores the pivotal role of coordination and robust human resource management in achieving performance benchmarks.

Musah et al. [8] conducted a questionnaire-based exploration of TAM employees to examine their cultural values and their impact on ethics and conflict management. The findings revealed that successful conflict resolution is often tied to job compatibility and overshadowing of individual temperament. Similarly, Waratimi et al. [9] used survey-based journeys to assess TAM performance. Their study highlighted that many TAM activities frequently miss deadlines, with inappropriate contractor selection emerging as a leading cause of overruns.

Wongthong et al. [41] further emphasize the importance of astute contractor selection. This model, which involves factors such as cost, time, quality, flexibility, reliability, and human resources, underpins the need for reliability in TAM. Similarly, Mazumder et al. [42] surveyed company employees to determine the extended inspection and testing times during TAM activities. Their efforts aimed to identify areas for optimization to enhance efficiency and curb costs.

In the dynamic realm of turnaround maintenance, these studies collectively paint a vivid picture of the challenges, successes, and strategies, providing insights to guide efficient and effective plant operations.

2.3. Improve TAM Efficiency with Assessment Tools

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In the realm of TAM, continuous efforts are underway to enhance efficiency, streamline processes, and optimize outcomes. Wenchi et al. [43] embarked on a case study using a value stream map (VSM) to dissect TAM processes, seeking to unveil inefficiencies and root causes. Their exploration revealed inherent uncertainty in the turnaround process of the oil and gas industry, which leads to workflow fluctuations and waste accumulation. Nonetheless, this case study underscores the potential of VSM as a tool to pinpoint waste and enhance value, thus promoting TAM efficiency.

Unveiling the core factors influencing TAM performance, the Analytic Hierarchy Process (AHP) method revealed the significance of labor skills, communication proficiency, supervision gaps, transportation idling, and safety concerns [6]. A unique challenge in the TAM realm is the influx of new workers, who often lack comprehensive training or task familiarity, a situation exacerbated by the transient nature of TAM teams. This scenario often triggers simultaneous work within confined areas, exposing communication gaps, idling workers, and spare part shortages, culminating in budget overrun.

Fabić et al. [44] introduced a logistic regression approach to dissect intricate factors affecting success. This analytical method dissected the roles of leadership, teamwork, policy, safety, and strategy, highlighting their role in orchestrating efficient and productive turnaround processes. This study provides a profound understanding of the management elements that contribute to improved turnaround outcomes, fostering a blueprint for refining future turnaround management strategies.

The integration of technology into maintenance practices was the focus of Yin et al. [4]. Their innovative methodology gathered global data on maintenance activities, seeking to identify opportunities for technological solutions to streamline processes and reduce maintenance time. Their approach aimed to foster continuous improvement by implementing technology-based solutions, which showed the potential for automating tasks and increasing maintenance efficiency.

Turning the spotlight to plant shutdown turnaround, Muralidharan et al. [7] introduced an activity-analysis approach tailored to site conditions. Their analysis revealed that turnaround personnel expended substantial waiting time beyond direct work, whether for permits, instructions, materials, or QA/QC inspections. This discovery prompted the adjustment of work cycles to enhance direct work percentage and improve overall productivity.

Similarly, Krishnankutty et al. [1] embraced a decision matrix to expand the scope of improvement for contractors and plant owners during the TAM. Their study revealed that auxiliary activities, including preparation, transportation, and material handling, absorbed substantial on-site work hours. The pursuit of efficiency has led to advancements in quality assurance/quality control (QA/QC) inspection assessment and NDT tracking systems, propelling documentation for real-time automated systems.

These studies reflect a dynamic landscape of TAM optimization efforts, unveiling factors, methodologies, and technologies that are pivotal in enhancing turnaround processes, reducing waste, and ensuring efficient and productive plant operations.

2.4. Improve TAM Efficiency with Software Development

Efforts to refine and optimize TAM processes encompass a range of innovative approaches, each striving to enhance efficiency and minimize disruptions. Shou et al. [45] introduced a cutting-edge approach involving four-dimensional building information modelling, enabling the simulation of TAM activities before execution. This strategy aids in familiarizing all parties involved with the process sequence, particularly scaffold and heavy equipment plans, effectively reducing the safety risks, TAM duration, and costs.

To comprehensively evaluate TAM's impact on equipment conditions, Khasanah et al. [46] recommended statistical analysis based on prior-year data, specifically examining plant downtime loss and availability in fertilizer production. Al-Turki et al. [47] devised a TAM measurement system, emphasizing the need for efficient agreements with external suppliers and contractors to ensure timely delivery of equipment and parts. This intricate process, often outsourced to specialized companies, requires strategic planning to minimize downtime.

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Nonlinear numerical model such as finite element method is widely used [48–50]. Altehmazi et al. [51] employed a nonlinear mathematical model to optimize schedules through labor distribution adjustments to address resource underutilization during TAM. This approach targets optimizing the task start and completion times, thereby minimizing the TAM length.

Ostadi et al. [52] introduced a maintenance management system that leveraged interviews and questionnaires with plant stakeholders to ensure a holistic understanding of the equipment life cycles. Chen et al. [53] harnessed an in-service inspection platform to streamline nuclear power plant inspections. The platform's core functions, database integration, and paperless reporting significantly enhance the data tracking and management efficiency.

In response to the complexity of accident cost assessments, Vianello et al. [10] developed inspection manager software based on the RBI methodology. This software aids in selecting response actions for unforeseen hazardous events, considering intricate cost implications.

Pursuing optimal maintenance planning led Tak et al. [54] to create a model by using a mixed-integer nonlinear programming algorithm. This model enhances inspection and replacement decisions for refinery piping, maximizing inspection intervals while ensuring safe operation based on the wall thickness, inspection frequency, and inspection time.

Lee et al. [55] devised an inspection framework and work-aid tool based on API 570 by further optimizing piping inspection. This comprehensive tool assists in calculating the remaining life and corrosion rates and generating inspection reports. Through its data-driven approach, the framework empowers efficient and informed inspection decision-making.

In summary, these diverse approaches collectively represent a dynamic landscape of strategies to enhance TAM efficiency, from simulation and modelling to statistical analysis, software development, and innovative inspection frameworks.

2.5. Improve TAM Efficiency with the Risk-Based Inspection Method

Various methodologies and approaches have been explored to enhance the efficiency and effectiveness of TAM to minimize downtime, reduce costs, and optimize asset management. Gunwan [56] interviewed TAM experts and leveraged risk-based identification from historical data to enhance the TAM interval and reduce its duration. Defective parts found during turnaround execution pose challenges, necessitating the rapid arrangement of human resources, spare parts, and logistics. An RBI and decision-making model were formulated to mitigate the turnaround delays caused by such contingencies. This model aims to strategically shift maintenance activities to routine schedules while addressing high-risk units during shutdowns. The implementation of this model yielded promising results: a substantial reduction in TAM duration from 30 to 21 days, attesting to the efficacy of risk-based strategies in bolstering turnaround efficiency [57].

Wagh [58] highlighted the benefits of RBI for assessing aboveground storage tanks and process piping in petrochemical plants. Unlike traditional remaining life calculations, this approach focuses on the risk, incident consequences, and probability. RBI assessments prioritize high-risk components by optimizing inspection resources, maximizing efficiency, and ensuring resource allocation.

Building upon this risk-based paradigm, researchers have sought to refine the maintenance schedules for plant heat exchangers [34,59]. By evaluating factors such as vibration, fouling, corrosion, and other failure modes, this approach aimed to extend TAM intervals while minimizing the maintenance duration. The advantages of this strategy include reduced downtime, increased plant reliability, and cost savings.

Elwerfalli et al. [11] applied a framework rooted in RBI to optimize the TAM for pressure drums. By balancing the TAM interval against risk exposure, this study aimed to determine an optimal interval that minimizes downtime and maintenance costs without compromising safety.

Elwerfalli et al. [60] proposed a comprehensive methodology to curtail the TAM duration in four steps: selecting noncritical equipment for standard maintenance, applying RBI to critical static equipment, utilizing risk-based failure analysis for rotating equipment, and generating probability failure distributions to fine-tune the TAM plan.

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Acknowledging the dual nature of plant shutdowns and reducing operational risk while potentially generating new risks, Hameed et al. [61] examined human errors introduced during shutdowns. Using maintenance optimization and RBI, they strived to define optimal shutdown intervals that balanced maintenance needs with the associated risks.

Priyanta et al. [62] conducted a systematic assessment focusing on equipment classification and failure modes. The vast amount of piping equipment used in refining and processing plants poses management challenges, emphasizing the need for structured maintenance strategies. Metal loss due to corrosion is a primary failure mode in carbon steel and stainless steel piping systems, although stainless steel with higher corrosion resistance [63], prompting the application of RBI methods to assess failure consequences and probabilities, as recommended by the American Petroleum Institute (API).

These studies reflect a concerted endeavor to revolutionize TAM practices, leveraging risk-based insights to fine-tune intervals, durations, and strategies, fostering enhanced efficiency, resource allocation, and asset management..

2.6. Phased Array Corrosion Mapping Application

The Ultrasonic Thickness Gauging (UTG) technique serves as a primary method for on-stream inspections in plants and effectively detects corrosion. Its notable advantage lies in its ability to operate at elevated temperatures, with some equipment functioning even at 500 °C [12]. However, UTG is not without limitations, such as reduced productivity in spot thickness measurements and limited sensitivity to localized corrosion. Addressing these limitations is crucial for further enhancing UTG's effectiveness in corrosion detection during plant inspections [64].

Phased Array Ultrasonic Testing (PAUT) has emerged as a compelling alternative, notably surpassing conventional Ultrasonic Testing (UT) and Radiography Testing (RT) techniques, both of which fall under volumetric inspection methods. The PAUT circumvents radiation hazards, making it safe for simultaneous on-site use with other trades. This technique offers rapid result processing, three-dimensional defect information, and permanent records, similar to RT. Its superiority over UT is evident in its multiple-element probe, which permits flexible beam steering, rendering superior scan coverage and speed [65,66]. The proficiency of PAUT is reflected in its ability to provide three-dimensional defect information through S-scan, C-scan, D-scan, and A-scan data, as shown in Figure 2 [67,68].

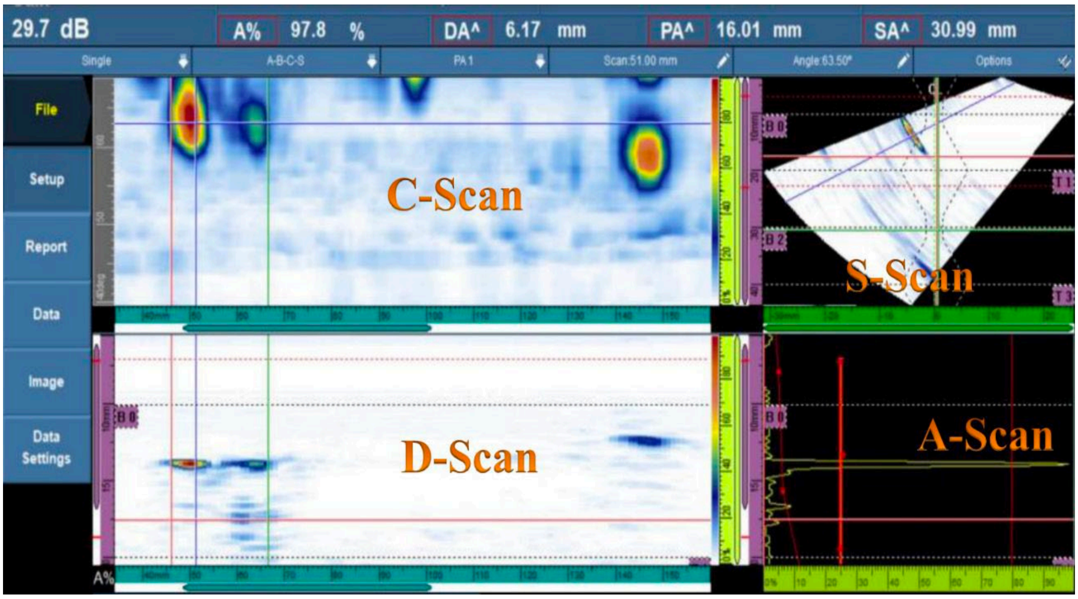

Figure 2. Phased array ultrasonic testing data presentation [adapted from 62???].

Comparative studies have affirmed the advantages of PAUT over traditional UT. Tangadi et al. [14] found that PAUT's scanning speed covered a 30mm width in a single scan. Similarly, Jamil et al.

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[13] reported that corrosion mapping using PAUT offers good detectability and comprehensive results through A-, B-, and C-scan displays. These studies underscore the superiority of PACM in terms of efficiency and accuracy for corrosion detection and analysis.

Further comparisons by researchers such as Turcotte et al. [69] highlighted PAUT's capacity to display a range of thicknesses simultaneously, distinguishing it from UT, which provides thickness information simultaneously. In pursuit of increased productivity, Mohan et al. [15] adopted a HydroFORM scanner, which yielded favorable results compared with UTG. However, while several studies have lauded UTG's high-temperature capabilities of UTG and explored PAUT for enhanced scanning speed and result display, most experiments have been conducted at ambient temperatures. Turcu et al. [16] extended the PAUT corrosion mapping experiment to 150 °C by using a Dual Linear Probe. This effort revealed challenges, such as couplant selection, scanner choice, velocity alteration due to temperature changes, and the risk of probe damage from prolonged contact with hot surfaces.

The field of corrosion detection and analysis benefits from the high-temperature functionality of the UTG technique, and the advancements introduced by PAUT overcome the limitations of the traditional UT methods. The capacity of the latter for rapid scanning, three-dimensional defect representation, and enhanced coverage makes it a promising solution for improved corrosion assessment, even in challenging environments.

2.7. Literature Review Summary

This literature review explores various strategies and methodologies employed in TAM for petrochemical plants and refineries. This review covers aspects ranging from maintenance strategies and their classifications to risk management, communication, inspection techniques, and optimization methods. The overall flow of the review was well-structured, providing a seamless (smooth) narrative that guided the reader through the complexities of the TAM in these industries.

The review begins with an overview of TAM's significance and impact on plant operations, emphasizing the necessity of efficient maintenance strategies to ensure safe and uninterrupted production. It then delves into different maintenance strategies, including PM, PdM, TPM, and RCM, each with unique equipment maintenance and interaction approaches. A clear delineation of these strategies will aid in understanding their respective merits and applications.

The review continued by focusing on the challenges and complexities associated with TAM activities, such as planning, execution, and communication among stakeholders. This highlights the fact that inadequate communication and coordination can lead to delays, cost overruns, and decreased operational efficiency during plant turnarounds. Additionally, the integration of risk management principles within the TAM is discussed, stressing the importance of identifying and mitigating potential risks to minimize the likelihood of unplanned downtime.

The review then shifted its focus to inspection techniques, where the utilization of UTG and PAUT for corrosion detection was introduced. This underscored the advantages and limitations of each technique and provided a comprehensive comparison between conventional UT and advanced PAUT. This section comprehensively explains these inspection methods, their applications, and the evolving technologies to overcome their limitations.

Table 3 lists a summary of the methods used by other researchers to investigate how to improve process-equipment maintenance systems.

Table 3. Summary of plant maintenance studies by researchers.

Improving method	**Assessment tools**	**Survey questionnaire**	**Software development**	**Risk-based Inspection**
Description	Leverage assessment methodologies such as the value stream map, Fuzzy decision	Administered a survey to identify the underlying causes and collect potential solutions	Creating a software tool to facilitate the planning and monitoring of Turnaround	Employing a Risk-based inspection approach to ascertain the remaining

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	techniques, and the AHP method		Maintenance (TAM) activities	operational lifespan of the plant
Journal Article	[1,4,6,7,34,43,44]	[8,9,38–42]	[10,45–47,51–55]	[11,56–62,70]

In the literature, a diverse range of research objectives have been observed among researchers studying TAM strategies. A distribution of 28% of the studies aimed to reduce the duration of TAM, which also emphasized the reduction of operational downtime. Another 11% focused on extending the examination intervals and identifying the challenges within the turnaround process. Approximately 9% of the studies delved into both defining TAM strategies and determining optimal turnaround intervals. Similarly, 7% of the studies targeted both mitigating production loss and evaluating TA performance.

Additionally, 3% of the studies concentrated on reducing the TA costs. The remaining 2% of the research objectives fell under the "other" category. Notably, the dominant themes were centered on reducing TAM duration and extending examination intervals, reflecting a shared priority among researchers to minimize production losses and enhance cost-effectiveness, as shown in the bar chart in Figure 3.

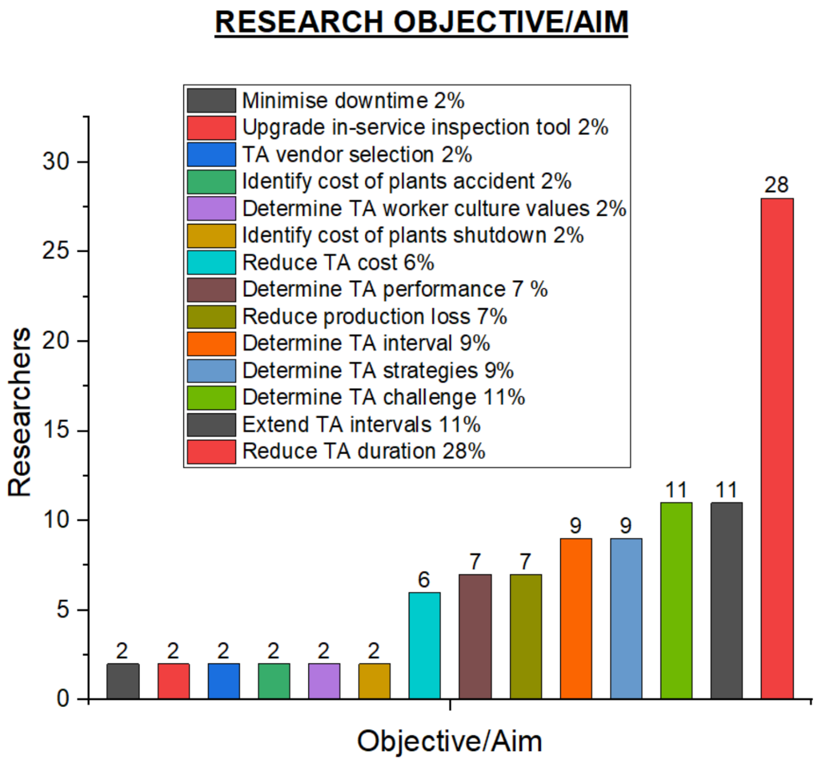

Figure 3. Research objective/aim summaries.

3. Conclusions

Numerous researchers have dedicated their efforts to minimizing the TAM duration and extending TAM intervals. Despite some studies proposing the integration of certain TAM activities into on-stream maintenance, none of these initiatives have explored corrosion assessment during plant operation.

Currently, on-stream inspection in high-temperature environments predominantly relies on UTG, with capabilities reaching material surface temperatures up to 500 °C [12]. However, UTG's drawback of the UTG lies in its time-intensive grid-by-grid measurement approach and the limitation of detecting localized corrosion. PAUT have garnered traction in various industries, expanding from weld inspection to corrosion mapping, even encompassing diverse materials. While multiple studies have presented phased array corrosion mappings, most have been conducted during equipment cool-down and at ambient temperatures. Notably, Turcu et al. [16] utilized a Dual Linear Probe to experiment with corrosion mapping on test samples up to 150 °C, although the accuracy of this technique has not been extensively explored.

The reviewed literature proposes a pivotal shift in TAM practices by incorporating on-stream inspections into regular plant operations. This would entail assessing piping systems and preparing for TAM without necessitating complete plant shutdown. PACM has emerged as a promising technique for on-stream inspections because it can detect localized corrosion within a notably shorter inspection timeframe than the other methods. Consequently, this technique warrants further exploration as a research subject. The potential benefits of integrating on-stream inspection and PACM include reduced TAM duration and extended intervals between TAM, thereby yielding diminished production downtime, heightened plant reliability and availability, and diminished maintenance expenses.

The forthcoming research phase in this domain should focus on assessing the efficacy of the PACM for on-stream inspections within piping systems and equipment, particularly those operating at high temperatures. This study reveals the capacity of this technique to detect general and localized corrosion in frequently employed materials within these systems.

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