

Vol. 4 No. 3 (2026)



RiESTech

JOURNAL
RECENT IN ENGINEERING
SCIENCE AND TECHNOLOGY



E-ISSN : 2985-704X
P-ISSN : 2985-8321



Recent in Engineering Science and Technology (RiESTech)

Vol. 4 No. 3, July 2026

FOCUS AND SCOPE

RIESTECH

Recent in Engineering Science and Technology (**RiESTech**): ISSN: 2985-704X (*online*), ISSN: 2985-8321 (*print*) a peer-reviewed quarterly engineering journal, publishes theoretical and experimental high-quality papers to promote engineering and technology's theory and practice. In addition to peer-reviewed original research papers, the Editorial Board welcomes original research reports, state-of-the-art reviews, and communications in the broadly defined field of recent engineering science and technology. **RiESTech** covers topics contributing to a better understanding of engineering, material science, computer science, environmental science, and their applications. **RiESTech** is concerned with scientific research on mechanical and civil engineering, Electrical/Electronics and Computer Engineering, and Metallurgical and Materials Engineering with specific analytical techniques and/or computational methods.

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Vol. 4 No. 3, July 2026

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Recent in Engineering Science and Technology (RiESTech)

PT MENCERDASKAN BANGSA INDONESIA [MBI]

Available online at: <http://www.mbi-journals.com/index.php/riestech>

E-ISSN : 2985-704X

P-ISSN : 2985-8321

Layout and Typesetting:

Imam Sapto Nugroho, Universitas Indonesia (Alumni), Indonesia

Kamil Raihan Permana, Universitas Indonesia, Indonesia

Raihan Trinanda Agsya, Politeknik Negeri Jakarta, Indonesia

PUBLISHER

PT MENCERDASKAN BANGSA INDONESIA (MBI)

**Address : 4th Floor Gedung STC Senayan Room 31-34, Jl. Asia Afrika Pintu IX,
Jakarta 10270, Indonesia.**

Recent in Engineering Science and Technology (RiESTech)

Vol. 4 No. 3, July 2026

PREFACE

Journal RiESTech (e-ISSN: 2985-704X (online), p-ISSN: 2985-8321 (print); is a peer review journal published by PT Mencerdaskan Bangsa Indonesia. The RiESTech journal is published four times a year in January, April, July, and October. This journal provides direct open access to its content on the principle that making research freely available to the public supports a greater global exchange of knowledge within the engineering field. This journal aims to provide a place for academics, researchers, and practitioners to publish original research articles or review articles. The scope of articles published in this journal relates to various topics in the field of outcomes of research activities.

The RiESTech journal publishes papers strictly following the RiESTech guidelines and templates for manuscript preparation. All submitted manuscripts will go through a double-blind peer review process. The paper is read by members of the editor (according to the area of specialization) and will be screened by the Managing Editor to meet the criteria required for RiESTech publication. Manuscripts will be sent to two reviewers based on their historical experience in reviewing manuscripts or based on their areas of specialization. RiESTech has review forms to keep the same item reviewed by two reviewers. Then the editorial board makes a decision on the comments or suggestions of the reviewers.

Reviewers provide an assessment of originality, clarity of presentation, contribution to the field/science. This journal publishes research articles, review articles/literature reviews, case reports and concept/policy articles, in all fields of Computer Science, Informatics Engineering, Multimedia, Arts. The article to be published is an original work and has never been published. Incoming articles will be reviewed by the reviewer team.

The Editorial Board will try to continue to improve the quality of the journal so that it can become an important reference in the development of engineering sciences. The greatest appreciation and gratitude to Mitra Bestari along with members of the Editorial Board and all parties involved in the publication of this journal. Complete writing instructions are displayed on the portal of this journal.

Regards,
Chief Editor

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Article

Risk-Based Integrity Evaluation of Hydrocarbon and Utility Piping Systems Using Corrosion Rate, Remaining Life, and Inspection Data: A Quantitative Case Study

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Abstract: Hydrocarbon and utility piping systems are critical assets in oil and gas facilities because they support fluid transfer under pressure, temperature variation, and corrosive service conditions. Failure of these systems can cause leakage, production disruption, safety hazards, environmental impact, and repair cost escalation. This study develops a risk-based integrity evaluation framework for piping systems by integrating corrosion rate assessment, remaining life estimation, Probability of Failure, Consequence of Failure, risk ranking, and Risk-Based Inspection prioritization within an Asset Integrity Management context. A quantitative case study was conducted using 2025 industrial inspection data from 82 piping lines grouped into Atmospheric Drains, Flare Line, Hydrocarbon Liquid, Utility Water, Produced Water, and Hydrocarbon Gas systems. The assessment used ultrasonic thickness measurement, actual wall thickness, required minimum thickness, corrosion rate, remaining life, PoF-CoF classification, risk category, and inspection planning year. The results show that 80 piping lines were categorized as Very Low Risk, 1 Utility Water line was categorized as Low Risk, and 1 Hydrocarbon Gas line was categorized as Medium Risk. Utility Water recorded the highest corrosion rate of 0.253 mmpy and the shortest remaining life of 8 years, indicating the highest degradation concern in the evaluated dataset. Hydrocarbon Gas recorded a corrosion rate of 0.076 mmpy and a remaining life of 38 years, but remained in the Medium Risk category due to its consequence profile. The proposed framework supports inspection prioritization, mitigation planning, and risk-informed maintenance decisions within an Asset Integrity Management context.

Keywords: Asset Integrity Management; corrosion assessment; hydrocarbon piping; remaining life; Risk-Based Inspection; risk ranking

Citation: Karina, E., Pratesa, Y., Mudaryanto, J. W. (2026). Risk-Based Integrity Evaluation of Hydrocarbon and Utility Piping Systems Using Corrosion Rate, Remaining Life, and Inspection Data: A Quantitative Case Study. *Recent in Engineering Science and Technology*, 4(3), 126–138. Retrieved from <https://www.mbi-journals.com/index.php/riestech/article/view/161>.

Academic Editor: Yudhi Ariadi

Received: 28 Mei 2026

Accepted: 21 June 2026

Published: 31 July 2026

Publisher's Note: MBI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



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1. Introduction

Piping systems are essential components in oil and gas facilities because they transfer hydrocarbon, water, flare, and utility fluids between process equipment. These systems operate under different pressure, temperature, fluid, and environmental conditions. Their integrity affects process safety, production continuity, environmental protection, and maintenance cost control [1], [2], [3]. Failure of piping systems can lead to loss of containment, shutdown, fire, explosion, environmental release, and unplanned repair activities [3], [4], [5].

Material degradation in piping systems can occur through internal corrosion, external corrosion, wall thinning, pitting, erosion-corrosion, corrosion under insulation, and localized degradation [6], [7], [8]. Corrosion remains one of the most important degradation mechanisms because it reduces wall thickness progressively and can remain undetected without proper inspection coverage [6], [8], [25]. Therefore, piping integrity evaluation should not rely only on current thickness data. It must also consider corrosion

rate, remaining life, degradation tendency, failure likelihood, failure consequence, and inspection effectiveness [13], [14], [15].

Asset Integrity Management provides a structured approach to ensure that assets remain safe, reliable, and fit for service throughout their operating life [9], [10]. AIM connects inspection, maintenance, operating control, risk assessment, degradation management, and mitigation planning [9], [10], [12]. Within this framework, Risk-Based Inspection supports inspection decision-making by prioritizing inspection based on risk rather than fixed inspection intervals [11], [13], [14]. RBI combines Probability of Failure and Consequence of Failure to determine risk level, inspection priority, and mitigation strategy [14], [15], [29].

Previous studies have shown that RBI can improve inspection planning, optimize inspection intervals, support risk-based maintenance, and strengthen pipeline integrity management [3], [4], [5], [13]. Li et al. [16] developed a risk-based maintenance decision model for subsea pipelines subject to pitting corrosion. Campari et al. [17] showed that machine learning can support risk-based inspection strategies for hydrogen handling equipment. Other studies have discussed dynamic risk assessment, safety barrier management, FMEA-MCDA risk management, digital twin application, corrosion defect prediction, and data-driven remaining useful life estimation [18], [19], [20], [21], [22], [23].

However, many prior studies still discuss corrosion evaluation, remaining life estimation, risk ranking, and AIM decision support as separate subjects [9], [13], [16], [23]. Limited studies present a traceable case-based framework that links actual inspection data with PoF-CoF classification, risk category, and inspection planning. This gap is important because operators need practical methods that can translate inspection findings into inspection priority and mitigation planning [10], [11], [12].

Therefore, this study develops a risk-based integrity evaluation framework for hydrocarbon and utility piping systems using a quantitative case study based on 2025 inspection data. The framework integrates corrosion rate analysis, remaining life estimation, PoF-CoF classification, risk ranking, and inspection planning. The contribution of this study is a practical and traceable engineering framework that supports inspection prioritization and mitigation planning within an AIM context [9], [10], [14], [15].

2. Materials and Experiment Methods

This study used a quantitative case study approach to evaluate the integrity condition of hydrocarbon piping systems through an RBI framework. The approach was selected because the analysis used numerical inspection parameters, including ultrasonic thickness measurement, corrosion rate, remaining life, PoF, CoF, and risk ranking. The case study used industrial inspection data from hydrocarbon and utility piping systems operated by PT X during the 2025 integrity inspection program. The methodological design integrated corrosion assessment, remaining life estimation, and risk evaluation within an AIM perspective, as illustrated in Figure 1.

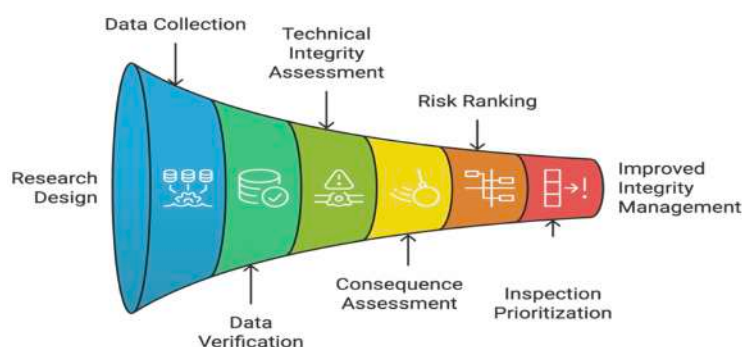


Figure 1. Risk-based inspection methodology.

2.1. Research Framework

This study used a quantitative case study approach. The research was designed as an applied integrity evaluation and framework-development study, not as a literature review. This position is important because the analysis used actual industrial inspection data, numerical corrosion rate values, remaining life values, risk categories, and inspection planning results [14], [15].

The quantitative approach was selected because the study evaluated measurable inspection parameters, including ultrasonic thickness measurement, actual wall thickness, minimum required thickness, corrosion rate, remaining life, PoF category, CoF category, risk ranking, and inspection planning year [24], [26], [29]. This workflow is shown in Figure 2.

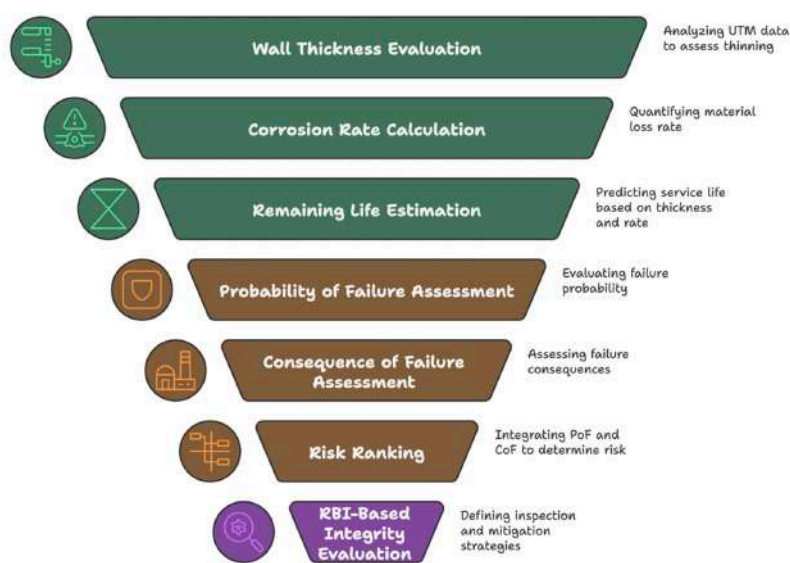


Figure 2. Integrity evaluation workflow based on inspection and risk assessment stages.

The first stage collected technical and operational data, including piping specifications, material types, pipe dimensions, operating pressure and temperature, fluid characteristics, inspection history, ultrasonic thickness measurement data, and operational exposure [24], [26], [28]. The second stage evaluated wall thickness to identify the minimum measured thickness, wall thinning, and degradation tendency in each piping segment [24], [26]. The third stage calculated the corrosion rate to quantify material loss during service [6], [7], [25]. The fourth stage estimated the remaining life by comparing the actual wall thickness, minimum required wall thickness, and corrosion rate [15], [27], [29]. The fifth and sixth stages assessed PoF and CoF [14], [15]. The seventh stage integrated PoF and CoF into an RBI risk matrix. The final stage translated the risk category into inspection priority, inspection interval, and mitigation strategy [11], [13], [14].

2.2. Data Collection and Inspection Parameters

The data were obtained from the 2025 Risk-Based Inspection program of PT X. The selected study scope consisted of 82 evaluated piping lines grouped into six service systems: Atmospheric Drains, Flare Line, Hydrocarbon Liquid, Utility Water, Produced Water, and Hydrocarbon Gas. The RBI executive summary reports that the piping integrity condition was generally acceptable because actual wall thickness was greater than required thickness, MAWP was greater than design pressure, and operating pressure remained below design pressure and MAWP.

The evaluated systems consisted of 13 Atmospheric Drain lines, 36 Flare Lines, 1 Hydrocarbon Liquid line, 15 Utility Water lines, 16 Produced Water lines, and 1

Hydrocarbon Gas line. These systems were selected because they represent different fluid characteristics, consequence profiles, corrosion exposure, and inspection priorities.

2.3. Risk-Based Inspection Procedure

The RBI evaluation followed the principles of API RP 580 and API RP 581. These standards provide a structured method for defining inspection priorities based on risk rather than fixed intervals. In this study, RBI combined system identification, damage mechanism evaluation, inspection effectiveness review, PoF assessment, CoF assessment, risk determination, risk-based inspection planning, and reassessment, as presented in Figure 3.

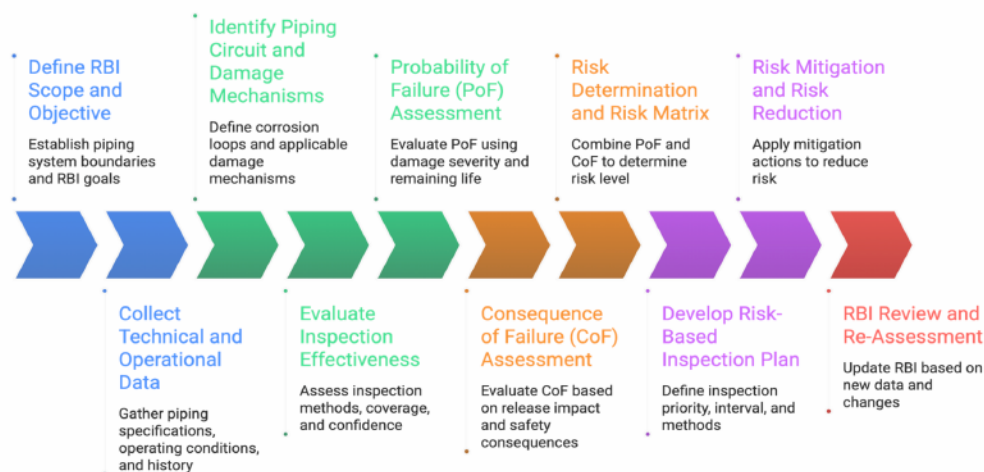


Figure 3. Risk-based inspection workflow procedure.

The procedure began with piping system identification, including material specification, pipe dimensions, operating conditions, fluid characteristics, inspection history, and possible damage mechanisms. Each piping system was classified according to service condition and corrosion susceptibility. Potential degradation mechanisms were then evaluated, with a focus on internal corrosion, external corrosion, wall thinning, pitting corrosion, and localized degradation associated with hydrocarbon and utility water service. PoF was evaluated based on corrosion severity, wall thinning progression, remaining wall thickness, and inspection effectiveness. CoF was evaluated based on hydrocarbon release, safety impact, environmental contamination, operational shutdown, repair cost, and production loss. The PoF and CoF results were integrated into a risk matrix to determine risk category and inspection priority.

2.4. Corrosion Rate Analysis

Corrosion rate analysis was conducted to determine the rate of wall thickness reduction during operation. The corrosion rate was calculated from the difference between the initial wall thickness and the actual measured wall thickness over the service period [40].

$$CR = (t_{\text{initial}} - t_{\text{actual}}) / T \quad (1)$$

where CR is the corrosion rate in mmpy, t_{initial} is the initial wall thickness in mm, t_{actual} is the actual measured wall thickness in mm, and T is the operating exposure time in years. A higher corrosion rate indicates faster material loss and greater vulnerability to wall thinning. In this study, the corrosion rate was used as an input for remaining life estimation and PoF evaluation.

2.5. Remaining Life Estimation

Remaining life estimation was conducted to predict the remaining operating period before the wall thickness reaches the minimum required limit. This parameter supports

inspection urgency, maintenance planning, and repair or replacement priority. The remaining life was calculated using Equation (2).

$$RL = (t_{\text{actual}} - t_{\text{required}}) / CR \quad (2)$$

where RL is the remaining life in years, t_{actual} is the actual measured wall thickness in mm, t_{required} is the minimum required wall thickness in mm, and CR is the corrosion rate in mm/year. A lower remaining life indicates the need for closer monitoring and shorter inspection intervals. A longer remaining life indicates that the piping system still has a sufficient wall thickness margin for continued operation under controlled conditions.

2.6. Risk Analysis

Risk analysis was performed by integrating PoF and CoF to determine the overall risk level of each piping system. The general risk relationship used in this study is shown in Equation (3).

$$\text{Risk} = \text{PoF} \times \text{CoF} \quad (3)$$

PoF represents the likelihood of piping failure due to corrosion, wall thinning, and localized degradation. CoF represents the consequence that may occur if piping failure takes place, including safety impact, environmental consequence, hydrocarbon release potential, production loss, operational shutdown, repair cost, and fire or explosion hazard. The integration of PoF and CoF produced the final risk category, which was used to determine inspection priority and mitigation strategy.

2.7. Data Analysis, Validity, and Reliability

The data were analyzed using a descriptive quantitative approach. The analysis identified the relationship between corrosion rate, remaining life, and risk category [13], [16], [23]. Spreadsheet-based calculations were used to process inspection data, calculate corrosion rate, estimate remaining life, and summarize risk categories. The outputs were interpreted using RBI principles and AIM concepts to support integrity-based decision-making [9], [10], [14], [15].

The validity of the analysis was strengthened by using API RP 580 and API RP 581 as the main references for RBI evaluation [14], [15], [29]. The analysis was also supported by API 570 for in-service piping inspection, API 571 for damage mechanism evaluation, API 574 for piping component inspection practice, API 579-1/ASME FFS-1 for fitness-for-service consideration, and ASME B31.3 for process piping requirements [24], [25], [26], [27], [28]. The reliability of the analysis was supported through consistency checks between thickness measurement records, operating data, and inspection documentation.

Multiple measurement points were used to reduce uncertainty and improve the representativeness of the wall thickness evaluation [24], [26]. The integration of corrosion rate, remaining life, and risk ranking improved the robustness of the assessment because piping integrity was evaluated from degradation severity, remaining serviceability, and operational consequence, not from a single parameter [13], [16], [23].

3. Results and Discussion

3.1. Corrosion Analysis

A total of 82 piping lines were evaluated in this study. The evaluated lines consisted of 13 Atmospheric Drains, 36 Flare Lines, 1 Hydrocarbon Liquid line, 15 Utility Water lines, 16 Produce Water lines, and 1 Hydrocarbon Gas line. This directly answers the reviewer's concern that the previous manuscript did not state the total number of evaluated piping systems.

The results show that the overall piping integrity condition remained acceptable. The actual wall thickness was still higher than the required minimum thickness, MAWP was

higher than design pressure, and operating pressure remained below design pressure and MAWP. This indicates that the evaluated piping systems were still fit for continued operation under the assessed operating conditions.

Table1. Summary of corrosion rate, remaining life, PoF, CoF, risk category, and inspection planning of evaluated piping systems.

No.	Piping System	Number of Evaluated Lines	Max. Corr. Rate (mmpy)	Critical Tag for CR	Lowest Remaining Life (years)	Critical Tag for RL	PoF Cat.	CoF Cat.	Risk Category Distribution	Next Inspection Plan
1	Atmospheric Drains	13	0.043	1"-DA-0373-1B	23	1"-DA-0373-1B	Very Low	Low	13 Very Low Risk	2033
2	Flare Line	36	0.140	3"-FL-0447-1B	29	3"-FL-0477-1B	Very Low	Low	36 Very Low Risk	2033
3	Hydrocarbon Liquid	1	0.040	4"-HL-1124-1B	31	4"-HL-1124-1B	Very Low	Moderate	1 Very Low Risk	2033
4	Utility Water	15	0.253	2"-UW-0224-1W	8	2"-UW-0224-1W	Very Low to High	Insignificant	14 Very Low Risk, 1 Low Risk	14 lines in 2033, 1 line in 2029
5	Produce Water	16	0.116	2"-WW-0310-6B	29	2"-WW-0310-6B	Very Low	Insignificant to Minor	16 Very Low Risk	2033
6	Hydrocarbon Gas	1	0.076	6"-HG-1132-6D	38	6"-HG-1132-6D	Low	Moderate	1 Medium Risk	2033

The maximum corrosion rate values in Table 1 were obtained from the RBI executive summary. The highest corrosion rate was recorded in Utility Water at 0.253 mmpy, followed by Flare Line at 0.140 mmpy, Produce Water at 0.116 mmpy, Hydrocarbon Gas at 0.076 mmpy, Atmospheric Drains at 0.043 mmpy, and Hydrocarbon Liquid at 0.040 mmpy.

The lowest remaining life values were also taken from the same RBI dataset. Utility Water had the lowest remaining life of 8 years, Atmospheric Drains had 23 years, Flare Line had 29 years, Produce Water had 29 years, Hydrocarbon Liquid had 31 years, and Hydrocarbon Gas had 38 years.

As shown in Figure 4, corrosion assessment should not rely only on periodic thickness measurement because wall thickness data alone may not explain the operational factors that accelerate degradation. A more reliable integrity evaluation requires the integration of corrosion rate, service environment, process condition, degradation mechanism, and risk exposure within the RBI framework. From an AIM perspective, the high corrosion rate in Utility Water Piping indicates the need for stronger mitigation actions, including improved water treatment, corrosion inhibitor optimization, chemical control, internal coating evaluation, and intensive corrosion monitoring [4,6,7].

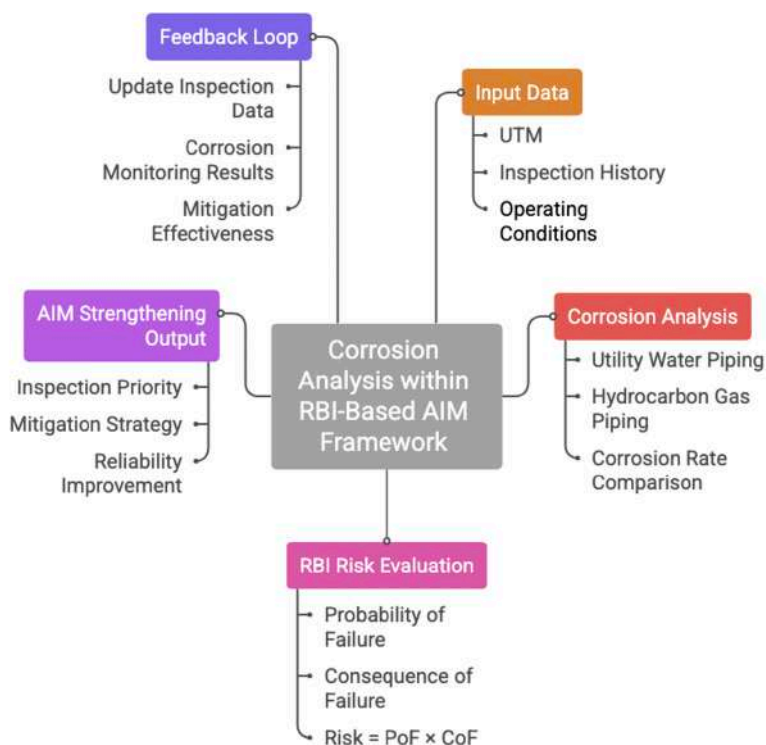


Figure 4. Corrosion analysis within the RBI-based AIM framework.

3.2. Remaining Life Analysis

The corrosion assessment shows that Utility Water had the highest corrosion rate at 0.253 mmpy. This result indicates that Utility Water was the most degradation-sensitive system in the evaluated dataset. The higher corrosion rate can be associated with continuous water exposure, dissolved oxygen, possible chloride contamination, deposit formation, and flow-related corrosion effects. Flare Line recorded the second highest corrosion rate at 0.140 mmpy. Produce Water recorded 0.116 mmpy. Hydrocarbon Gas recorded 0.076 mmpy, while Atmospheric Drains and Hydrocarbon Liquid recorded lower corrosion rates of 0.043 mmpy and 0.040 mmpy. This variation confirms that service fluid and operating environment strongly influence corrosion behavior.

The result also shows that corrosion rate alone should not be used as the only basis for inspection priority. Utility Water had the highest corrosion rate and shortest remaining life, but Hydrocarbon Gas remained in the Medium Risk category because consequence also affects final risk ranking. Therefore, inspection prioritization should combine corrosion rate, remaining life, PoF, CoF, and risk category. The lower remaining life of Utility Water Piping reflects the cumulative effect of wall thinning caused by prolonged exposure to corrosive water service. As actual wall thickness approaches the minimum allowable thickness, the system becomes more vulnerable to leakage, pressure containment loss, and unplanned operational disruption. Therefore, piping systems with shorter remaining life should receive higher inspection priority, closer monitoring, and stronger mitigation actions. Figure 5 summarizes the relationship between corrosion rate and remaining life across the evaluated piping systems.

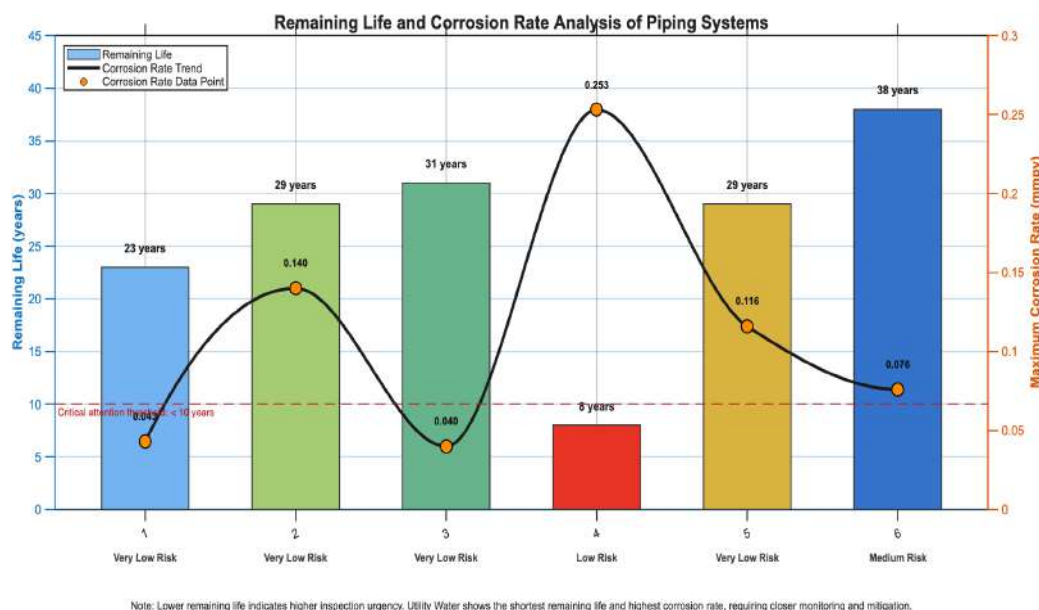


Figure 5. Remaining life and corrosion rate analysis.

3.3. Risk Ranking Analysis

Remaining life evaluation confirms that Utility Water had the highest inspection concern. The lowest remaining life in Utility Water was 8 years. This value was much shorter than Atmospheric Drains at 23 years, Flare Line at 29 years, Produce Water at 29 years, Hydrocarbon Liquid at 31 years, and Hydrocarbon Gas at 38 years. A shorter remaining life indicates that the wall thickness margin is closer to the required minimum thickness. Although the Utility Water system was still acceptable for operation, the 8-year remaining life supports closer monitoring and an earlier inspection plan for the affected line.

Hydrocarbon Gas had a longer remaining life of 38 years, indicating lower wall thinning severity under the evaluated condition. However, it was still categorized as Medium Risk because the consequence profile of hydrocarbon gas service is higher than utility water service. This finding shows that remaining life must be interpreted together with consequence.

Integrating risk ranking into the RBI framework strengthens inspection decision-making by directing inspection resources toward piping systems with the highest degradation severity and operational consequence. Compared with conventional inspection methods that apply uniform intervals, RBI provides a more selective, risk-informed, and technically justified inspection strategy. From an engineering and AIM perspective, Medium Risk systems have not reached critical failure conditions, but their degradation tendency requires stronger control measures, including advanced ultrasonic testing, corrosion mapping, online corrosion monitoring, periodic operating condition review, and targeted mitigation planning [13,18,].

The risk mapping results show that 80 of 82 evaluated piping lines were categorized as Very Low Risk, 1 Utility Water line was categorized as Low Risk, and 1 Hydrocarbon Gas line was categorized as Medium Risk. This revises the previous manuscript statement that “several lines remained in the Medium Risk category.” The corrected result shows that only one line was categorized as Medium Risk. Atmospheric Drains, Flare Line, Hydrocarbon Liquid, and Produce Water were fully categorized as Very Low Risk. Utility Water consisted of 14 Very Low Risk lines and 1 Low Risk line. Hydrocarbon Gas consisted of 1 Medium Risk line. This distribution indicates that most evaluated piping lines were in

acceptable integrity condition, but selected systems still required different inspection priorities.

The Utility Water line assigned to the Low Risk category requires closer attention because the Utility Water system recorded the highest corrosion rate and shortest remaining life. The Hydrocarbon Gas line requires attention because hydrocarbon gas service has a higher consequence profile, even though its corrosion rate and remaining life were not the most critical.

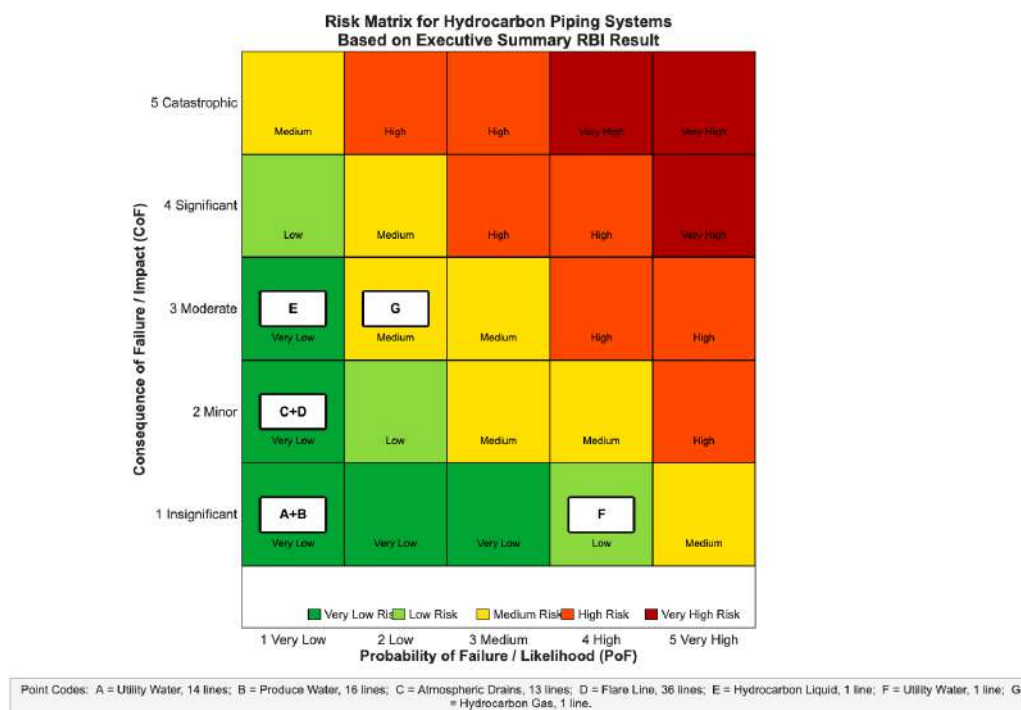


Figure 6. Risk ranking matrix for hydrocarbon piping systems.

3.4. RBI Evaluation

The implementation of RBI provides a clearer and more defensible basis for inspection prioritization, integrity evaluation, and operational decision-making than conventional time-based inspection. In this study, RBI integrates corrosion rate, remaining life, PoF, and CoF into a single risk evaluation framework. This allows inspection planning to reflect actual degradation conditions and operational consequences for each piping system. Conventional inspection methods often apply fixed intervals without fully considering equipment condition, corrosion severity, remaining wall thickness, or failure consequence. This practice can produce inefficient inspection activities because low-risk systems may be inspected too frequently, while systems with higher degradation potential may not receive sufficient attention.

By contrast, RBI enables inspection resources to be focused on systems with higher risk exposure, particularly Medium Risk systems. This approach improves inspection effectiveness, reduces unnecessary maintenance activities, lowers the possibility of unexpected shutdowns, and supports reliability-centered asset management. These findings are consistent with previous studies showing that RBI improves inspection efficiency through risk-based prioritization and that the integration of RBI with operational control parameters improves degradation mitigation [10,24].

3.5. AIM Strengthening Framework

This study proposes an RBI-based AIM strengthening framework consisting of six components: corrosion assessment, remaining life estimation, risk prioritization, inspection optimization, operational control enhancement, and integrity-based mitigation planning. These components are integrated to support adaptive and sustainable integrity management. The proposed framework demonstrates that AIM strengthening depends not only on inspection activities but also on the ability to understand the relationship between material degradation, operational risk, mitigation strategy, and asset sustainability.

The integration of corrosion assessment and remaining life estimation enables operators to evaluate the actual degradation condition more accurately. Risk prioritization then supports inspection and maintenance planning based on actual operational risk. From a strategic perspective, the framework extends RBI beyond inspection scheduling toward broader integrity management that supports long-term operational sustainability. Figure 7 shows the proposed AIM strengthening framework.

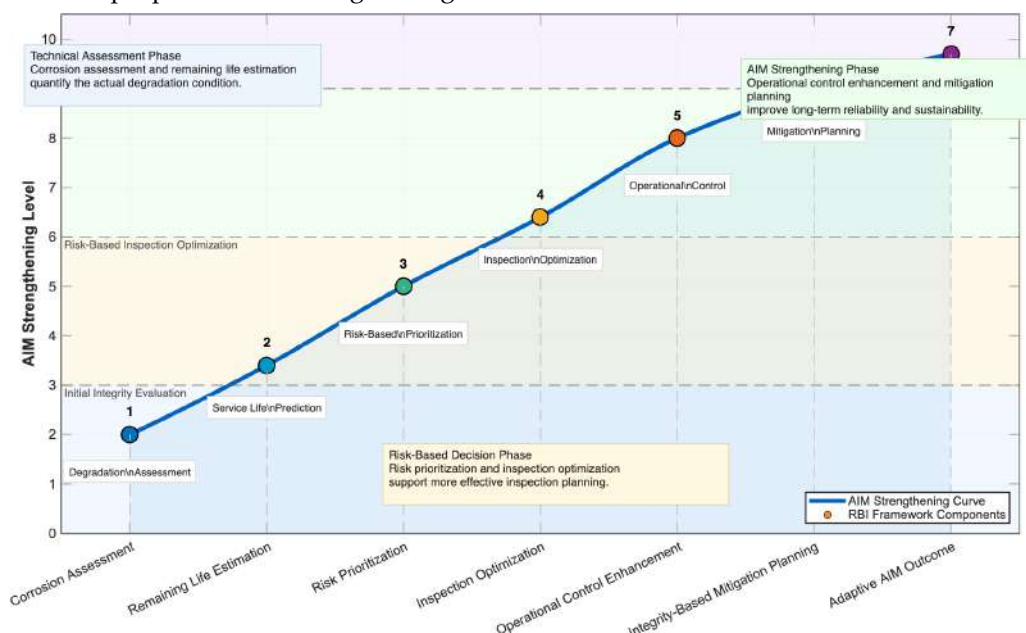


Figure 7. AIM strengthening framework.

3.6. Comparative Discussion

Compared with studies that mainly focus on inspection optimization or probabilistic risk calculation, this study provides a case-based framework using actual industrial inspection data. It connects corrosion rate, remaining life, PoF, CoF, risk category, and inspection planning into one traceable evaluation process.

Previous studies have shown that RBI improves inspection planning, risk-based maintenance, and pipeline integrity management [16], [17], [18], [19]. Other studies have explored dynamic risk assessment, safety barrier management, FMEA-MCDA risk management, digital twin implementation, and data-driven remaining useful life estimation [20], [21], [22], [23], [25]. This study adds value by showing how actual inspection data can be translated into inspection priority and mitigation planning within an AIM context. The contribution of this study should be interpreted as practical decision support, not as proof of a full strategic transformation of AIM. This moderated claim is more consistent with the case study design and the available data, as summarized in Table 1.

Table 2. Comparison between previous studies and the present study.

Aspect	Previous Studies	This Study	Research Added Value
Main research focus	Inspection optimization, quantitative risk calculation, probabilistic assessment, and inspection cost efficiency.	Integration of corrosion evaluation, remaining life assessment, risk ranking, and operational integrity management within AIM.	Provides a broader integrity approach because risk results are linked with asset strategy and operational decision-making.
RBI implementation approach	RBI is commonly used to define inspection priority, inspection interval, and cost-efficient inspection planning.	RBI is used as an integrated integrity evaluation framework connected to degradation, remaining life, operational risk, and maintenance decisions.	Extends RBI from an inspection planning tool into a strategic instrument for strengthening AIM.
Degradation and remaining life evaluation	Some studies do not clearly connect risk optimization with actual degradation condition and remaining service life.	Corrosion rate and remaining life are used to evaluate actual degradation level and serviceability.	Provides a stronger technical basis for inspection prioritization, mitigation planning, and condition-based maintenance.
Risk-based decision-making	Previous studies are more dominant in probabilistic risk assessment, risk matrix, mathematical optimization, or standalone risk calculation.	PoF, CoF, risk ranking, corrosion rate, and remaining life are connected in one integrity evaluation process.	Risk becomes a technical basis for inspection, maintenance, operational control, and mitigation decisions.
Contribution to AIM strengthening	The relationship between RBI and AIM is often limited to inspection efficiency and cost reduction.	AIM links inspection data, degradation assessment, risk prioritization, mitigation strategy, and long-term reliability.	Shows how RBI can strengthen AIM in an adaptive, condition-based, and sustainability-oriented manner.

3.7. Practical Implications

The proposed framework provides direct practical value for operators. It helps identify systems that require earlier inspection and stronger mitigation based on actual inspection data. Utility Water requires closer monitoring because it recorded the highest corrosion rate and the shortest remaining life. Hydrocarbon Gas requires attention because it has a Medium Risk category due to the consequence profile.

For Utility Water, recommended mitigation may include closer UT monitoring, corrosion mapping, water treatment review, deposit control, corrosion inhibitor evaluation, and inspection interval reassessment. For Hydrocarbon Gas, recommended actions may include periodic thickness monitoring, leak history review, external corrosion inspection, operating condition control, and consequence-based inspection planning.

The framework supports risk-informed maintenance because it connects technical data with inspection decisions. This improves inspection efficiency, supports safer operation, and helps allocate inspection resources to the most relevant systems.

4. Conclusions

This study developed a risk-based integrity evaluation framework for hydrocarbon and utility piping systems using 2025 industrial inspection data from 82 evaluated piping lines. The framework integrates corrosion rate, remaining life, PoF-CoF classification, risk ranking, and inspection planning to support inspection prioritization and mitigation planning within an Asset Integrity Management context.

The results show that 80 of 82 evaluated piping lines were categorized as Very Low Risk, 1 Utility Water line was categorized as Low Risk, and 1 Hydrocarbon Gas line was categorized as Medium Risk. Utility Water was identified as the most degradation-sensitive system because it recorded the highest corrosion rate of 0.253 mmpy and the shortest remaining life of 8 years. This condition justifies closer monitoring and an earlier inspection plan for the affected Utility Water line in 2029.

Hydrocarbon Gas recorded a lower corrosion rate of 0.076 mmpy and a remaining life of 38 years. However, it remained in the Medium Risk category due to its consequence profile. This confirms that inspection priority should not be based only on corrosion rate or remaining life. It should combine degradation likelihood and failure consequence.

The proposed framework does not claim to transform the overall AIM system. It provides a practical decision-support method for linking inspection data with inspection priority, risk category, and mitigation planning. Future research should include a wider dataset, full quantitative API RP 581 calculation, probabilistic degradation modelling, real-time corrosion monitoring, digital twin integration, and life cycle cost analysis.

Supplementary Materials: Not applicable.

Author Contributions: Conceptualization, E.K.; methodology, E.K. and Y.P.; formal analysis, E.K.; investigation, E.K.; resources, E.K.; data curation, E.K.; writing-original draft preparation, E.K.; writing-review and editing, Y.P. and J.W.M.; visualization, E.K.; supervision, Y.P. and J.W.M. All authors have read and agreed to the published version of the manuscript.

Funding: This study received no specific funding from government, commercial, or non-profit organizations.

Acknowledgments: The authors acknowledge the technical and academic support provided during the preparation of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- [1] Huang, Y., et al. A risk-based approach to inspection planning for pipelines considering external corrosion and dents. *Process Safety and Environmental Protection*, 2023.
- [2] Silva, A., et al. Towards resilient pipeline infrastructure: Lessons learned from pipeline failures and integrity management. *SN Applied Sciences*, 2024.
- [3] Khan, F., Yarveisy, R., and Abbassi, R. Risk-based pipeline integrity management: A road map for resilient pipelines. *Journal of Pipeline Science and Engineering*, 2021, 1, 74-87.
- [4] Hameed, H., Bai, Y., and Ali, L. A risk-based inspection planning methodology for integrity management of subsea oil and gas pipelines. *Ships and Offshore Structures*, 2021, 16, 687-699.
- [5] Javid, Y.J. A bi-objective mathematical model to determine risk-based inspection programs. *Process Safety and Environmental Protection*, 2021, 146, 893-904.
- [6] Wang, S., Wu, L., Cheng, Y., Chen, P., and Hao, W. Failure analysis: Sulfur stress corrosion cracking of stainless steel components. *Engineering Failure Analysis*, 2020, 118, 104859.
- [7] Okyere, M.S., et al. Assessment of internal corrosion risk in wet sour gas pipeline systems utilizing computational fluid dynamics. *Journal of Engineering and Applied Science*, 2025.
- [8] Popova, K., Montemor, M.F., and Prosek, T. Application of resistometric sensors for real-time corrosion monitoring of coated materials. *Corrosion and Materials Degradation*, 2024, 5, 573-592.
- [9] Wahono, T., Purniawan, A., Mukhlash, I., and Putri, E.R.M. Risk-based asset integrity management in the oil and gas industry from traditional to machine learning approaches: A systematic review. *Results in Engineering*, 2025, 28, 107287.
- [10] Permana, M.S., et al. Innovation in inspection planning using corrosion asset integrity system. *Scientific Contributions Oil and Gas*, 2025.
- [11] Arena, E., Fargione, G., Giudice, F., and Latona, E. RBI-IOWs integrated approach to risk assessment: Methodological framework and application. *Journal of Loss Prevention in the Process Industries*, 2022, 79, 104838.
- [12] Han, Z., et al. Integrated application of dynamic risk-based inspection and integrity operating windows. *Processes*, 2024, 12, 1509.
- [13] Javid, Y.J. Efficient risk-based inspection framework: Balancing safety and maintenance cost. *Reliability Engineering & System Safety*, 2025.
- [14] API RP 580. *Risk-Based Inspection*. American Petroleum Institute, Washington, DC, USA.
- [15] API RP 581. *Risk-Based Inspection Methodology*. 4th Edition. American Petroleum Institute, Washington, DC, USA, 2025.
- [16] Li, X., et al. A risk-based maintenance decision model for subsea pipelines subject to pitting corrosion. *Process Safety and Environmental Protection*, 2024.
- [17] Campari, A., et al. Machine learning-aided risk-based inspection strategy for hydrogen handling equipment. *Process Safety and Environmental Protection*, 2024.
- [18] Yakubu, M.A., Caines, S., Khan, F., and Adumene, S. Dynamic risk assessment framework for offshore pipelines corrosion under insulation. *Journal of Pipeline Science and Engineering*.

- [19] Hosseinnia Davatgar, B., Paltrinieri, N., and Bubbico, R. Safety barrier management: Risk-based approach for the oil and gas process area. *Journal of Marine Science and Engineering*, 2021, 9, 722.
- [20] Shafiee, M., et al. An integrated FMEA and MCDA-based risk management approach for offshore oil and gas assets. *International Journal of Maritime Engineering*, 2022.
- [21] Ren, S., et al. Application and development of digital twinning in oil and gas engineering. *Digital Twin*, 2025.
- [22] Cui, B., et al. Analysis and prediction of pipeline corrosion defects based on machine learning. *Journal of Petroleum Exploration and Production Technology*, 2023.
- [23] Hosseinzadeh, S., et al. Data-driven remaining useful life estimation of subsea pipelines. *Ocean Engineering*, 2025.
- [24] API 570. *Piping Inspection Code: In-Service Inspection, Rating, Repair, and Alteration of Piping Systems*. 5th Edition. American Petroleum Institute, Washington, DC, USA, 2024.
- [25] API 571. *Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*. American Petroleum Institute, Washington, DC, USA.
- [26] API 574. *Inspection Practices for Piping System Components*. American Petroleum Institute, Washington, DC, USA.
- [27] API 579-1/ASME FFS-1. *Fitness-For-Service*. American Petroleum Institute and American Society of Mechanical Engineers, 2021.
- [28] ASME B31.3. *Process Piping*. American Society of Mechanical Engineers.
- [29] ASME. *Boiler and Pressure Vessel Code*. American Society of Mechanical Engineers.

Article

Failure Analysis of Economizer Tube Leakage Caused by Localized Internal Corrosion at Weld-Root Regions

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Abstract: Economizer tube leakage is a common failure in industrial boiler systems that can result in unplanned shutdowns and significant production losses. This study investigates the leakage failure of ASTM A210 Grade C economizer tubes removed from a pulp and paper boiler after long-term service. The investigation combined field inspection, wall-thickness measurements, chemical composition analysis, hardness testing, metallographic examination, and SEM-EDS characterization to determine the failure mechanism. Leakage was identified in Tube Row 99 and Tube Row 185 adjacent to circumferential and stopper-weld regions, where severe wall thinning was concentrated near the weld root while neighbouring tube sections remained largely unaffected. The minimum remaining wall thickness decreased from 3.00 mm to 1.85 mm. Chemical composition analysis confirmed compliance with ASTM A210 Grade C requirements, and hardness testing showed no evidence of abnormal hardening or thermal degradation, indicating that material nonconformity was not responsible for the failure. Metallographic examination revealed disruption of the protective oxide layer and corrosion penetration originating from the internal surface, while SEM-EDS analysis identified corrosion products dominated by iron oxides, confirming an internally initiated corrosion process. The morphology of the perforated regions demonstrated that corrosion propagated from the internal diameter toward the external surface, resulting in progressive wall thinning and through-wall perforation. Operating records indicated fluctuations in dissolved oxygen concentration that may have reduced oxide-layer stability and contributed to corrosion propagation. The failure mechanism was identified as weld-root-associated localized internal corrosion promoted by weld-root geometric irregularities, with dissolved oxygen fluctuations acting as a contributing rather than primary factor. These findings provide practical guidance for improving weld quality control, inspection planning, predictive maintenance, and boiler water chemistry management to reduce the risk of similar failures.

Citation: Ramadhan, D. R., Pratesa, Y., Mudaryoto, J. W. (2026). Failure Analysis of Economizer Tube Leakage Caused by Localized Internal Corrosion at Weld-Root Regions. *Recent in Engineering Science and Technology*, 4(3), 139–154. Retrieved from <https://www.mbi-journals.com/index.php/riestech/article/view/163>.

Academic Editor: Yudhi Ariadi

Received: 6 June 2026

Accepted: 28 July 2026

Published: 31 July 2026

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Keywords: Economizer tube; Failure analysis; Localized internal corrosion; Weld-root; SEM-EDS

1. Introduction

Economizers are widely used in industrial boiler systems to improve thermal efficiency by recovering heat from flue gases and transferring it to feedwater before entering the steam drum (Subramanian, 2020; Incropera et al., 2021). During long-term operation, economizer tubes are continuously exposed to high-temperature water-steam environments that may promote corrosion, degradation of the protective oxide layer, and progressive wall thinning. These degradation processes can compromise tube integrity and eventually lead to leakage, resulting in unplanned shutdowns, production losses, and increased maintenance costs (Dooley, 2020; Gabrielli et al., 2021). ASTM A210 Grade C is a seamless medium-carbon steel extensively used for economizer and boiler tubes because of its good mechanical strength, weldability, and resistance to high-temperature water-steam service. Nevertheless, prolonged exposure to aggressive operating environments may still result in localized corrosion and progressive wall-thickness reduction, making this material an appropriate subject for failure analysis.

Leakage of economizer tubes has been associated with several degradation mechanisms, including internal corrosion, pitting attack, flow-accelerated corrosion, erosion-corrosion, and breakdown of protective oxide layers under unfavorable water chemistry conditions (Pal et al., 2020; Kumar et al., 2020; Duarte et al., 2021). In welded components, susceptibility to localized degradation may increase due to geometric discontinuities, residual stresses, and microstructural heterogeneity introduced during fabrication. These factors create localized electrochemical conditions that accelerate metal loss in specific regions of the tube (Kim et al., 2021; Ghosh et al., 2022).

Among welded regions, the weld-root area is particularly vulnerable because it is directly exposed to the internal water–steam environment. Excessive weld-root penetration or irregular root profiles may create crevice-like geometries that promote deposit accumulation, disturb local flow characteristics, and generate localized chemical environments favorable for corrosion initiation. Once the protective magnetite layer becomes unstable, corrosion preferentially develops beneath retained deposits at the weld-root region, resulting in localized wall thinning. Continued material loss eventually leads to through-wall perforation and tube leakage. Fluctuations in dissolved oxygen concentration may further reduce magnetite-layer stability, thereby increasing the susceptibility of weld-root regions to localized corrosion (Dooley, 2020; Li et al., 2022). These effects become more pronounced in geometrically restricted regions where stagnant flow conditions and oxygen concentration gradients may develop.

Failure of economizer tubes is particularly critical in continuous-process industries because even a single tube leakage may require boiler shutdown, resulting in substantial production losses and costly maintenance interventions. Numerous studies have investigated economizer tube failures associated with general internal corrosion, flow-accelerated corrosion, overheating, and fireside corrosion. However, direct metallurgical evidence linking weld-root geometric irregularities, oxide-layer deterioration, and localized internal corrosion remains limited. In particular, the role of weld-root morphology as a preferential corrosion-initiation site has not been thoroughly clarified using an integrated failure-analysis approach combining field observations, metallography, and SEM–EDS characterization. Consequently, the degradation sequence connecting weld-root geometry, localized corrosion development, wall-thickness reduction, and through-wall perforation remains insufficiently documented.

Therefore, this study investigates the leakage failure of ASTM A210 Grade C economizer tubes removed from a pulp and paper boiler after long-term service. The investigation integrates field inspection, wall-thickness measurements, chemical composition analysis, hardness testing, metallographic examination, and SEM–EDS characterization to establish the degradation sequence and identify the dominant failure mechanism responsible for leakage.

The novelty of this study lies in providing direct metallurgical evidence that weld-root geometric irregularities act as preferential sites for localized internal corrosion by promoting deposit retention and oxide-layer deterioration. By integrating field inspection, wall-thickness measurements, metallographic examination, and SEM–EDS characterization, this study reconstructs the degradation sequence from corrosion initiation to through-wall perforation and clarifies the interaction between weld-root geometry, oxide-layer instability, and localized corrosion under boiler operating conditions. The findings provide practical guidance for improving weld quality control, inspection planning, predictive maintenance, and boiler water chemistry management to reduce the risk of economizer tube failures in industrial boiler systems.

2. Materials and Methods

2.1. Sample Description

The investigated specimens were obtained from failed economizer tubes removed from a water-tube boiler operating in a pulp and paper facility following a scheduled boiler shutdown. Leakage was detected in the economizer section during routine operation, and two representative tubes exhibiting visible perforation adjacent to circumferential and stopper-weld joints were selected for detailed examination. The tubes were manufactured from ASTM A210 Grade C carbon steel and had been exposed to high-temperature water–steam service conditions for an extended operating period.

Visual inspection was performed as the initial stage of the failure investigation prior to specimen removal. Loose corrosion products and surface contaminants were carefully removed to expose the damaged regions, after which the tubes were examined by direct visual observation and documented using digital photographs. The inspection aimed to identify the location of leakage, characterize the visible damage, and evaluate its relationship with the welded joints before detailed laboratory examinations were conducted.

The visual inspection procedure consisted of: (1) identifying the leakage location within the economizer assembly; (2) recording the tube row identification and weld configuration; (3) examining the external tube surface for evidence of wall thinning, deformation, overheating, or mechanical damage; (4) observing the distribution of oxide deposits and corrosion products around the damaged regions; (5) documenting the morphology of the perforated areas and their relationship to the weld-root region; and (6) photographing representative damage for subsequent metallurgical evaluation.

The inspection data included tube identification, leakage location, weld type, visible wall-thinning characteristics, oxide-deposit distribution, corrosion-product accumulation, perforation morphology, and any evidence of external damage, overheating, or deformation. The inspection results were subsequently used to determine representative sampling locations for wall-thickness measurements, chemical composition analysis, hardness testing, metallographic examination, and SEM–EDS characterization as part of the integrated failure investigation.

2.2 Failure Assessment Procedure

The failure investigation was conducted through an integrated approach comprising visual inspection, wall-thickness measurement, material characterization, metallographic examination, and corrosion-product analysis to identify the degradation mechanism responsible for economizer tube leakage. The complementary results obtained from these examinations were integrated to reconstruct the degradation sequence leading to tube perforation.

Visual and macroscopic examination was performed to identify leakage morphology, corrosion distribution, and the relationship between damaged regions and welded joints (Pal et al., 2020; Oliveira et al., 2023). The examination included direct visual observation, documentation using digital photographs, and recording of corrosion products, oxide deposits, perforation morphology, and weld characteristics.

Wall-thickness measurements were carried out using an ultrasonic thickness gauge (Gauge: Olympus 38DL Plus, Olympus Corporation, Japan) in accordance with ASTM E797. After cleaning the tube surface, thickness readings were obtained at representative locations around the leakage region and adjacent unaffected areas to determine the remaining wall thickness.

Chemical composition was analyzed using an Optical Emission Spectrometer (OES) (Bruker Q4 TASMAN, Bruker, Germany) following ASTM A751. The specimen surface was ground and cleaned prior to analysis, and the measured composition was compared with the ASTM A210 Grade C specification.

Hardness testing was performed using a Rockwell hardness tester (Future-Tech FR-3, Japan) in accordance with ASTM E18 on the HRB scale. Five indentations were made in each of the base metal, weld metal, and heat-affected zone (HAZ), and the average hardness was calculated.

Metallographic specimens were prepared according to ASTM E3 and etched with a 2% Nital solution in accordance with ASTM E407. The specimens were examined using an optical microscope (Olympus BX53, Olympus Corporation, Japan) to characterize the microstructural features and corrosion penetration.

Corrosion morphology and corrosion products were characterized using a Scanning Electron Microscope (SEM) ([Manufacturer, Model, Country]) equipped with an Energy Dispersive Spectroscopy (EDS) detector (JEOL JSM-6510LV with Oxford Instruments EDS, Japan). SEM observations were conducted under high-vacuum conditions at an accelerating voltage of 15 kV, and the elemental composition of corrosion products was determined in accordance with ASTM E1508 and the procedure described by Tavares et al. (2022).

The experimental methods and characterization techniques employed in this investigation are summarized in Table 1.

Table 1. Experimental Methods and Characterization Techniques

Examination	Standard / Reference	Objective
Visual and Macroscopic Examination	Pal et al. (2020); Oliveira et al. (2023)	Identify leakage morphology, corrosion distribution, and degradation characteristics
Wall Thickness Measurement	ASTM E797; API RP 571	Quantify wall thinning and material loss
Optical Emission Spectrometry (OES)	ASTM A751	Verify material conformity with ASTM A210 Grade C
Hardness Testing	ASTM E18	Evaluate hardness variation across the weld region
Metallographic Examination	ASTM E3; ASTM E407	Characterize microstructural features and corrosion penetration
SEM–EDS Analysis	ASTM E1508; Tavares et al. (2022)	Identify corrosion morphology and corrosion products
Failure Mechanism Evaluation	API RP 571; Wang et al. (2023)	Correlate metallurgical evidence with leakage development

The examination methods summarized in Table 1 were selected to provide complementary information regarding the condition of the failed economizer tubes. Visual inspection and wall-thickness measurements established the location and extent of material degradation, while chemical composition analysis and hardness testing verified material conformity and mechanical integrity. Metallographic examination and SEM–EDS characterization were subsequently employed to investigate microstructural changes and corrosion-product formation. The combined findings from these complementary techniques were integrated to reconstruct the degradation sequence and identify the dominant failure mechanism responsible for economizer tube leakage.

3. Results and Discussion

The results of the failure investigation are presented in a systematic sequence by integrating the findings obtained from field inspection, wall-thickness measurements, material characterization, metallographic examination, SEM–EDS analysis, and operating history. Rather than interpreting each examination independently, the results from these

complementary techniques are correlated to establish the origin of damage, evaluate the progression of material degradation, and identify the dominant failure mechanism responsible for economizer tube leakage.

3.1. Field Inspection and Macroscopic Examination

Field inspection was conducted during a scheduled boiler shutdown following the detection of leakage within the economizer section. The inspection focused on identifying leakage locations, corrosion distribution, damage morphology, and the condition of welded joints associated with the failed tubes. Leakage was identified in Tube Row 99 and Tube Row 185, both located near welded connections within the economizer assembly, as shown in Figure 2(a).

Visual examination revealed that the damage was confined to limited regions adjacent to the circumferential weld and stopper-weld interfaces rather than being uniformly distributed along the tube surface. The external surfaces of the affected tubes remained relatively intact and showed no indication of severe overheating, creep deformation, fireside corrosion, or mechanical damage. In contrast, oxide deposits and corrosion products were concentrated around the leakage locations, particularly on surfaces exposed to the internal water–steam environment.

The morphology of the perforated regions provides evidence regarding the progression of corrosion attack. In both failed tubes, the cavity opening was noticeably larger on the internal diameter (ID) side than on the external diameter (OD) side, indicating that material loss originated from the tube interior and advanced progressively through the wall thickness. Such morphology is characteristic of internally initiated corrosion and is inconsistent with damage arising from external exposure.

The failed tubes removed from service are presented in Figure 2(b), while close-up views of the perforated regions are shown in Figure 2(c). Leakage was concentrated near circumferential and stopper-weld locations where wall thinning and corrosion products were evident. In contrast, adjacent tube sections remained comparatively intact. The confinement of damage to the welded regions suggests that local geometric and environmental factors played a more significant role than generalized corrosion across the economizer tubing system. These observations were subsequently examined through thickness measurements and microstructural characterization to determine the mechanism responsible for leakage formation.



Figure 1. Field inspection and macroscopic appearance of failed economizer tubes.

- (a) Leakage locations identified in Rows 99 and 185 during boiler shutdown inspection.
 (b) Failed tubes removed from service showing the position of leakage.

(c) Close-up views of perforated regions adjacent to welded joints. The damage was concentrated near the weld-root vicinity, whereas adjacent tube surfaces remained comparatively unaffected.

Table 2. Summary of Field Inspection Findings

Location	Observation	Interpretation
Row 99	Leakage near circumferential weld	Localized internal corrosion
Row 185	Leakage near stopper weld	Weld-root-associated deterioration
Internal surface	Oxide deposits and corrosion products	Internally initiated degradation
Leakage morphology	Larger opening on ID side	ID-to-OD corrosion propagation

The field observations indicate that leakage originated from localized regions adjacent to the welded joints and progressed from the internal tube surface. However, visual inspection alone cannot determine whether the observed deterioration resulted from localized corrosion, material nonconformity, or changes in mechanical properties. Therefore, wall-thickness measurements, chemical composition analysis, and hardness testing were subsequently performed to quantify material loss, verify material conformity, and evaluate the integrity of the affected regions.

3.2. Material Characterization

Material characterization was conducted to evaluate the extent of wall thinning, verify material conformity, and assess whether changes in mechanical properties contributed to leakage formation.

Wall-thickness measurements revealed localized wall thinning in the vicinity of the leakage locations. The most severe reduction was identified in Tube Row 99, where the remaining wall thickness decreased from the nominal value of 3.00 mm to 1.85 mm. A similar pattern was observed in Tube Row 185, while adjacent regions retained considerably greater wall thickness. The uneven distribution of thickness loss indicates that material loss was concentrated near the welded regions rather than occurring uniformly across the tube surface. Representative wall-thinning features are shown in Figure 2, while the measurement results are summarized in Table 3.

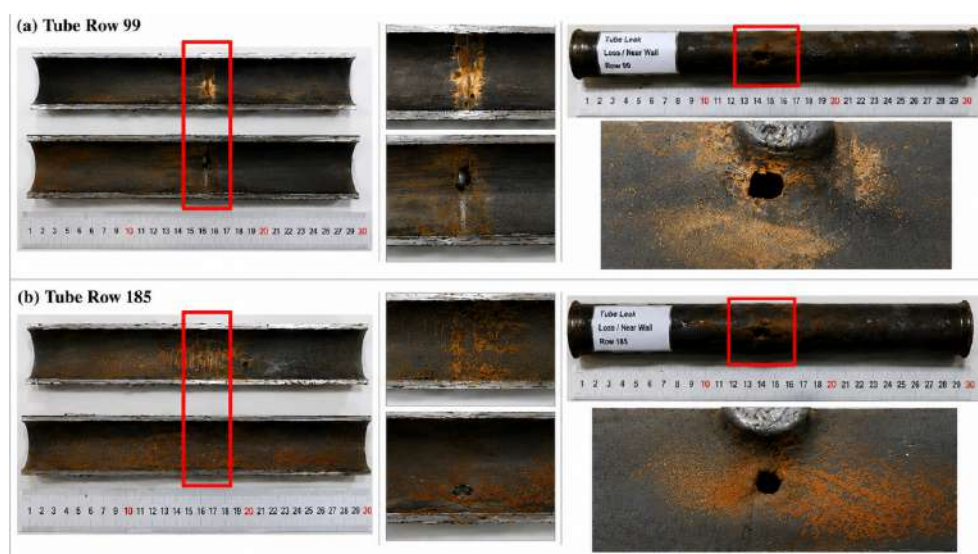


Figure 2. Wall thinning and perforation near welded regions.

- (a) Tube Row 99 showing localized wall thinning and through-wall perforation adjacent to the welded region.
- (b) Tube Row 185 exhibiting similar localized material loss and perforation near the weld penetration area. Damage was concentrated within confined regions, whereas surrounding tube sections remained comparatively unaffected.

Table 3. Thickness Measurement Results

No.	Tube Location / Row	Original Thickness (mm)	Remaining Thickness (mm)	Thickness Loss (mm)
1	Row 99 – Weld Region	3.00	1.85	1.15
2	Row 185 – Stopper Weld	3.00	2.10	0.90
3	Adjacent Non-Degraded Area	3.00	2.85	0.15

The thickness measurements confirm that material loss was highly localized and concentrated near the leakage locations. The substantial difference between the failed regions and adjacent tube sections indicates that deterioration progressed within confined areas rather than through uniform wall reduction across the tube surface.

Chemical composition analysis confirmed that the investigated tubes satisfied the requirements of ASTM A210 Grade C. The measured concentrations of carbon, manganese, silicon, phosphorus, sulfur, and other alloying elements remained within the specified limits. These findings indicate that material nonconformity was not associated with the observed leakage. The chemical composition results are presented in Table 4.

Table 4. Chemical Composition Results

Sample Code	C	Si	Mn	P	S	Fe
Good Tube	0.136	0.206	0.961	0.024	0.020	Bal.
Tube Row 185	0.187	0.212	0.863	0.017	0.020	Bal.
ASTM A210 Grade C	Max 0.35	Min 0.10	0.29–1.06	Max 0.035	Max 0.035	Bal.

The chemical composition data demonstrate that all measured elements remained within the specified limits. Therefore, the leakage failure cannot be attributed to deviations in chemical composition or material specification.

Hardness testing revealed only minor differences between the failed and unaffected tube sections. The measured hardness values remained within the expected range for ASTM A210 Grade C carbon steel and showed no evidence of abnormal hardening, embrittlement, or thermal degradation. These results indicate that significant changes in mechanical properties were unlikely to have contributed to leakage formation. The hardness results are summarized in Table 5.

Table 5. Hardness Test Results

Code	Indentation 1	Indentation 2	Indentation 3	Indentation 4	Indentation 5	Average Hardness (HRB)
Good Tube	84	86	86	85	85	85
Tube Row 185	89	90	89	90	91	90
ASTM A210 Grade C	-	-	-	-	-	Max 89

The hardness values obtained from the failed and unaffected specimens were generally comparable, with average hardness values of 90 HRB and 85 HRB, respectively. The hardness values obtained from the failed and unaffected specimens were generally

comparable, with average hardness values of 90 HRB and 85 HRB, respectively. Although the average hardness of Tube Row 185 was marginally higher than that of the reference tube, the difference was small and remained within the expected variation for service-exposed ASTM A210 Grade C tubing. No localized hardness increase indicative of abnormal hardening, embrittlement, phase transformation, or thermal degradation was identified. Therefore, the hardness results suggest that changes in mechanical properties did not play a significant role in the leakage failure, the difference is considered insignificant and may be attributed to normal measurement variability associated with Rockwell hardness testing. No localized hardness increase indicative of abnormal hardening, embrittlement, phase transformation, or thermal degradation was identified. Therefore, the hardness results suggest that changes in mechanical properties did not play a significant role in the leakage failure. Collectively, the material characterization results indicate that neither material nonconformity nor mechanical-property variation was responsible for leakage formation. In contrast, localized wall thinning was consistently concentrated near the failed regions, highlighting progressive material loss as the most significant feature identified during this stage of the investigation. These findings suggest that the observed leakage was primarily associated with a localized corrosion process rather than metallurgical degradation. To determine the underlying cause of this localized deterioration, detailed metallographic and SEM-EDS examinations were subsequently performed.

3.3. Metallographic and SEM-EDS Analysis

Metallographic and SEM-EDS examinations were performed to investigate the damaged sections of the economizer tubes and identify the features associated with leakage development. The analysis focused on the area surrounding the weld root, where field inspection and thickness measurements revealed the greatest loss of material.

Cross-sectional observations revealed a marked contrast between the reference and failed specimens. The reference weld exhibited a sound profile and a continuous internal surface without visible signs of deterioration. In the failed specimen, a through-wall opening was present adjacent to the weld root. As illustrated in Figure 4(a–b), the perforation was wider on the internal diameter (ID) side than on the external diameter (OD) side, indicating that metal loss progressed outward from the tube interior. The geometry of the damaged area is characteristic of corrosion-driven wall reduction rather than mechanical rupture.

Representative microstructures from the base metal (BM), heat-affected zone (HAZ), and weld metal (WM) are shown in Figure 4(c–e). All examined regions displayed ferrite–pearlite structures typical of ASTM A210 Grade C carbon steel. No evidence of overheating, creep damage, abnormal phase transformation, or grain-boundary deterioration was observed. The microstructural features therefore remained consistent with those expected for the material under normal service conditions.

A different condition was observed at the damaged weld-root interface, shown in Figure 4(f). The affected area exhibited disruption of the oxide layer accompanied by corrosion penetration and significant wall reduction. Material removal was confined to a narrow zone adjacent to the weld root, whereas the surrounding microstructure remained largely intact. This observation agrees with the thickness measurements presented in Section 3.2 and confirms that degradation was concentrated within a restricted area of the tube wall.

Further evidence was obtained from SEM examination. The corroded surfaces were characterized by irregular topography, shallow cavities, and discontinuities within the oxide layer. These features became increasingly pronounced closer to the perforated region, reflecting progressive deterioration of the protective surface film during service exposure. Representative SEM images and EDS results are presented in Figure 5.

The EDS spectra and elemental maps revealed that the corrosion deposits were composed primarily of iron and oxygen, confirming the presence of iron-oxide products. Sulfur-rich compounds were not detected in significant quantities. This compositional evidence is consistent with degradation occurring under the internal water-steam environment and does not support external fireside corrosion as the governing process.

Taken together, the metallographic and SEM-EDS findings establish a consistent sequence of damage development. Breakdown of the protective oxide layer was followed by corrosion penetration and progressive wall reduction within the same confined location. As the remaining wall thickness decreased, a through-wall opening eventually formed, providing a direct path for leakage.

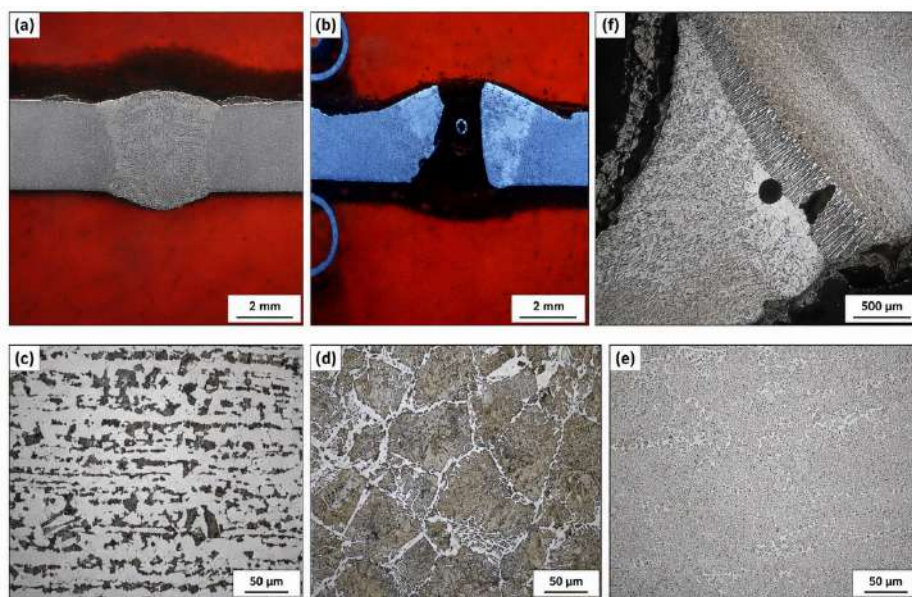


Figure 3. Metallographic comparison between reference and failed specimens.

- (a) Reference weld cross section from a non-leaked tube.
- (b) Failed weld cross section showing perforation adjacent to the weld-root interface.
- (c) Base metal (BM).
- (d) Heat-affected zone (HAZ).
- (e) Weld metal (WM).
- (f) Corrosion penetration and wall-thickness reduction at the weld-root interface.

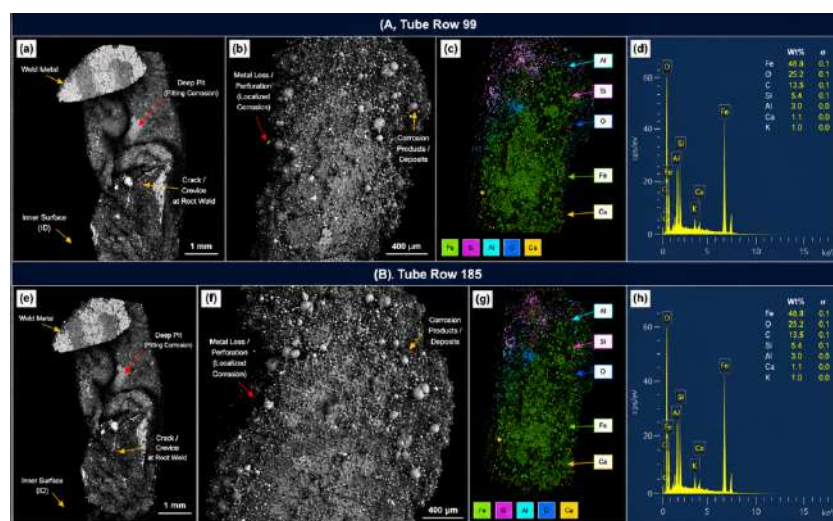


Figure 4. SEM-EDS characterization of leakage regions.

(A) Tube Row 99:

- (a) SEM overview of the weld-root region,
- (b) higher-magnification image of the perforated area,
- (c) EDS elemental map of corrosion products, and
- (d) corresponding EDS spectrum.

(B) Tube Row 185:

- (e) SEM overview of the weld-root region,
- (f) higher-magnification image of the perforated area,
- (g) EDS elemental map of corrosion products, and
- (h) corresponding EDS spectrum.

Table 6. Summary of Metallographic and SEM-EDS Observations

Observation	Interpretation
Ferrite-pearlite microstructure in BM, HAZ, and WM	Material characteristics remained consistent with ASTM A210 Grade C
No evidence of overheating, creep damage, or abnormal phase transformation	Thermal degradation did not contribute significantly to failure
Severe wall reduction adjacent to weld root	Material loss occurred within a confined region
Oxide-layer disruption near damaged areas	Breakdown of surface protection facilitated corrosion development
Corrosion penetration extending from ID toward OD	Damage originated from the internal surface
Iron-oxide corrosion products	Degradation occurred under water-steam service conditions
No significant sulfur enrichment	Fireside corrosion was not the governing mechanism

The metallographic and SEM-EDS findings are consistent with the field observations and wall-thickness measurements presented in the previous sections. The regions exhibiting the greatest wall reduction corresponded to localized oxide-layer deterioration and corrosion penetration adjacent to the weld root. Furthermore, SEM-EDS analysis confirmed that the corrosion products consisted predominantly of iron oxides, providing complementary evidence that the observed material loss resulted from an internally initiated corrosion process rather than external degradation or metallurgical instability.

3.4 Operating History and Water Chemistry

Although the available dissolved oxygen (DO) records were incomplete, the observed fluctuations, together with the metallographic and SEM-EDS findings, suggest that unstable oxygen conditions may have contributed to the corrosion process.

**Figure 5.** Record of Dissolved Oxygen (DO) at PB1

DO monitoring records from August to October 2025 are presented in Figure 5. The available measurements indicate dissolved oxygen (DO) concentrations ranging from approximately 1 to 19 ppb during the monitoring period. However, the records contain two intervals where no monitoring data were available, limiting the continuity of the dataset. Consequently, the available data are insufficient to establish a direct relationship between dissolved oxygen concentration and the observed corrosion behavior.

Although fluctuations in DO were observed in the available records, their influence on tube degradation cannot be conclusively determined because of the incomplete monitoring history. Nevertheless, the observed DO variations are consistent with the metallographic evidence of oxide-layer deterioration and the SEM–EDS identification of iron-oxide corrosion products. Therefore, dissolved oxygen fluctuations are interpreted as a possible contributing factor that may have influenced oxide-film stability, rather than as definitive evidence of the primary cause of economizer tube failure.

Fluctuations in dissolved oxygen are known to affect the stability of the protective magnetite layer on carbon-steel surfaces, thereby increasing susceptibility to localized corrosion. This effect may become more significant in geometrically restricted weld-root regions, where deposit accumulation and localized chemical variations can develop. Metallographic and SEM–EDS examinations revealed oxide-layer disruption, corrosion penetration, and localized wall thinning adjacent to the weld-root interface, supporting the role of oxygen instability as a contributing factor in the degradation process.

The values presented in Table 7 are generalized ranges compiled from industrial boiler chemistry guidelines and should be regarded as indicative rather than absolute corrosion-rate values.

Table 7. Corrosion Rate vs DO in Economizer Tube (Carbon Steel)

DO Level	Typical Corrosion Rate	Notes
< 5 ppb	< 0.1 mpy	Protective magnetite layer stable
5–10 ppb	0.1–0.5 mpy	Generally acceptable for high-pressure systems
10–20 ppb	0.5–2 mpy	Increased tendency for pitting initiation
20–50 ppb	2–10 mpy	Localized deep pits commonly observed
50–200 ppb	10–50 mpy	Severe pitting associated with tube failures
> 200 ppb	> 50 mpy	Rapid tube penetration may occur

Table 7 illustrates the general relationship between dissolved oxygen concentration and corrosion behavior in carbon-steel economizer tubes. Low DO levels generally promote the stability of the protective magnetite layer, whereas elevated or fluctuating DO concentrations may increase the tendency for localized corrosion and pitting. Although the available operational records do not establish a direct quantitative correlation between DO and corrosion rate, the observed fluctuations are consistent with conditions that may accelerate oxide-layer deterioration and localized corrosion development near the weld-root region.

3.5 Failure Mechanism Discussion

The results obtained from field inspection, wall-thickness measurements, metallographic examination, and SEM–EDS characterization provide a consistent explanation for the leakage observed in the economizer tubes. The damage originated from the internal surface and developed progressively within a confined region adjacent to the weld root. Unlike generalized corrosion, deterioration was concentrated at specific locations while neighbouring tube sections remained comparatively unaffected.

Leakage was identified in Tube Row 99 and Tube Row 185 near circumferential and stopper-weld interfaces. Thickness measurements showed that the most severe wall reduction occurred in these regions, where the remaining thickness was significantly

lower than the nominal tube wall. The confinement of material loss to areas adjacent to welded joints suggests that local conditions governed the degradation process rather than uniform corrosion throughout the economizer tubing system.

The weld-root geometry is considered a key factor influencing damage initiation. Geometric irregularities at the weld-root interface can alter local flow characteristics and promote the retention of deposits and corrosion products. The accumulation of these species may create localized chemical conditions that differ from those on the surrounding tube surface. Under such circumstances, the stability of the protective oxide layer can be reduced, increasing susceptibility to corrosion attack.

Metallographic examination revealed disruption of the oxide layer together with corrosion penetration in the damaged regions. In contrast, the base metal, heat-affected zone, and weld metal retained ferrite-pearlite microstructures characteristic of ASTM A210 Grade C carbon steel. No evidence of overheating, creep damage, grain-boundary deterioration, or abnormal phase transformation was observed. These findings indicate that the leakage event was not associated with thermal degradation or metallurgical instability.

The morphology of the perforated areas provides direct evidence of the direction of degradation. Cross-sectional observations showed that the cavity opening was larger on the internal diameter (ID) side than on the external diameter (OD) side. This feature indicates that corrosion progressed from the internal surface toward the outer wall. The same regions also exhibited the greatest wall reduction, establishing a direct relationship between corrosion penetration and material loss.

SEM observations identified corrosion cavities, irregular surface morphology, and discontinuities within the oxide layer surrounding the leakage locations. EDS analysis showed that the corrosion deposits consisted predominantly of iron and oxygen, confirming the presence of iron-oxide products formed during service exposure. Sulfur-bearing compounds were not detected in significant quantities, indicating that external fireside corrosion was not the governing degradation mechanism.

Operational records indicated fluctuations in dissolved oxygen (DO) concentration during boiler operation. Although oxide-film stability was not measured directly, variations in dissolved oxygen are known to influence the formation and persistence of protective magnetite layers on carbon-steel surfaces. In areas where geometric discontinuities and deposit accumulation already exist, disturbances in oxide stability may increase the likelihood of corrosion activity. The weld-root region therefore provided favourable conditions for continued degradation once the protective oxide layer had been compromised.

The collective findings indicate a degradation sequence in which oxide-layer deterioration was followed by corrosion penetration and progressive wall reduction near the weld root. As material loss continued, the remaining wall thickness gradually decreased until a through-wall perforation was formed. Leakage occurred when the tube wall could no longer maintain pressure containment under normal operating conditions.

The proposed degradation sequence is illustrated in Figure 6, while the relationship between the immediate cause of leakage and the underlying contributing factors is summarized in the Root Cause Failure Analysis (RCFA) presented in Figure 7. Both models are consistent with the field observations, thickness measurements, metallographic findings, and SEM-EDS results obtained throughout the investigation.

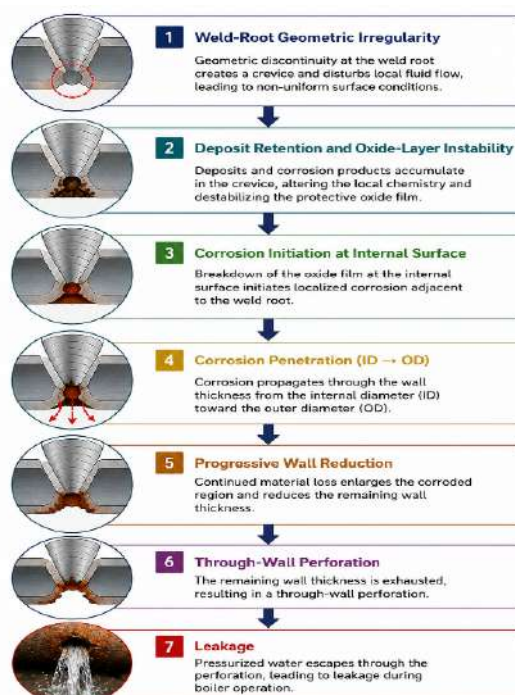


Figure 6. Sequential degradation mechanism of economizer tube failure associated with weld-root geometric irregularities.

Geometric irregularities at the weld-root interface promoted deposit retention and disturbed local flow conditions, creating a favorable environment for oxide-layer instability. The resulting breakdown of the protective oxide layer initiated localized corrosion at the internal tube surface. Corrosion subsequently propagated from the internal diameter (ID) toward the external diameter (OD), causing progressive wall thinning adjacent to the weld root. Continued material loss reduced the remaining wall thickness until through-wall perforation occurred, allowing pressurized water to escape and resulting in tube leakage during service operation.

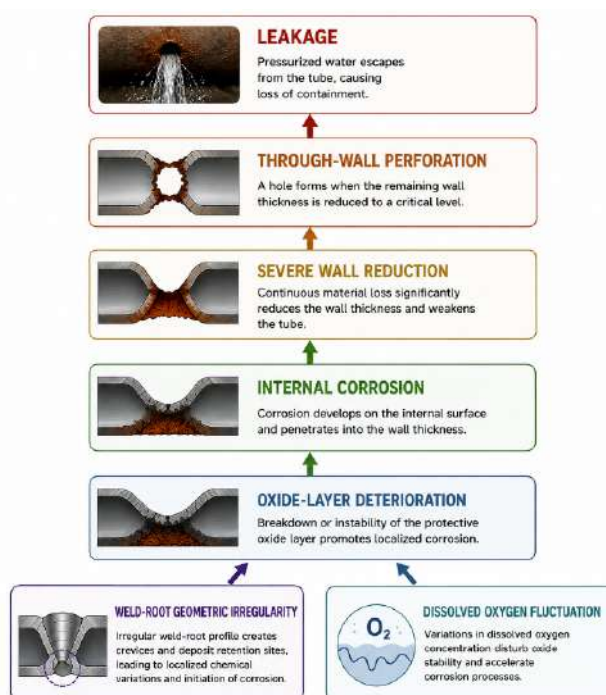


Figure 7. Root Cause Failure Analysis (RCFA) of economizer tube leakage.

Figure 7. Root Cause Failure Analysis (RCFA) of economizer tube leakage. Leakage resulted from through-wall perforation caused by severe wall reduction. The wall reduction developed through internal corrosion associated with oxide-layer deterioration. The underlying contributing factors were weld-root geometric irregularities and fluctuations in dissolved oxygen concentration, which promoted sustained corrosion activity near the internal tube surface.

4. Conclusions

A comprehensive failure investigation was conducted on ASTM A210 Grade C economizer tubes removed from service following leakage in a water-tube boiler operating at a pulp and paper facility. Representative findings indicate that leakage was consistently confined to the weld-root regions, where severe localized wall thinning, oxide-layer deterioration, and internally initiated corrosion were observed, while the material retained its specified chemical composition, microstructure, and mechanical properties. These representative findings demonstrate that the leakage resulted from localized degradation associated with internally initiated corrosion rather than material nonconformity or thermal degradation.

Based on the integrated findings, the following conclusions are drawn:

1. Leakage was localized in Tube Row 99 and Tube Row 185 adjacent to circumferential and stopper-weld interfaces. Severe wall thinning was concentrated near the weld-root regions, whereas adjacent tube sections remained comparatively unaffected, indicating a localized degradation process.
2. The tubes satisfied the requirements of ASTM A210 Grade C and exhibited no evidence of metallurgical instability, abnormal hardening, overheating, creep damage, or phase transformation. Therefore, material nonconformity and thermal degradation were excluded as the primary causes of failure.
3. Metallographic examination revealed oxide-layer deterioration and corrosion penetration originating from the internal tube surface, while SEM-EDS analysis confirmed corrosion products dominated by iron oxides. The absence of significant sulfur enrichment further indicates that fireside corrosion was not the governing degradation mechanism.
4. The morphology of the perforated regions demonstrated that corrosion propagated from the internal diameter toward the external surface, resulting in progressive wall thinning and eventual through-wall perforation.
5. The dominant failure mechanism was identified as weld-root-associated localized internal corrosion. Weld-root geometric irregularities promoted deposit accumulation that facilitated corrosion initiation, while fluctuations in dissolved oxygen are considered a contributing factor that may have reduced oxide-layer stability and facilitated corrosion propagation.

Overall, the investigation demonstrates that economizer tube leakage resulted from the combined effects of weld-root geometric irregularities, oxide-layer deterioration, and progressive internally initiated corrosion. Improving weld-root quality, implementing periodic inspection of susceptible welded regions, and maintaining effective boiler water chemistry control are recommended to reduce the risk of similar failures during long-term operation.

Acknowledgments: The authors gratefully acknowledge the operating company for providing access to operational records, field inspection activities, and failed economizer tube samples used in this investigation. Appreciation is also extended to the technical personnel for their assistance with specimen preparation, metallographic examination, and material characterization. Their support was essential to the successful completion of this study.

Author Contributions

Conceptualization, D.R.R. and Y.P.; Methodology, D.R.R. and Y.P.; Investigation, D.R.R.; Formal analysis, D.R.R.; Data curation, D.R.R.; Writing – original draft preparation, D.R.R.; Writing – review and editing, Y.P.; Supervision, Y.P. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Subramanian P. Deterioration of economizer tubes in utility boilers. *Engineering Failure Analysis*. 2020;112:104515.
2. Dooley RB. Boiler tube failures associated with oxygen corrosion and magnetite instability. *PowerPlant Chemistry*. 2020;22(6):321–330.
3. Gabrielli F, et al. Water chemistry related tube failures in industrial boilers. *Materials at High Temperatures*. 2021;38(2):112–124.
4. Pal S, et al. Failure analysis of boiler economizer tubes at power house. *Engineering Failure Analysis*. 2020;97:1–10.
5. Kumar P, et al. Root cause failure analysis of industrial boiler tubes. *Engineering Failure Analysis*. 2020;118:104866.
6. Duarte CA, et al. Failure analysis of water-tube boiler components under corrosive environment. *Engineering Failure Analysis*. 2021;119:104983.
7. Ghosh S, et al. Localized corrosion behavior in welded boiler tubes under high-temperature service. *Journal of Failure Analysis and Prevention*. 2022;22:455–468.
8. Li H, et al. Failure assessment of carbon steel boiler tubes subjected to dissolved oxygen attack. *Materials Today Communications*. 2022;33:104598.
9. Oliveira P, et al. Failure investigation of economizer tube leakage by metallographic and SEM analysis. *Engineering Failure Analysis*. 2023;148:107183.
10. Wang L, et al. Corrosion failure in welded economizer tubes under high dissolved oxygen conditions. *Engineering Failure Analysis*. 2023;151:107412.
11. ASM International. *Failure Analysis and Prevention*. ASM Handbook. Vol. 11. Materials Park (OH): ASM International; 2020.
12. American Society of Mechanical Engineers. *Boiler and Pressure Vessel Code, Section I: Power Boilers*. New York: ASME; 2021.
13. ASTM International. *ASTM A210/A210M: Standard Specification for Seamless Medium-Carbon Steel Boiler and Superheater Tubes*. West Conshohocken (PA): ASTM International; 2021.
14. ASTM International. *ASTM A751: Standard Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products*. West Conshohocken (PA): ASTM International; 2021.
15. ASTM International. *ASTM E3: Standard Guide for Preparation of Metallographic Specimens*. West Conshohocken (PA): ASTM International; 2021.
16. ASTM International. *ASTM E18: Standard Test Methods for Rockwell Hardness of Metallic Materials*. West Conshohocken (PA): ASTM International; 2021.
17. ASTM International. *ASTM E407: Standard Practice for Microetching Metals and Alloys*. West Conshohocken (PA): ASTM International; 2021.
18. ASTM International. *ASTM E797/E797M: Standard Practice for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method*. West Conshohocken (PA): ASTM International; 2021.
19. ASTM International. *ASTM E1508: Standard Guide for Quantitative Analysis by Energy-Dispersive Spectroscopy*. West Conshohocken (PA): ASTM International; 2021.

20. American Petroleum Institute. API Recommended Practice 571: Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. Washington (DC): American Petroleum Institute; 2021.
21. American Petroleum Institute. API Standard 570: Piping Inspection Code: In-Service Inspection, Rating, Repair, and Alteration of Piping Systems. Washington (DC): American Petroleum Institute; 2024.
22. Baboian R. Corrosion Tests and Standards: Application and Interpretation. West Conshohocken (PA): ASTM International; 2020.
23. Callister WD Jr, Rethwisch DG. Materials Science and Engineering: An Introduction. 10th ed. Hoboken (NJ): Wiley; 2021.
24. Tavares S, et al. SEM–EDS evaluation of oxide deposits in boiler economizer tubes. *Materials Characterization*. 2022;193:112187.

Article

Design of a Heavy-Duty Manual Turntable for Heavy Material Handling Activities to Reduce the Potential Risk of Musculoskeletal Disorders (MSDs)

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Abstract: Heavy material handling and rotation activities in the fabrication area are still performed manually using a conventional worktable without a material rotation system. This condition requires the observed operator to bend, twist the body, and repeatedly lift and reposition the material during the work process. These non-neutral working postures have the potential to cause Musculoskeletal Disorders (MSDs), particularly in the neck, shoulders, lower back, arms, and wrists due to excessive and repetitive physical loading. Therefore, this study aims to analyze ergonomic risks in heavy material handling activities and design a Heavy-Duty Manual Turntable to improve operator working posture. The methods used include field observation, work posture documentation, Nordic Body Map (NBM) analysis, posture angle measurement, ergonomic evaluation using Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA), anthropometric analysis, CAD-based design simulation, and simple biomechanical analysis. The NBM screening was completed by one observed operator and identified complaints in the neck, shoulders, lower back, upper arms, wrists, and lower legs. The initial condition had a RULA score of 6–7 and a REBA score of 9–11. The proposed solution is a Heavy-Duty Manual Turntable Model VP1-R with 360° rotational capability and an adjustable working height. Based on the proposed posture simulation, the estimated RULA score decreased to 2–3 and the estimated REBA score decreased to 2–3. The simplified biomechanical comparison also indicated an approximately 45% reduction in the lower-back moment. Because the post-design assessment was based on CAD simulation and not on a fabricated prototype, these results should be interpreted as preliminary design estimates. This study presents an ergonomic assistive-device design that can be used as a basis for prototype development and field testing.

Keywords: Ergonomics; RULA; REBA; Nordic Body Map; Anthropometry; Manual turntable; CAD simulation

Citation: Dwiyanto, A., Pramono, A. E., Zuhri, A. (2026). Design of a Heavy-Duty Manual Turntable for Heavy Material Handling Activities to Reduce the Potential Risk of Musculoskeletal Disorders (MSDs). *Recent in Engineering Science and Technology*, 4(3), 155–164. Retrieved from <https://www.mbi-journals.com/index.php/riestech/article/view/154>.

Academic Editor: Noor Hidayati

Received: 11 May 2026

Accepted: 17 June 2026

Published: 31 July 2026

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1. Introduction

Manual handling of heavy materials remains common in manufacturing and fabrication activities [1,2]. These activities involve lifting, twisting, bending, and maintaining static postures for certain periods, thereby increasing the risk of Musculoskeletal Disorders (MSDs). According to the National Institute for Occupational Safety and Health (NIOSH), MSDs are disorders affecting muscles, tendons, ligaments, nerves, and joints caused by exposure to ergonomic risk factors such as non-neutral postures, excessive force, repetitive movements, and static working positions [17].

Ergonomic posture analysis has been conducted using the Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA), and Ovako Working Analysis System (OWAS) methods [1,9]. The RULA method is used to evaluate upper-limb, neck, and trunk postures during work activities [13]. The REBA method evaluates whole-body posture and also considers load, coupling, and activity factors [6]. Recent

studies have also used image- and sensor-based joint-angle measurements to support RULA and REBA assessment [3,4].

In the actual fabrication process, operators perform heavy material handling and repositioning activities using conventional worktables without a material rotation mechanism. The dimensions and weight of the workpiece require the operator to reposition the material manually during the work process. This condition forces the operator to work in a bent posture, twist the body, partially lift the material, and maintain static postures for certain periods. Preliminary observations also indicate that the operator has difficulty reaching specific processing areas because the existing table cannot rotate the workpiece. These activities increase biomechanical loading and may raise the risk of MSDs due to non-neutral working postures [12]. Recent industrial intervention and field-evaluation studies likewise support workstation redesign and adjustable equipment as practical controls for reducing musculoskeletal risk [5,8].

Several previous studies have applied RULA, REBA, and NBM to evaluate ergonomic risk in manual material handling activities [1,2,9,10]. These methods are useful for identifying risk, but the observed fabrication process also requires a practical device that can rotate a heavy workpiece and maintain an appropriate working height. Therefore, the research gap addressed in this study is the design and simulation-based ergonomic evaluation of a manually controlled heavy-duty turntable for the observed task.

Based on the literature review, this study aims to identify musculoskeletal complaints using NBM, analyze ergonomic risks using RULA and REBA, determine the main design dimensions from the available operator anthropometric data, and redesign a Heavy-Duty Manual Turntable equipped with a 360° material rotation system and adjustable working-height features. The proposed design is evaluated through CAD-based posture simulation and a simplified biomechanical comparison; therefore, the post-design results are not presented as field-tested effectiveness.

The observed posture shown in Figure 1 illustrates the main problems identified in the initial process, including trunk and neck flexion, elevated arms, wrist flexion, and an unstable standing position.

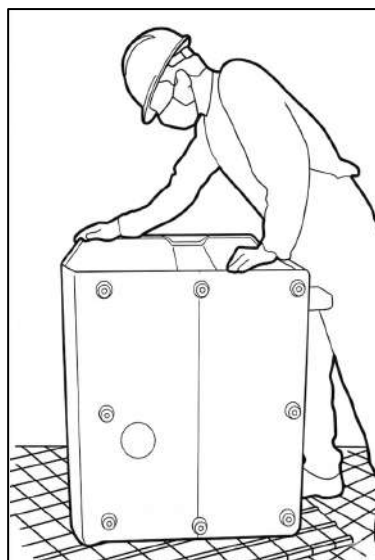


Figure 1. Non-neutral working posture observed in the initial process

2. Materials and Methods

This study uses a descriptive quantitative approach to analyze ergonomic risks in heavy material handling activities and to design a rotary turntable assistive device to improve the operator's working posture. The study focuses on one observed operator and one representative heavy material handling task in a fabrication area. The proposed

condition was evaluated through CAD-based posture simulation; a fabricated prototype was not tested in this study.

2.1. Research Tools and Materials

The tools used in this study included a smartphone camera for work posture documentation, posture angle measurement software, CAD software for assistive device design, and assessment sheets for Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA), and Nordic Body Map (NBM).

The research materials consisted of the observed operator's heavy material handling activity, the available operator anthropometric data, and the design of the Heavy-Duty Manual Turntable Model VP1-R.

2.2. Research Method

The study began with direct observation of the operator's work activities to identify postures that pose a risk of MSDs. The observation covered lifting, moving, reaching, and rotating the heavy workpiece. Photo and video documentation were then used to obtain body-posture angles. The posture shown in Figure 2 was selected because it represents the main non-neutral positions found during the task and was used for the subsequent angle measurement and RULA–REBA scoring.



Figure 2. Representative initial posture used for angle measurement and ergonomic assessment

The observed operator completed the NBM questionnaire ($n = 1$) to identify body regions that felt uncomfortable during the task. Because the questionnaire involved one operator, the results are reported descriptively and are not expressed as complaint prevalence. Posture angles of the neck, trunk, upper arm, lower arm, and wrist were measured from the visual documentation using posture-angle measurement software. Figure 3 shows the posture-angle measurement used in the assessment.

The measured posture angles were analyzed using RULA and REBA. RULA was used to assess the upper limbs, neck, trunk, and legs [13], while REBA was used to assess whole-body posture together with load/force, coupling, and activity [6]. The available anthropometric measurements were then used to determine the proposed working height and reach of the assistive device.

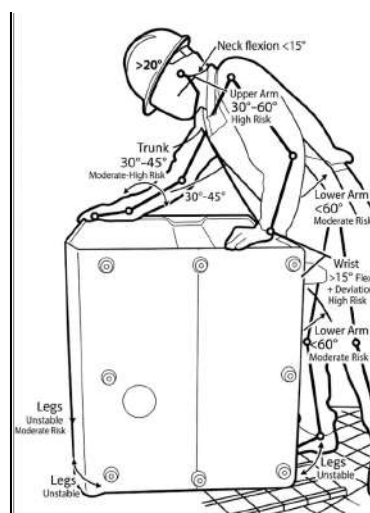


Figure 3. Posture-angle measurement of the representative initial condition

2.3. NBM, RULA, REBA, and Anthropometric Procedures

The Nordic Body Map is a body-region questionnaire used to identify perceived musculoskeletal discomfort [11]. In this study, the questionnaire was completed by the observed operator after the work activity. The results were used only to identify complaint locations and were not used to estimate prevalence among workers.

RULA assesses the upper arm, lower arm, wrist, neck, trunk, and legs, followed by adjustments for muscle use and force. The final score ranges from 1 to 7; higher scores indicate a greater need for corrective action [13].

REBA assesses the neck, trunk, legs, upper arm, lower arm, and wrist, and then adds load/force, coupling, and activity scores. The final score ranges from 1 to 15; higher scores indicate a higher ergonomic risk and a more urgent need for corrective action [6].

The anthropometric inputs used in the design were the observed operator's standing elbow height of 105 cm and forward arm reach of 68 cm. These values were treated as individual measurements, not as population averages. The proposed platform-height range of 100–110 cm was selected as an adjustable range around the measured elbow height.

The Heavy-Duty Manual Turntable Model VP1-R was developed in CAD and the proposed operator posture was simulated using the same body-segment variables applied in the initial RULA and REBA assessments. The simplified biomechanical comparison used the load, horizontal distance, and trunk-angle values already presented in the study.

All post-design posture scores and biomechanical values in this article are simulation-based estimates. They were not obtained from a fabricated prototype or from a second field measurement.

2.4. Analysis Techniques

The analysis techniques used in this study were:

1. Working posture analysis using RULA and REBA for the initial documented posture and the proposed simulated posture;
2. Descriptive musculoskeletal complaint analysis using NBM for the observed operator ($n = 1$);
3. Operator-specific anthropometric analysis using standing elbow height and forward arm reach;
4. A simplified biomechanical comparison of the estimated lower-back moment; and
5. Comparative analysis of the documented initial condition and the CAD-simulated proposed condition.

The biomechanical comparison was used to estimate changes in lower-back loading associated with the initial and proposed scenarios. It was treated as a simplified engineering comparison rather than a direct measurement of spinal load or a complete application of the Revised NIOSH Lifting Equation [18].

2.5. Research Methodology Steps

The research stages are summarized in Figure 4, starting with observation and posture documentation, followed by NBM, posture-angle measurement, RULA–REBA assessment, anthropometric analysis, turntable design, CAD posture simulation, and simplified biomechanical comparison.

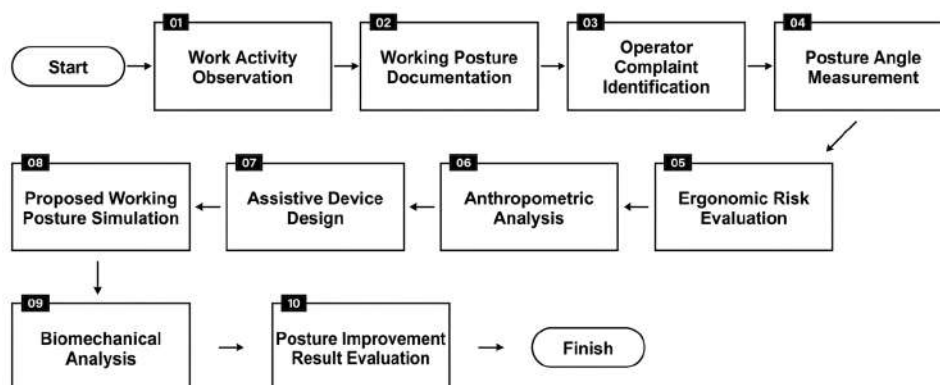


Figure 4. Research methodology flowchart

3. Results and Discussion

The observation results showed that the operator performed heavy material handling and workpiece repositioning manually. The representative posture in Figure 2 involved trunk and neck flexion, upper-arm elevation, wrist deviation, and unstable lower-limb support. These conditions indicate a non-neutral posture that may increase musculoskeletal loading during the task [1,9,14].

3.1. Operator Complaint Analysis

The NBM questionnaire was completed by the observed operator ($n = 1$). The reported complaints were located in the following body regions:

- Lower back;
- Neck, shoulders, and upper arms;
- Wrists and lower legs.

The complaint locations are consistent with the body segments loaded in the posture shown in Figure 2. Because the NBM involved one operator, the findings are interpreted as a description of the observed task and not as a percentage of workers with complaints.

3.2 Posture Angle Analysis

The posture-angle measurements shown in Figure 3 produced the following initial values:

- Neck flexion: approximately 35°;
- Trunk flexion: approximately 35°;
- Upper-arm flexion: approximately 45°;
- Lower-arm flexion: approximately 50°;
- Wrist flexion: approximately 25° with deviation.

These angle values were used as the scoring inputs for Table 1. The combined deviations of the trunk, neck, upper arm, and wrist explain the high initial RULA and REBA scores.

Table 1. RULA score calculation for the representative initial condition

Component	Condition	Score
Upper Arm	$\pm 45^\circ$	3
Lower Arm	$\pm 50^\circ$	2
Wrist Position	$\pm 25^\circ$ + deviation	3
Wrist Twist	Near end range	2
Neck Position	$\pm 35^\circ$	3
Trunk Position	$\pm 35^\circ$	3
Legs	Unstable	1

Final RULA score = 6–7 (changes required soon to immediately)

The RULA assessment resulted in a score range of 6–7. A score of 6 indicates that investigation and change are required soon, whereas a score of 7 indicates that investigation and change are required immediately [13].

The RULA result is consistent with the NBM complaint locations, particularly the neck, shoulders, lower back, upper arms, and wrists. This agreement is descriptive because the study involved one observed operator.

3.3. Ergonomic Risk Evaluation

The initial RULA and REBA results were:

- RULA score = 6–7;
- REBA score = 9–11.

Table 2. REBA component scores for the initial and simulated proposed conditions

REBA component	Initial condition	Score	Simulated proposed condition	Score
Neck	$\approx 35^\circ$ flexion	2	$< 15^\circ$ flexion	1
Trunk	$\approx 35^\circ$ flexion	3	$< 10^\circ$ flexion	1
Legs	Unstable/asymmetrical	2	Stable support	1
Load/force	50 kg workpiece; partial lifting	3	No manual lifting during rotation	0
Upper arm	$\approx 45^\circ$ flexion	2–3	$< 20^\circ$ flexion	1
Lower arm	$\approx 50^\circ$ flexion	2	$\approx 90^\circ$ flexion	1
Wrist	$\approx 25^\circ$ with deviation	2–3	$\approx 5^\circ$ deviation	1
Coupling/activity	Constrained; repeated repositioning	1–2	Controlled rotation	0–1
Final REBA score	High to very high risk	9–11	Low risk (estimated)	2–3

Table 2 presents the REBA components used for the initial posture and the proposed CAD-simulated posture. The initial score of 9–11 indicates high to very high risk. The proposed score of 2–3 is an estimate based on the simulated posture and should not be interpreted as a result of field implementation.

3.4. Anthropometric Analysis

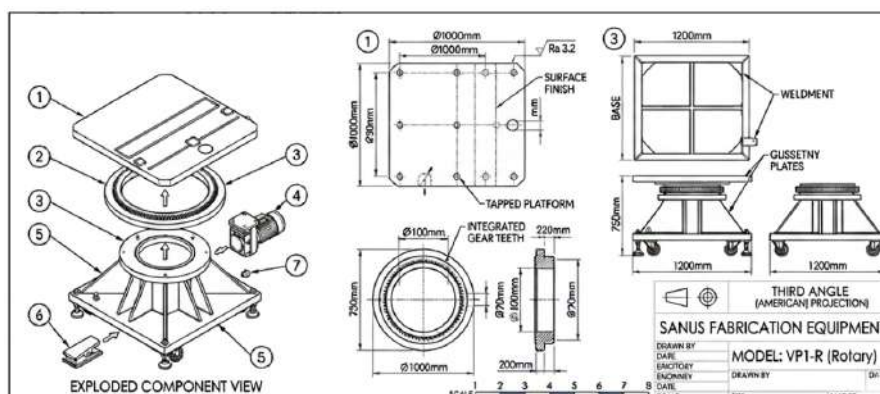
The design dimensions were based on the observed operator's standing elbow height of 105 cm and forward arm reach of 68 cm. The term "average" was removed because the study did not use a population sample. The proposed platform was designed to be adjustable from 100 to 110 cm, providing an adjustment range around the measured elbow height.

Table 3. Operator anthropometric inputs and proposed working height

Parameter	Initial condition	Proposed condition	Design basis
Observed operator standing elbow height	105 cm	105 cm	Direct measurement (n = 1)
Working platform height	75 cm	Adjustable 100–110 cm	±5 cm around measured elbow height
Observed forward arm reach	68 cm	68 cm	Direct measurement (n = 1)
Upper-arm flexion angle	45°	<20°	RULA–REBA posture target
Trunk flexion angle	35°	<10°	RULA–REBA posture target

3.5. Design Simulation and Posture Improvement

The Heavy-Duty Manual Turntable Model VP1-R was designed with 360° rotation capability, an adjustable work platform, and a foot-pedal system to facilitate material rotation without requiring the operator to partially lift the workpiece. These features address the trunk twisting, reaching, and lifting observed in the initial process.

**Figure 5.** Heavy-Duty Manual Turntable Model VP1-R: components and principal dimensions

The modification of the Heavy-Duty Manual Turntable Model VP1-R was intended to improve the operator's working posture through a 360° material rotation system and adjustable work-area height. The main modifications included the manual rotation mechanism, platform-height adjustment based on the available operator anthropometric data, and a foot-pedal system. The design shown in Figure 5 is a CAD proposal and was not fabricated during this study.

The posture shown in Figure 6 was generated through CAD simulation using the proposed dimensions. The simulation was used to estimate changes in posture angles and ergonomic scores; it was not a post-implementation measurement.

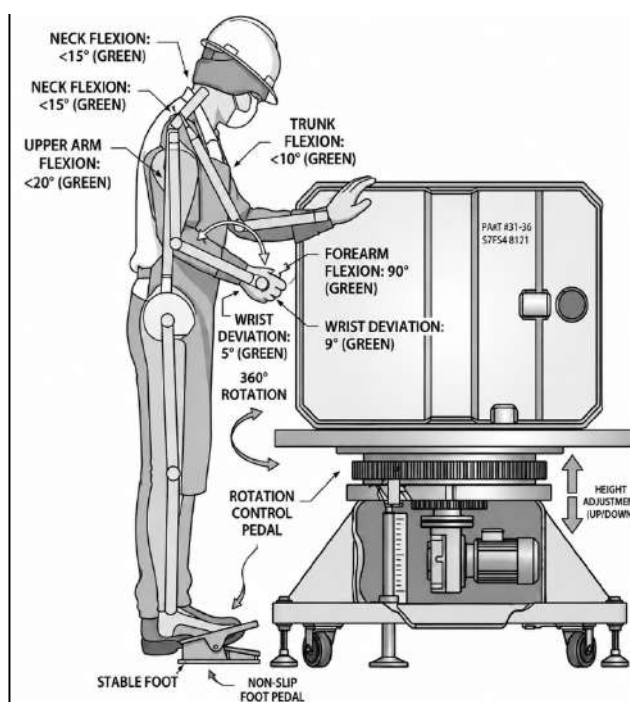


Figure 6. CAD-simulated working posture using the proposed turntable

3.6. Working Posture Analysis After Using the Heavy-Duty Manual Turntable Model VP1-R

Based on the CAD posture simulation, the proposed condition showed a more upright trunk, lower neck flexion, reduced upper-arm elevation, a more neutral wrist, and more stable foot support than the initial condition. These changes occurred because the workpiece could be rotated toward the operator and the working height could be adjusted.

The simulated posture showed neck flexion of less than 15°, trunk flexion of less than 10°, upper-arm flexion of less than 20°, lower-arm flexion of approximately 90°, and wrist deviation of approximately 5°. These values, shown in Figure 6, were used to estimate the post-design RULA and REBA scores. More neutral postures are associated with lower ergonomic loading [12].

The foot-pedal concept allows rotation control without using the hands and may help the operator maintain a more stable stance. However, pedal force, slip resistance, braking, and locking reliability still require verification during prototype testing.

Using the simulated posture angles, the estimated RULA score decreased from 6–7 to 2–3 and the estimated REBA score decreased from 9–11 to 2–3. The REBA component scores are presented in Table 2. These results indicate a lower predicted ergonomic risk, but they do not establish actual effectiveness because no prototype was tested.

The simulation supports the design approach of reducing reach, trunk flexion, body rotation, upper-arm elevation, and wrist deviation. The proposed design therefore requires prototype fabrication and field validation before conclusions are generalized.

3.7. Biomechanical Analysis

The simplified biomechanical comparison estimated a lower L5/S1 moment for the proposed condition because the simulated task removed manual lifting during rotation and reduced the horizontal distance and trunk-flexion angle.

Using the scenario values in Table 4, the estimated lower-back moment decreased from 312 Nm to 172 Nm, or approximately 45%. This value is a simplified engineering estimate and should not be interpreted as a directly measured spinal load or as a complete Revised NIOSH Lifting Equation analysis [18].

Table 4. Simplified comparison of estimated lower-back moments (L5/S1)

Condition	Lifting Force	Horizontal Distance	Trunk Angle	Moment (Nm)	Reduction
Initial Condition	50 kg	40 cm	35°	312	-
Using Turntable	0 kg	20 cm	<10°	172	-45%

4. Conclusions

The results of this study indicate that the observed heavy material handling task has a high ergonomic risk based on RULA and REBA. The operator worked in a non-neutral posture characterized by trunk flexion, upper-arm elevation, wrist deviation, and unstable foot support. The NBM questionnaire completed by the observed operator identified complaints in the neck, shoulders, lower back, upper arms, wrists, and lower legs. The initial assessment produced a RULA score of 6–7 and a REBA score of 9–11, indicating that corrective action was required.

To address these issues, a Heavy-Duty Manual Turntable Model VP1-R was designed with a 360° material rotation system, an adjustable 100–110 cm working height, and a foot-pedal mechanism. The CAD-simulated posture produced estimated RULA and REBA scores of 2–3. The simplified biomechanical comparison also indicated an approximately 45% reduction in the estimated lower-back moment. These results support continued prototype development, but they do not demonstrate field effectiveness.

This study is limited to one observed operator, a CAD-simulated proposed posture, and a simplified biomechanical comparison. Future studies should fabricate and test the VP1-R prototype, verify structural capacity and locking safety, measure pedal and rotation forces, repeat the RULA and REBA assessments during actual use, and involve additional operators before the findings are generalized to other industrial settings.

Acknowledgments:

The author would like to express sincere gratitude to Politeknik Negeri Jakarta for providing academic support, facilities, and an educational environment that greatly contributed to the completion of this research. The author also extends heartfelt appreciation to all lecturers who have shared their knowledge, guidance, experience, and valuable insights throughout the learning process. Their dedication and support have played an important role in the development of the author's academic understanding and research abilities.

In addition, the author would like to thank all individuals who directly or indirectly contributed to this study, whether through technical assistance, constructive discussions, or moral support during the research and preparation of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

- [1] D. Kee, "Systematic Comparison of OWAS, RULA, and REBA Based on a Literature Review," *International Journal of Environmental Research and Public Health*, vol. 19, no. 1, 595, 2022, doi: 10.3390/ijerph19010595.
- [2] A. S. Rezki, A. H. Maksum, D. Herwanto, and M. T. Rahmat, "Analisis Risiko Postur Kerja dengan Metode Nordic Body Map, RULA dan REBA pada Proses Manual Material Handling Pabrik Kecap," *Jurnal Media Teknik dan Sistem Industri*, vol. 7, no. 2, pp. 86–94, 2023, doi: 10.35194/jmtsi.v7i2.2677.
- [3] P. Paudel, Y.-J. Kwon, D.-H. Kim, and K.-H. Choi, "Industrial Ergonomics Risk Analysis Based on 3D-Human Pose Estimation," *Electronics*, vol. 11, no. 20, 3403, 2022, doi: 10.3390/electronics11203403.

- [4] W. F. Senjaya, B. N. Yahya, and S.-L. Lee, "Sensor-Based Motion Tracking System Evaluation for RULA in Assembly Task," *Sensors*, vol. 22, no. 22, 8898, 2022, doi: 10.3390/s22228898.
- [5] M. Rostami, A. Choobineh, M. Shakerian, M. Faraji, and H. Modarresifar, "Assessing the effectiveness of an ergonomics intervention program with a participatory approach: Ergonomics settlement in an Iranian steel industry," *International Archives of Occupational and Environmental Health*, vol. 95, no. 5, pp. 953–964, 2022, doi: 10.1007/s00420-021-01811-x.
- [6] Ö. Ayvaz, B. A. Özyıldırım, H. İşsever, G. Öztan, M. Atak, and S. Özel, "Ergonomic risk assessment of working postures of nurses working in a medical faculty hospital with REBA and RULA methods," *Science Progress*, vol. 106, no. 4, Art. no. 00368504231216540, 2023, doi: 10.1177/00368504231216540.
- [7] R. Darussalam, "Analisis Penilaian Postur Kerja Karyawan dengan Menggunakan Metode NBM, RULA dan REBA," *Jurnal Indonesia Sosial Sains*, vol. 3, no. 9, pp. 1278–1285, 2022, doi: 10.59141/jiss.v3i09.706.
- [8] J. G. Ramsey and S. M. Hatcher, *Ergonomic and Musculoskeletal Evaluation of Distribution Tasks at a Logistics Agency in California*, NIOSH Health Hazard Evaluation Report 2019-0024-3398, Cincinnati, OH, USA, 2024.
- [9] D. Kee, "Comparison of OWAS, RULA, and REBA for assessing potential work-related musculoskeletal disorders," *International Journal of Industrial Ergonomics*, vol. 83, 103139, 2021, doi: 10.1016/j.ergon.2021.103139.
- [10] N. R. Kodle, S. P. Bhosle, and V. B. Pansare, "Ergonomic Risk Assessment of Tasks Performed by Workers in Granite and Marble Units Using REBA," *Materials Today: Proceedings*, vol. 72, pp. 1903–1916, 2023.
- [11] M. E. Beatrix and A. W. Wijayanto, "Posture Analysis Using the Rapid Entire Body Assessment (REBA) & Nordic Body Map (NBM) Methods to Reduce the Risk of Musculoskeletal Disorders (MSDs) in Automotive Company," *International Journal of Advances in Scientific Research and Engineering*, vol. 9, no. 2, pp. 29–35, 2023, doi: 10.31695/IJASRE.2023.9.2.4.
- [12] C. M. Lind, F. Abtahi, and M. Forsman, "Wearable Motion Capture Devices for the Prevention of Work-Related Musculoskeletal Disorders in Ergonomics—An Overview of Current Applications, Challenges, and Future Opportunities," *Sensors*, vol. 23, no. 9, Art. no. 4259, 2023, doi: 10.3390/s23094259.
- [13] K. Sirikasemsuk, P. Kittipanya-Ngam, D. Luanwiset, and K. Leerojanaprapa, "Work posture risk comparison of RULA and REBA based on measures of assessment-score variability: A case study of the metal coating industry in Thailand," *International Journal of Innovative Research and Scientific Studies*, vol. 7, no. 3, pp. 926–935, 2024, doi: 10.53894/ijirss.v7i3.2978.
- [14] F. Motta, T. Varrecchia, G. Chini, A. Ranavolo, and M. Galli, "The Use of Wearable Systems for Assessing Work-Related Risks Related to the Musculoskeletal System—A Systematic Review," *International Journal of Environmental Research and Public Health*, vol. 21, no. 12, Art. no. 1567, 2024, doi: 10.3390/ijerph21121567.
- [15] M. K. A. Serunting and H. Hz, "Analisis risiko ergonomi pada karyawan bengkel utama yang mengalami keluhan Musculoskeletal Disorders di PT Bukit Asam Tanjung Enim," *Jurnal Ilmu Kesehatan Masyarakat*, vol. 3, no. 2, pp. 58–66, 2017.
- [16] D. Suryanto and R. A. F. Ginanjar, "Hubungan risiko ergonomi dengan keluhan Musculoskeletal Disorders (MSDs) pada pekerja informal bengkel las," *Jurnal Ilmu Kesehatan Masyarakat*, vol. 3, pp. 196–202, 2019.
- [17] National Institute for Occupational Safety and Health, "About Ergonomics and Work-Related Musculoskeletal Disorders," *Centers for Disease Control and Prevention*, Feb. 21, 2024. Accessed: Aug. 7, 2026.
- [18] T. R. Waters, V. Putz-Anderson, and A. Garg, *Applications Manual for the Revised NIOSH Lifting Equation*, DHHS (NIOSH) Publication No. 94-110, revised Sept. 2021, doi: 10.26616/NIOSH PUB94110revised092021.

Article

Dynamometer Testing of Electric Vehicles: Methods, Standards, and Emerging Trends

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Abstract: Dynamometer testing (dynotest) is essential for evaluating electric vehicle (EV) performance under controlled laboratory conditions, enabling repeatable measurement of power, torque, efficiency, and energy consumption while emulating real-world driving cycles. This review surveys recent developments in EV dynotesting, highlighting IEEE and international test standards, key performance parameters, and evolving methodologies. We compare chassis and hub dyno architectures, including new “vehicle-in-the-loop” and modular test benches, and discuss integration of hardware-in-the-loop (HIL) simulation for real-time controller validation. Standardized drive cycles (e.g. WLTP, EPA/UDDS, JC08) are widely used on dynos to benchmark EV energy use. We summarize representative studies that apply dynotests to EV powertrains, including single-motor and dual-/multi-motor drivetrains. Emerging challenges are reviewed: bidirectional (regen) energy flow, thermal management under high load, synchronization of multiple drive units and batteries, and specialized needs for all-wheel-drive (AWD) and multi-motor EV testing. The review concludes that comprehensive dynotest methods, combined with rigorous standards, HIL integration, and advanced data analysis, are critical for validating next-generation EV drivetrains and enabling accurate energy-consumption benchmarking. Future work should address remaining gaps in multi-axis dyno platforms, long-term durability tests, and AI-driven real-time analysis during dyno runs.

Keywords: Electric Vehicle; Chassis Dynamometer; Drive Cycle; Hardware-In-The-Loop, Regenerative Braking; All-Wheel-Drive

Citation: Noval, R., Apriana, A., Danardono, A. S., Heryana, G., Zainuri, F., Adhitya, M., Hidayat Tullah, M., Ramdhan, F. R. (2026). Dynamometer Testing of Electric Vehicles: Methods, Standards, and Emerging Trends. *Recent in Engineering Science and Technology*, 4(3), 165–175. Retrieved from <https://www.mbi-journals.com/index.php/riestech/article/view/133>.

Academic Editor: Noor Hidayati

Received: 17 April 2026

Accepted: 11 June 2026

Published: 31 July 2026

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1. Introduction

The shift to electrified mobility has driven demand for precise EV performance evaluation. Unlike internal combustion engines, EV drivetrains offer high efficiency but introduce new testing requirements such as energy recovery and rapid thermal dynamics. Dynamometer test benches (dynotests) enable simulation of road-load conditions in a repeatable way[1, 2]. A chassis dynamometer (“roller dyno”) uses motorized rollers to impose road-load torque on the vehicle’s wheels, while a hub dynamometer tests individual motors or e-axes directly on torque-rated shafts. IEEE 1515-2000 (Electronic Power Subsystems) provides foundational test definitions for powertrain subsystems, and related standards (e.g. IEEE 112-2017 for motors) specify measurement procedures[3]. Regulatory cycles (EPA urban/FTP, WLTP, JC08, etc.) have been codified as dynamometer driving schedules for EV certification and comparison[1, 4].

Dynamometer testing is crucial throughout EV development. For example, Alhanouti and Gauterin (2023) used an IEEE-compliant chassis dyno to examine measurement repeatability and accurately estimate EV energy use, validating dyno-based benchmarking

methods[1, 5-7]. Zainuri et al. (2022) evaluated a converted electric vehicle on a hub dyno, measuring torque, RPM and power to assess motor controller performance under dynamic load[8]. Experimental studies on standardized drive cycles (e.g. WLTC, EPA UDDS) have quantified EV energy consumption per km and illustrated the influence of load patterns [1,9-11]. These efforts demonstrate that dynotests are pivotal for drivetrain validation, efficiency mapping, and ensuring compliance with EV performance targets[12].

This review synthesizes recent literature (2019–2025) on EV dynamometer testing. We first outline common dyno architectures and test parameters, and then examine IEEE and industry standards that guide EV dynotest setups[13]. Next, we review drive-cycle and HIL-based methodologies used for EV testing. Key challenges—bidirectional energy flow, multi-motor synchronization, thermal effects, etc.—are discussed with supporting references[14]. We summarize representative studies (Table 1) illustrating various test configurations and research focuses. Throughout, we highlight gaps and recommend directions for future high-fidelity EV dynotest research.

2. Review Methodology

2.1 Literature Search Strategy

A structured literature search was conducted using IEEE Xplore, Google Scholar, and ScienceDirect from January to July 2026. The primary review period was limited to publications from 2019 to 2025. The search combined terms related to electric vehicles, dynamometer testing, and performance evaluation, with supplementary searches addressing drive cycles, hardware-in-the-loop (HIL), regenerative braking, thermal behavior, and multi-motor/all-wheel-drive (AWD) systems.

Core search string: ("electric vehicle" OR EV) AND ("dynamometer" OR "chassis dynamometer" OR "hub dynamometer" OR "motor dynamometer") AND (testing OR "performance testing" OR evaluation). Selected publications before 2019 were retained separately as foundational references when they provided essential historical, methodological, or technical context. The search and reporting structure was informed by PRISMA 2020 principles for transparent reporting of identification, selection, appraisal, and synthesis [1].

5.2 Inclusion and Exclusion Criteria

Tabel 1

Criterion	Inclusion	Exclusion
Publication period	2019–2025 for primary corpus	Outside the primary period, unless retained as foundational reference
Topic	EV dynamometer or closely related EV test-bench studies	Unrelated to EV testing or dynamometer evaluation
Testing focus	Power, torque, efficiency, energy, drive cycle, HIL, regeneration, thermal, multi-motor/AWD	Outside defined review scope
Publication type	Peer-reviewed journals, relevant conference papers, and technical papers with sufficient technical information	Duplicate, non-scientific, or insufficiently documented sources
Language	English	Non-English sources for the primary corpus

Publications meeting the inclusion criteria proceeded to screening and full-text assessment. Duplicate records and studies outside the defined scope were excluded from the primary evidence synthesis.

2.3 Study Selection

The study-selection process consisted of record identification, duplicate removal, title and abstract screening, and full-text assessment. A total of 185 records were identified from IEEE Xplore (n = 48), Google Scholar (n = 79), and ScienceDirect (n = 58). After duplicate

removal, 100 unique records remained for screening. Title and abstract screening excluded 50 records that did not satisfy the predefined relevance criteria. The remaining 50 records underwent full-text assessment, and 30 records were retained in the primary evidence set.

Tabel 2

c	Records
IEEE Xplore	48
Google Scholar	79
ScienceDirect	58
Total identified	185
Duplicates removed	85
Records screened	100
Excluded after title/abstract screening	50
Full-text assessed	50
Full-text excluded	20
Included in primary evidence set	30

The selection flow is summarized in Table 1. The 30-source primary evidence set was used for the structured synthesis; selected standards and pre-2019 foundational publications were treated separately as methodological or historical references.

2.4 Data Extraction and Synthesis

Data were extracted using a structured framework covering publication year, dynamometer type, vehicle or powertrain configuration, drive cycle or test condition, measured parameters, HIL integration, main research focus, key findings, and identified limitations or research gaps. The extracted information was synthesized across five dimensions: (1) dynamometer architecture, (2) testing objective, (3) testing methodology, (4) vehicle or powertrain configuration, and (5) emerging testing capability.

This classification was used to compare the literature rather than to reproduce each study as an isolated narrative summary. The resulting evidence map links test architecture and test objective to the methods and vehicle configurations used in recent EV dynamometer research. Representative studies are presented in Table 2.

2.5 Quality Assessment

Included sources were considered according to publication type, methodological clarity, relevance to the review scope, and the availability of sufficient technical or experimental information. Peer-reviewed journal articles with clearly described methods and direct relevance to EV dynamometer testing were treated as higher-strength evidence. Relevant conference and SAE technical papers were treated as supporting evidence when methods and findings were sufficiently documented. Foundational references and other supporting sources were used primarily for historical or methodological context and were not used to establish the principal evidence base.

2.6 Review Scope and Limitations

The primary evidence synthesis was limited to literature published from 2019 to 2025 and retrieved from IEEE Xplore, Google Scholar, and ScienceDirect. Relevant studies indexed exclusively in other databases may therefore have been missed. In addition, heterogeneity in dynamometer architecture, vehicle configuration, drive cycles, test conditions, and reported parameters limits direct quantitative comparison across all

studies. Pre-2019 publications were retained selectively as foundational references rather than as part of the primary evidence set.

3. EV Dynotest Architectures and Standards

3.1 EV Dynotest Architectures and Standards

Dynamometer test systems for EVs range from simple single-axle rigs to advanced multi-axis platforms. The most common setup is a chassis dynamometer with two rollers for one axle; it spins the wheels while measuring torque and speed[15]. A more modular approach is a hub dynamometer, where individual wheels or e-motor shafts are connected directly to torque sensors, isolating drivetrain losses such as tire slip[16-18]. For example, Alhanouti et al. (2023) describe a vehicle-in-the-loop chassis dyno at KIT that uses wheel-hub dynos to remove tire uncertainty, enabling precise drivetrain power and efficiency measurements[1, 19]. In general, chassis dynos include tire effects and inertia but allow testing of the full vehicle (including auxiliaries), whereas hub dynos provide more controlled motor-only tests.

Key performance parameters measured on an EV dyno include:

1. Power and Torque: Real-time wheel torque and speed are used to compute motor output; measurement uncertainty depends on sensor accuracy and dynamometer calibration [2, 16].
2. Efficiency: Comparison of input electrical power (from battery) to mechanical output yields motor-inverter efficiency. Mapping efficiency over torque–speed space requires multiple dyno sweeps.
3. Energy Consumption: Simulating standard drive cycles allows calculation of Wh/km (or miles/kWh) for the whole vehicle [16].
4. Regenerative Braking: Bidirectional power flow must be handled; dyno braking modules (dyno-in-the-loop) absorb or return energy to the battery during deceleration tests. Accurately emulating regenerative torque is challenging and requires careful control algorithms.
5. Thermal Response: Long-duration tests track motor/inverter temperatures under sustained load, which is critical for thermal management evaluation. Few studies explicitly focus on thermal behavior, but it is recognized as a limiting factor in continuous dyno testing.
6. Dynamic Response: High-speed data acquisition is used during step inputs (acceleration, deceleration) to capture transient behavior and any control system latency [20, 21].

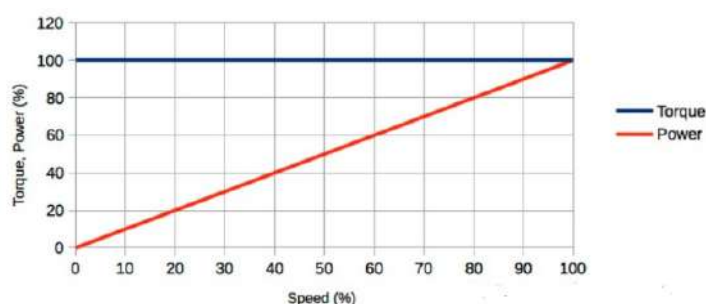


Figure 1. Torque vs Motor Speed.

http://engineeringtoolbox.com/electrical-motors-hp-torque-rpm-d_1503.html

Standards play a guiding role in dyno testing. IEEE Std. 1515-2000 (Recommended Practice for Electronic Power Subsystems) provides parameter definitions and test conditions for EV powertrains. IEEE 112-2017 defines induction motor test procedures that are applicable to EV traction motors. More recent guidelines, like IEEE Std. 1679.1-2017,

address battery characterization (though for stationary use) and suggest approaches for battery testing in vehicle setups[3]. In practice, dynotest facilities often adapt automotive regulations (UNECE, SAE J1634, etc.) for EV energy and efficiency testing, embedding standard drive cycles into the dyno control software. For example, WLTP and US EPA driving schedules are routinely programmed into chassis dynos to ensure consistency with certification procedures.

3.2 Drive Cycles and Test Protocols

A primary function of EV dynotests is to reproduce standardized drive cycles under laboratory conditions. These include urban and highway cycles specified by regulatory bodies (e.g. EPA's UDDS and HWFET, WLTP low/mid/high classes, Japan's JC08). On a chassis dyno, the vehicle's wheels are driven to follow a target speed profile; accompanying rollers generate the requisite road-load torque via a polynomial "road load" curve derived from coast-down tests. Tests may be done by a human driver or by steering/throttle robots for repeatability. The resulting energy use per cycle is used to compute consumption (Wh/km) and range estimates under that drive pattern.

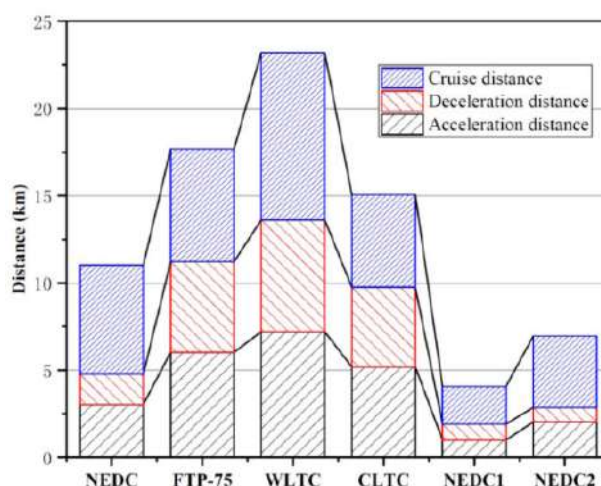


Figure 2. Energy Consumption per Drive Cycle

<https://www.evengineeringonline.com/how-is-the-energy-consumption-and-range-of-evs-measured/>

Dynotest studies have leveraged these cycles to compare EV performance. For example, Lairenlakpam et al. (2019) ran a converted EV through WLTC and Indian driving cycles on a chassis dyno and reported speed, torque, and energy-consumption metrics[9]. These data helped assess the prototype powertrain's city/highway efficiency. Similarly, Alhanouti and Gauterin (2023) tested an EV on both NEDC and WLTP cycles, identifying discrepancies between expected and measured energy due to tire-roller interactions. Their work underlines that even with standardized profiles, physical dyno conditions (roller inertia, tire slip) can affect results[1]. They ultimately developed a tire-roller friction model (LuGre model) to reconcile dyno measurements with vehicle simulations. This finding shows the importance of accounting for dynamometer system dynamics when interpreting drive-cycle tests[22, 23].

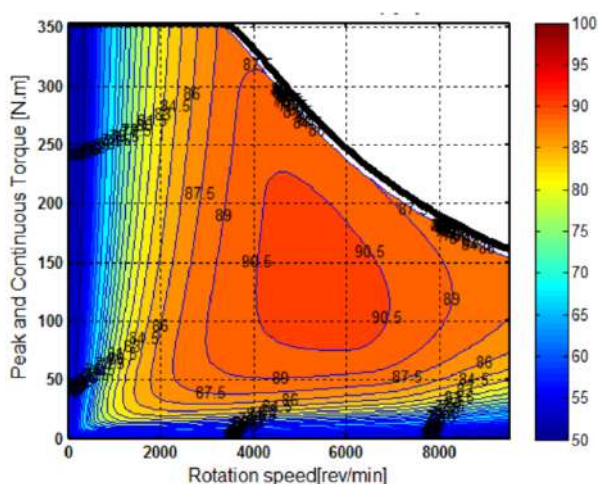


Figure 3. Motor Efficiency Map

https://www.researchgate.net/figure/Efficiency-map-of-the-electric-motor-and-inverter_fig4_323522307

In summary, drive-cycle dynotesting provides a consistent basis for energy consumption benchmarking. By using harmonized procedures, researchers can compare EV models and validate simulations. The literature repeatedly emphasizes that strict adherence to standard cycles (and proper dyno calibration) is needed to yield meaningful efficiency and power metrics.

3.3 Drives Cycles and Protocols

Integrating hardware-in-the-loop (HIL) simulation with dynotesting enables advanced control validation. In an HIL setup, part of the vehicle (often the control unit) is real hardware, while the plant (motor, vehicle dynamics, etc.) is emulated by a real-time simulator. For EVs, HIL platforms have been developed to accelerate drivetrain and controller testing. Poon et al. (2012) pioneered an EV HIL rig where a small-scale EV drive controller was tested against real-time models of vehicle dynamics and road-load; they demonstrated successful use of the EPA UDDS drive cycle in closed-loop tests[24]. More recently, Badardin and Abu Bakar (2023) described a modular EV dyno platform with an HIL subsystem that simulated driving cycles and validated control logic under dynamic loads[25].

Crucially, Düzgün et al. (2025) have demonstrated that a well-designed HIL testbench can emulate a full PHEV drivetrain with high fidelity. In their study, the HIL system ran a series-parallel hybrid control unit through WLTC driving profiles; the chassis simulation matched target speeds ($R^2 \approx 0.9993$) and battery state-of-charge (SoC) stayed within ± 50 Wh of the real cycle. Overall energy errors were under 1%, and fuel/ CO_2 deviations under 3%[5]. This shows HIL can closely reproduce vehicle-level efficiency and energy flow. However, such complex HIL-dyno rigs remain mostly in research labs due to high cost and integration effort.

Hardware-in-the-loop dynotesting allows real-time controller calibration and fault injection (e.g. grid disturbances, battery faults) without risking a full vehicle[26, 27]. While substantial HIL work on EVs exists (Poon et al., 2012; Düzgün et al., 2025), published studies of HIL with actual dyno benches are still emerging. In practice, some labs use “dyno-in-the-loop” by connecting a dyno with real-time simulation of battery and loads[24]. For example, an autonomous vehicle test at WMich described a CAN-bus-enabled drive kit on a chassis dyno to replay EPA cycles, demonstrating that dyno controllers can mirror real EV behavior under software control[28, 29]. In this way, HIL and dyno testing converge to create “virtual vehicles” on the bench[5].

3.4 Representative Dynotest Studies

The literature was synthesized by comparing architecture, testing objective, methodology, and vehicle configuration rather than repeating each study as an independent narrative. Table 2 provides a representative extraction of studies that directly illustrate the dominant approaches identified in the review.

Study	Dyno / Testbench	Vehicle / System	Test / Method	HIL	Main measurements	Main focus
Alhanouti & Gauterin (2023) [6]	Roller chassis	EV	NEDC / WLTP-class 2	No	Energy, torque, power	Repeatability and energy estimation
Noval et al. (2025) [7]	Chassis dyno	Light EV	Controlled dynamometer tests	No	RPM, torque	Dynamometer accuracy
Lairenlakpam et al. (2019) [8]	Chassis dyno	Converted EV	IDC, MIDC, WLTC	No	Speed, torque, energy	Drive-cycle performance and energy
Zainuri et al. (2022) [9]	Hub dyno	Converted EV	Dynamic loading	No	Torque, RPM, power	Retrofitted EV powertrain
Düzgün et al. (2025) [10]	HIL testbench	PHEV	WLTC / closed loop	Yes	Speed, energy, SoC	Controller validation
Gong et al. (2023) [11]	HIL / simulation	EV powertrain	Real-time HIL	Yes	Control variables	Controller-HIL methods
Reick et al. (2021) [12]	Chassis dynamometer	EV/HEV	Power measurement	Optional	Wheel power, motor power	EV power-test procedure
Rautenberg et al. (2023) [13]	VIL chassis / hub dyno	BEV	WLTP	No	Power, efficiency	Reproducible drivetrain testing
Badardin & Abu Bakar (2023) [14]	HIL system	EV test platform	Driving-cycle simulation	Yes	Torque, cycle response	HIL drive-cycle validation
Goberville et al. (2025) [15]	Modular dynamometer	Vehicle + virtual scenario	Automated-driving scenarios	Yes	Energy, propulsion response	Interoperable VIL/ADS testing

The representative studies reveal a progression from conventional chassis-dynamometer measurements toward increasingly modular and simulation-integrated test environments. Chassis systems remain important for vehicle-level energy and performance measurements, while hub and powertrain configurations are useful when component-level isolation is required. HIL and VIL methods are increasingly used for controller validation and automated-driving scenarios, but their additional model and synchronization requirements limit their use to more specialized laboratories [6,10–15].

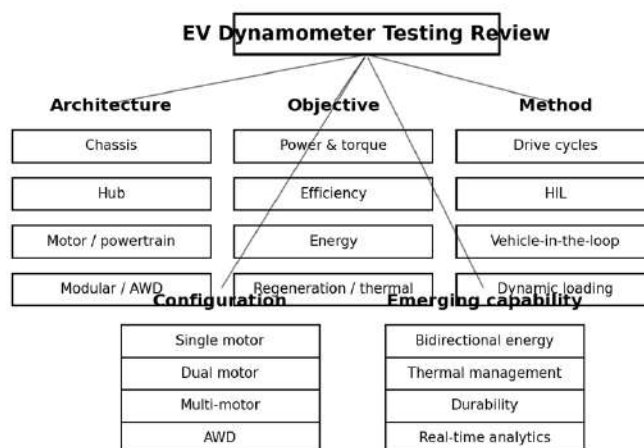
The synthesis also indicates that energy consumption, power, and torque are better represented in the literature than long-duration durability or comprehensive thermal characterization. Multi-motor and AWD testing is emerging, particularly where torque-vectoring and automated-driving scenarios require independent control of multiple axles. These patterns motivate the taxonomy shown in Figure 3.

3.5 Challenges and Emerging Trends

EV dynotesting presents several unique challenges beyond those of conventional ICE vehicles:

1. **Bidirectional Energy Flow:** Regenerative braking means the dyno must absorb returned energy or feed it back to the battery. Emulating precise regen torque profiles requires fast-response dyno brakes and control loops. Studies note that test setups must handle both motoring and generating modes seamlessly. In practice, many dynos dissipate regen energy in resistors or recirculate it, but sophisticated rigs can return it to the grid or battery. This “bidirectional” operation can introduce stability issues if control is not tightly synchronized with vehicle feedback loops[35, 36].

2. **Thermal Effects:** EV motors and inverters heat up quickly under test conditions. Continuous high-load dyno runs (e.g. sustained full power) can lead to thermal saturation, altering performance. Only a few studies have addressed this, but it is widely recognized as a limitation on test duration. Proper cooling (liquid jackets, fans) and thermal monitoring are essential to maintain steady-state test conditions and to characterize component limits[37-39].



3. **System Synchronization:** Accurate dyno results require tight synchronization among vehicle subsystems. Motor controllers, inverters, and the battery management system (BMS) must be coordinated with the dyno's control. Any latency or misalignment (e.g. time lags in control signals) can skew the power or torque readings. Lairenlakpam et al. note that mismatches in controller response can affect energy-consumption measurements under drive cycles. Similarly, when multiple motors (AWD) are tested, synchronizing torque and speed across axles is complex[9, 40, 41].
4. **HIL Complexity:** While HIL offers richer testing, it adds cost and complexity. Building a stable real-time simulation that includes battery dynamics, power electronics, and mechanical loads is nontrivial. The benefit is accelerated calibration (as Düzgün et al. showed), but setting up vehicle-in-the-loop "dyna-sims" requires extensive model validation. Moreover, PHIL (power hardware-in-loop) to include actual battery or motor hardware with simulated loads is an emerging area but not yet mainstream in EV dyno labs[25, 42].
5. **Multi-Axle and AWD EV Testing:** Many current dynos are single-axle. Testing AWD or multiple motor EVs (common in high-performance and commercial vehicles) necessitates multi-belt or multi-roller setups. Statically linking two rollers can test a 4WD vehicle, but dynamic torque-vectoring scenarios require independent control of each wheel's load. Few published studies have reported full multi-axis EV dynos; Goberville et al. (2025) is a rare example of a planned modular AWD testbed. The literature calls for more research on dyno methods that can impose uneven loads for torque vectoring and differential braking – conditions that single-axle tests cannot simulate[18, 43, 44].
6. **Environmental Factors:** Standard dynos typically simulate level, uniform road conditions. Real-world factors like inclines, crosswinds, or rough pavement are usually omitted. Some advanced rigs now incorporate adjustable road-load profiles or climate chambers, but these remain specialized. Future high-fidelity dynos may need to emulate these variables to fully predict EV performance in varied conditions[30, 45-48].
7. **Long-Term Durability Testing:** Current studies focus on short-cycle performance. The community has identified a gap in accumulated mileage or endurance tests on dynos to

- simulate aging of batteries, motors, and power electronics. Extended stress testing (e.g. thousands of hours) on a dyno could reveal reliability issues, but standardized protocols for such tests are not yet established[22, 49-53].
8. Addressing these challenges requires harmonized protocols and new instrumentation. One underexplored area is real-time data analytics during dyno tests. Integrating machine learning or AI for anomaly detection could improve calibration (e.g. identifying friction changes) on the fly. Additionally, mobile testbeds and vehicle-in-loop approaches hint at a future where dyno labs can incorporate live or recorded traffic data for even more realistic driving simulations[24, 29, 54, 55].

4. Conclusions

Dynamometer testing is foundational for EV development, offering controlled, repeatable evaluation of powertrain performance. The literature shows that chassis and hub dynos—when coupled with standardized drive cycles—provide critical data on power, torque, efficiency, and energy use. IEEE and automotive test standards ensure that measurements are comparable across studies. Emerging trends include modular multi-motor dynos and integration of hardware-in-the-loop simulation for real-time controller validation.

To meet the needs of modern EVs, test benches must handle bidirectional energy flow (regeneration) and multiple motors, and they must accommodate advanced features like torque vectoring. High-impact studies in recent years (see Table 1) have begun to explore these aspects, but significant gaps remain. Notably, there is a need for standardized protocols on durability cycling, for multi-axis AWD testing, and for leveraging real-time analytics in dyno environments.

In sum, rigorous dynamometer methods—grounded in established standards and enhanced with modern simulation technologies—are essential for validating next-generation EV technologies. Future work should pursue unified test protocols for EV-specific phenomena, incorporate HIL and AI tools for smarter testing, and expand testing frameworks to cover the full range of multi-motor and real-world driving scenarios. These developments will ensure that dynotest remains a vital part of the EV design and certification process, helping to accelerate the transition to cleaner transportation.

Table 1 Sources: Study details are drawn from the cited literature, including Alhanouti & Gauterin (2023), Zainuri et al. (2022), Lairenlakpam et al. (2019), Badardin & Abu Bakar (2023), Rautenberg et al. (2022), and Goberville et al. (2025), among others.

This review provides a structured synthesis of EV dynamometer testing across test architecture, testing objective, methodology, vehicle configuration, and emerging capability. The literature indicates that chassis dynamometers remain central to vehicle-level power, torque, efficiency, and energy-consumption evaluation, while hub and powertrain dynamometers provide greater isolation of drivetrain components. Standardized procedures such as SAE J1634, SAE J2263, UN GTR No. 15, and UN Regulation No. 85 provide complementary foundations for energy consumption, road-load determination, drive-cycle testing, and electric-drive power measurement [2–5].

HIL and VIL approaches expand the capability of dynamometer laboratories by enabling closed-loop controller validation and integration with simulated driving environments. At the same time, they introduce additional requirements for model accuracy, synchronization, and instrumentation. The evidence synthesis indicates that conventional power and energy measurements are more mature than thermal characterization, long-term durability, and multi-axis AWD testing.

The principal research gaps are therefore methodological and infrastructural: harmonized EV-specific dynamometer procedures, robust bidirectional energy-flow control,

standardized multi-axis AWD testing, longer-duration thermal and durability protocols, and validated real-time data analytics. These gaps provide a clearer basis for future research than broad calls for “advanced testing” alone. The review should be interpreted within its scope and database limitations; nevertheless, the proposed evidence map provides a practical framework for organizing future EV dynamometer studies.

Declarations

Data Availability: The review is based on published literature and the structured search and screening procedure described in Section 2.

Conflict of Interest: The authors declare that they have no financial, personal, professional, or other relationships that could influence the objectivity or interpretation of this work.

Conflic of Interest

This sentence explicitly states that the author of the article or scientific report has no financial, personal, professional, or other affiliations that could be considered a potential conflict that could affect the objectivity, integrity, or transparency of the scientific work. This statement is made to maintain reader confidence in the neutrality of the research

References

1. Alhanouti, M. and F. Gauterin, Thorough Analysis of the Reliability of Measurements on Chassis Roller Dynamometer and Accurate Energy Consumption Estimation for Electric Vehicles. *Energies*, 2023. 16(24): p. 7994.
2. Noval, R., et al., Performance Evaluation and Accuracy Analysis of a Chassis Dynamometer for Light Electric Vehicles. *World Electric Vehicle Journal*, 2025. 16(3): p. 170.
3. Lairenlakpam, R., P. Kumar, and G.D. Thakre, Experimental investigation of electric vehicle performance and energy consumption on chassis dynamometer using drive cycle analysis. *SAE International Journal of Sustainable Transportation, Energy, Environment, & Policy*, 2019. 1(13-01-01-0002): p. 23-38.
4. Subsystems, E.P., IEEE Standards. 2004.
5. Düzgün, M.T., et al., Dynamic Closed-Loop Validation of a Hardware-in-the-Loop Testbench for Parallel Hybrid Electric Vehicles. *World Electric Vehicle Journal*, 2025. 16(5): p. 273.
6. Fanesi, M., Study of intelligent test bench for development and project of electric systems for traction of innovative vehicles. 2021.
7. Gong, W., et al., A model review for controller-hardware-in-the-loop simulation in EV powertrain application. *IEEE Transactions on Transportation Electrification*, 2023. 10(1): p. 925-937.
8. Zainuri, F., et al., Performa Performa Kendaraan Konversi Listrik melalui Pengujian Dynotest. *Jurnal Mekanik Terapan*, 2022. 3(2): p. 44-49.
9. Lairenlakpam, R., P. Kumar, and G.D. Thakre, Experimental Investigation of Electric Vehicle Performance and Energy Consumption on Chassis Dynamometer Using Drive Cycle Analysis. *SAE International Journal of Sustainable Transportation, Energy, Environment, & Policy*, 2019. 1(1): p. 23-38.
10. Du, W., et al., Optimization design and performance comparison of different powertrains of electric vehicles. *Mechanism and Machine Theory*, 2021. 156: p. 104143.
11. Heryana, G., et al., Analysis of behavior in the use of plug-in hybrid electric vehicle and hybrid electric vehicle in the tropics. *EUREKA: Physics and Engineering*, 2021(1): p. 97-105.
12. Osman, A.G., et al. Evaluation of Electric Vehicle Performance Based on High-Fidelity Modeling and Experimental Testing. in *2024 6th Novel Intelligent and Leading Emerging Sciences Conference (NILES)*. 2024. IEEE.
13. Di Russo, M., Investigation in the Uncertainty of Chassis Dynamometer Testing for the Energy Characterization of Conventional, Electric and Automated Vehicles. 2023, Illinois Institute of Technology.
14. D'Alvia, L., et al., Scaled test bench for the measurement of a hybrid full-electric powertrain efficiency. *Measurement: Sensors*, 2024: p. 101433.
15. Waraich, R.A., Agent-based simulation of electric vehicles: design and implementation of a framework. 2013, ETH Zurich.

16. Rautenberg, P., et al., Battery Electric Vehicle-in-the-Loop Power and Efficiency Measurement Test Method. SAE International Journal of Advances and Current Practices in Mobility, 2023. 6(2023-24-0182): p. 1925-1935.
17. Xu, S., et al., Research on Optimal Driving Torque Control Strategy for Multi-Axle Distributed Electric Drive Heavy-Duty Vehicles. Sustainability, 2024. 16(16): p. 7231.
18. Goberville, N., et al., Modular Dynamometer Testing Framework to Evaluate Energy Impacts of Longitudinal Automated Driving Systems. 2025, SAE Technical Paper.
19. Gonzalez-Jimenez, D., et al., Data-driven fault diagnosis for electric drives: A review. Sensors, 2021. 21(12): p. 4024.
20. Li, W., et al., A test technology of a vehicle driveline test bench with electric drive dynamometer for dynamic emulation. 2015, SAE Technical Paper.
21. Rjabtšikov, V., et al., Review of electric vehicle testing procedures for digital twin development: a comprehensive analysis. Energies, 2023. 16(19): p. 6952.
22. Jaworski, A., et al., Assessment of the Effect of Road Load on Energy Consumption and Exhaust Emissions of a Hybrid Vehicle in an Urban Road Driving Cycle—Comparison of Road and Chassis Dynamometer Tests. Energies, 2023. 16(15): p. 5723.
23. Zamzam, A.S., X. Fu, and N.D. Sidiropoulos, Data-driven learning-based optimization for distribution system state estimation. IEEE Transactions on Power Systems, 2019. 34(6): p. 4796-4805.
24. Poon, J.J., et al. Hardware-in-the-loop testing for electric vehicle drive applications. in 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC). 2012. IEEE.
25. Badardin, E.D. and S.A.A. Bakar, SIMULATING ELECTRIC VEHICLE DRIVING CYCLES WITH A HARDWARE-IN-LOOP (HIL) SYSTEM. Journal of Transport System Engineering, 2023: p. 73-77.
26. Kaarthik, R.S. and P. Pillay. Real-time power hardware-in-the-loop emulation of a parallel hybrid electric vehicle drive train. in 2017 IEEE Transportation Electrification Conference (ITEC-India). 2017. IEEE.
27. Sumarsono, D.A., et al., Performance Analysis of a Main Drive Motor—Initial Study of an EV Modeling Software Design. World Electric Vehicle Journal, 2021. 12(4): p. 246.
28. Brown, N.E., et al. Evaluation of Autonomous Vehicle Sensing and Compute Load on a Chassis Dynamometer. in 2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC). 2023. IEEE.
29. Provencher, H., Design and implementation process for controls integration using CAN bus on a full function electric vehicle conversion. 2014, UOIT.
30. Zhang, J., et al., Energy consumption analysis and prediction of electric vehicles based on real-world driving data. Applied Energy, 2020. 275: p. 115408.

Optimization of Fork Tines Design on a 3-Ton Capacity Forklift Using Heel Radius and Thickness Geometry Variation via Finite Element Analysis

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Abstract: Structural failure at the heel area of forklift fork tines due to high stress concentration is a serious safety concern in the logistics industry. This study aims to optimize the geometry of ISO Class 3 fork tines with a 3-ton capacity to achieve a design with maximum strength and efficient mass. The design methodology utilizes a 3² factorial design via the Taguchi approach (L9 orthogonal array) by varying the Heel Radius (65, 75, 85 mm) and Base Thickness (40, 50, 60 mm). Testing was performed numerically through static Finite Element Analysis (FEA) on AISI 4140 Alloy Steel, assuming a uniform load of 15,000 N per fork arm at a Load Center distance of 500 mm. Initial validation of the numerical model against analytical cantilever-beam calculations resulted in an error below 1%, confirming simulation accuracy. ANOVA results prove that base thickness is the primary and most dominant parameter significantly affecting stress (P-value 0.003 < 0.05). Through comparative analysis, Design 6 (D6), combining an 85 mm Heel Radius and 50 mm Thickness, was selected as the most optimal configuration, reducing maximum stress to 208.5 MPa and increasing the Factor of Safety (FoS) to 1.99, significantly safer than the factory-standard design (FoS 1.84) while maintaining a mass efficiency of 97 kg. The optimized AISI 4140 design is structurally safe for static operation and is recommended as a fabrication standard.

Keywords: Forklift; Fork Tines; Finite Element Analysis; Taguchi Method; AISI 4140.

Citation: Wahid, E. N., Silitonga, M. P. (2026). Optimization of Fork Tines Design on a 3-Ton Capacity Forklift Using Heel Radius and Thickness Geometry Variation via Finite Element Analysis. *Recent in Engineering Science and Technology*, 4(3), 176–184. Retrieved from <https://www.mbi-journals.com/index.php/riestech/article/view/179>.

Academic Editor: Noor Hidayati

Received: 12 May 2026

Accepted: 15 July 2026

Published: 31 July 2026

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1. Introduction

Material handling efficiency is a critical requirement of modern logistics and warehousing systems, and the forklift remains the primary vehicle used to transport heavy loads that cannot be handled manually. The operational effectiveness of a forklift is strongly dependent on the reliability of its critical components, particularly the lifting system and the fork tines, which interact directly with the load and must withstand extreme, repetitive bending moments during service.

Structural failure of forklift fork tines is a serious safety issue in industrial operations. Field failure data indicate that damage most frequently occurs at the heel, the right-angle transition zone between the vertical shank and the horizontal blade. This failure mode is generally caused by fatigue resulting from high stress concentration at the heel radius; when the geometry of this critical area is not optimized, the risk of sudden fracture during operation increases sharply, endangering both equipment and operator safety [1].

Mechanically, the L-shaped geometry of the fork creates a substantial stress-concentration zone at the inner corner radius [2]. Consequently, the heel radius and the base thickness of the fork are the two dominant geometric parameters governing how bending loads are distributed and whether the resulting stresses remain below the

material's elastic limit. Evaluating and reducing the risk of structural failure therefore requires a design approach built on computer simulation. Finite Element Analysis (FEA) allows a wide range of fork-tine geometries to be tested virtually, enabling identification of the location and magnitude of the maximum von Mises stress and the resulting Factor of Safety in a comprehensive and repeatable manner [3].

Previous studies have examined forklift design and structural performance from several perspectives. Sun et al. investigated the structural design and load-carrying performance of a transportation fork used in a hot-stamping production line [4], while Wu et al. successfully integrated finite element analysis with Taguchi statistics to reduce the mass of a precision machine-tool bed without compromising its stiffness, a methodology directly relevant to fork-tine optimization [5]. More specifically, Mahdiah et al. redesigned the lifting system of a large-capacity (10-ton) forklift using FEM simulation [6], although that work focused on validating a design for an extreme load case rather than exploring the combined effect of heel radius and base thickness at standard capacities.

Despite this body of work, the combined influence of heel radius and base thickness on the Factor of Safety of a 3-ton class fork tine manufactured from AISI 4140, a chromium-molybdenum alloy steel known for its favorable fatigue resistance, has not been thoroughly explored [7], [8], [9]. This research gap motivates the present study, which applies Finite Element Analysis together with a Taguchi 3^2 factorial design to systematically vary the heel radius and base thickness of a standard 3-ton forklift fork tine, with the objective of identifying an optimal configuration that satisfies industrial safety standards while remaining mass-efficient [10], [11].

Under the international classification ISO 2328, forklifts are grouped by lifting capacity, and a unit rated at 3000 kg falls under Class 3, a category widely used in manufacturing, logistics, and warehousing for pallet mobilization [9]. The overall performance of such a unit is governed not only by its ability to lift a rated load but also by its safety margin, commonly expressed as the Factor of Safety (FoS), the ratio between the material's yield strength and the maximum working stress. A component is considered structurally optimal when it can sustain the maximum operating load without plastic deformation or fracture while avoiding unnecessary mass, since excessive dead weight reduces the efficiency of the vehicle's hydraulic lifting system and its overall load-to-weight ratio [8], [14]. Balancing these two competing requirements, strength and efficiency, is therefore the central engineering problem addressed by this research, and it is approached here through a combined FEA-Taguchi optimization framework.

The remainder of this paper is organized as follows. Section 2 describes the fork-tine geometry, material properties, Taguchi experimental design, and the finite element simulation procedure, including the analytical validation method. Section 3 presents the validation results, the FEA outcomes for all nine design variations, the Signal-to-Noise ratio analysis, and the ANOVA-based statistical evaluation of factor significance, culminating in the selection of the optimal design. Section 4 concludes the paper and outlines directions for future work, including experimental fatigue validation and dynamic loading analysis.

2. Materials and Experiment Methods

The object of this study is an ISO Class 3 forklift fork tine with a nominal lifting capacity of 3 tons (3000 kg), which operates on the mechanical principle of a cantilever beam fixed at the carriage and free at the loaded end [9], [12]. The material selected for the fork tine is AISI 4140 alloy steel (Chromium-Molybdenum Steel), a low-alloy steel widely used in heavy-equipment components such as axles, gears, and forklift forks because of its combination of high toughness, good tensile strength, and favorable fatigue resistance [7]. The mechanical properties of AISI 4140 used as simulation input were: Yield Strength 415 MPa, Tensile Strength 655 MPa, Elastic Modulus 210 GPa, and Poisson's Ratio 0.29. A

3^2 factorial design based on the Taguchi L9 orthogonal array was applied to obtain nine design variations while minimizing the number of required simulations. Two control factors were varied: Heel Radius (Factor A) and Base Thickness (Factor B), each at three levels, as summarized in Table 1. Other dimensions, including the total blade length and the 140 mm cross-sectional width, were held constant across all variations.

Table 1. Factors and levels of the 3^2 factorial design for geometry variation.

Factor	Level 1	Level 2	Level 3
Heel Radius (A)	65 mm	75 mm	85 mm
Base Thickness (B)	40 mm	50 mm	60 mm

Nine 3D CAD models (D1–D9), each corresponding to one row of the Taguchi L9 matrix, were constructed in SolidWorks. Each model was analyzed using static structural Finite Element Analysis. A fixed-geometry (fixed support) boundary condition was applied to the vertical shank, representing attachment to the carriage, while a uniform load of 15,000 N was distributed over the horizontal blade at a Load Center distance of 500 mm from the base, in accordance with standard forklift load-rating conventions [10], [13]. Each model was then meshed and solved, as described below, to extract three response variables for every design: maximum von Mises stress, total displacement, and the resulting Factor of Safety (FoS), computed as the ratio of the material's yield strength to the maximum von Mises stress.

The finite element mesh was generated in SolidWorks Simulation using second-order (10-node) tetrahedral solid elements and a curvature-based mesher. A global element size of 10 mm was applied to the fork body, while a local mesh control with an element size of 2 mm was imposed on the heel fillet surfaces, where the peak stress occurs, so that at least 8 elements span the fillet arc. For the baseline design D5 this produced 145,230 elements and 215,480 nodes, and the element count across the nine designs ranged from 138,500 to 152,400. Mesh independence was verified on the baseline design D5 by progressively reducing the local element size at the heel fillet and monitoring the maximum von Mises stress. The mesh was considered converged when the change in maximum stress between two successive refinements was below 2%; the converged local mesh settings were then applied unchanged to all nine designs. As shown in Figure 1, reducing the local element size from 10 mm to 5 mm changed the maximum von Mises stress by 17.6%, whereas further refinement from 3 mm to 2 mm and from 2 mm to 1.5 mm changed it by only 0.45% and 0.13%, respectively. A local element size of 2 mm was therefore adopted, giving a converged maximum stress of 225.5 MPa for D5, the value used in the validation and parametric study.

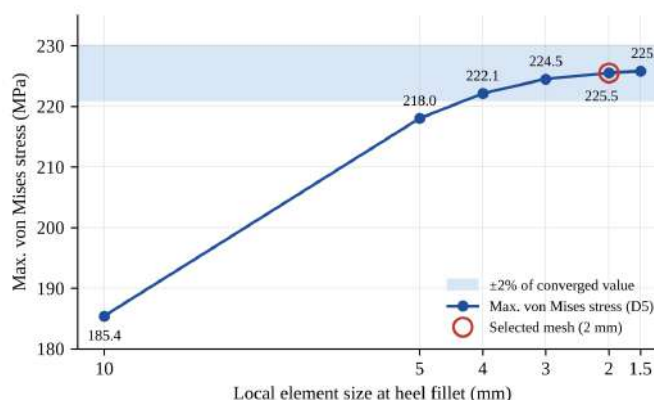


Figure 1. Mesh-convergence study for the baseline design (D5): maximum von Mises stress versus local element size at the heel fillet.

Prior to the parametric study, the numerical model was validated against analytical cantilever-beam calculations. The bending stress was computed from $\sigma = M \cdot y / I$, where M is the bending moment ($F \cdot L$), y is the distance from the neutral axis to the outer fiber, and I is the second moment of area of the rectangular cross-section, then corrected using a stress-concentration factor (K_t) derived from Peterson's charts for a filleted cantilever corner. Validation was accepted when the percentage error between the analytical and simulated stress values remained below the 10% tolerance limit [3], [6].

The nine sets of simulation responses were subsequently processed using the Taguchi Signal-to-Noise (S/N) ratio, with the Smaller-is-Better criterion selected because the optimization objective was to minimize stress and deformation. Analysis of Variance (ANOVA) was then performed at a 95% confidence level ($\alpha = 0.05$) to statistically determine which of the two geometric factors, heel radius or base thickness, exerts the more significant influence on the stress and deformation responses, following an approach analogous to Taguchi-FEA optimization frameworks applied in other precision-manufacturing contexts [5], [14]. Because each FEA run is deterministic and the L9 (3^2) design contains a single run per factor-level combination (no replication), only the two main effects were included in the ANOVA model. The Heel Radius $\times$ Thickness interaction, which has $(3 - 1)(3 - 1) = 4$ degrees of freedom, cannot be estimated separately in an unreplicated 3×3 design, since fitting it would leave no degrees of freedom for error. Consequently, the "Error" term ($DF = 4$) reported in Tables 4 and 5 represents the pooled interaction and higher-order effects rather than random measurement error, and the resulting F-tests for the main effects are conservative, because any genuine interaction inflates the error mean square.

The bending stress produced by the cantilever loading condition was computed analytically as $\sigma = M \cdot y / I$, where the bending moment M equals the applied force F multiplied by the load-center distance L , y is half of the base thickness (distance from the neutral axis to the outer fiber), and I is the second moment of area of the rectangular cross-section, $I = (1/12) \cdot b \cdot h^3$, with b the 140 mm section width and h the local thickness. The nominal stress was then multiplied by an empirical stress-concentration factor K_t , obtained from Peterson's charts for a filleted right-angle cantilever, to yield the theoretical maximum stress used for validation.

The Factor of Safety for each design was computed as $FoS = \sigma_{yield} / \sigma_{von-Mises}$, where σ_{yield} is the 415 MPa yield strength of AISI 4140 and $\sigma_{von-Mises}$ is the maximum von Mises stress obtained from the FEA solution for that design. Model accuracy was quantified using the percentage error, $\%Error = |(\sigma_{theoretical} - \sigma_{FEA}) / \sigma_{theoretical}| \times 100\%$, and a design was accepted as valid when this error remained below the 10% tolerance threshold commonly applied in FEA validation studies [6]. Finally, the Taguchi Smaller-is-Better S/N ratio for each factor level was computed as $S/N = -10 \cdot \log_{10}[(1/n) \cdot \sum(1/y^2)]$, where y represents the response value (stress or displacement) and n is the number of observations at that level; higher S/N values indicate a more favorable (lower-stress or lower-deflection) combination of factor levels.

3. Results and Discussion

Validation was performed by comparing the analytical bending stress of the baseline design (D5: 75 mm heel radius, 50 mm thickness) with the corresponding FEA result. The analytical nominal stress was calculated as 128.57 MPa, and after applying an estimated stress-concentration factor of $K_t \approx 1.75$, the theoretical maximum stress was 225.0 MPa, compared with an FEA result of 225.5 MPa, an error of only 0.22%.

The same procedure applied to all nine design variations produced errors consistently below 1%, well within the 10% tolerance limit, confirming that the mesh density and boundary conditions used in the simulation accurately represent the underlying mechanics of the fork tine.

Table 2. Recapitulation of FEA results for the nine fork-tine design variations.

Design	Heel Radius (mm)	Thickness (mm)	Max Stress (MPa)	Displacement (mm)	FoS	Mass (kg)
D1	65	40	261.4	24.61	1.59	76
D2	75	40	307	29.57	1.35	77
D3	85	40	315.5	31.42	1.32	78
D4	65	50	224.5	15.09	1.85	95
D5 (Standard)	75	50	225.5	15.82	1.84	96
D6 (Optimal)	85	50	208.5	16.54	1.99	97
D7	65	60	164.8	9.11	2.52	114
D8	75	60	169.9	9.53	2.44	115
D9	85	60	159	9.96	2.61	116

Two clear trends emerge from Table 2. First, increasing base thickness consistently and substantially reduces both stress and displacement: the 40 mm group (D1–D3) reached stresses as high as 315.5 MPa and deflections up to 31.42 mm, while the 60 mm group (D7–D9) remained below 170 MPa with deflections under 10 mm. Second, the effect of heel radius depends strongly on thickness. In the thin-plate group (40 mm), enlarging the radius from 65 to 85 mm unexpectedly increased stress from 261.4 to 315.5 MPa, a throat-thinning effect in which a larger inner radius, without a corresponding increase in outer wall thickness, reduces the net cross-sectional area at the heel. In the thicker groups (50 mm and 60 mm), the same increase in radius instead reduced stress by smoothing the stress-flow path around the corner, indicating that radius and thickness interact rather than act independently.

With respect to mass, Table 2 shows that the fork mass increases by approximately 19 kg for each 10 mm increase in base thickness and by only about 1 kg for each 10 mm increase in heel radius at constant thickness. This pattern is consistent across all three thickness groups and reflects the fact that thickness changes the cross-section along the entire blade and shank, whereas the heel radius only modifies the material volume locally at the corner.

The Taguchi S/N ratio analysis (Smaller-is-Better) shows that thickness has a far greater effect on the response than heel radius. For the stress response, the Delta value for thickness (130.1) is roughly 7.5 times larger than that for heel radius (17.2); a similar pattern is found for the displacement response, where thickness produced a Delta of 19.0 compared with only 3.0 for heel radius. Both response tables rank thickness first and heel radius second, indicating that thickness is the dominant control factor for both structural strength and stiffness. Table 3 presents the mean stress response for each factor level, from which the Delta and rank values were derived.

Table 3. Response table for mean stress by factor level (Taguchi analysis).

Level	Heel Radius (mean stress, MPa)	Thickness (mean stress, MPa)
1	216.9	294.6
2	234.1	219.5
3	227.7	164.6
Delta (Max–Min)	17.2	130.1
Rank	2	1

Table 4. ANOVA results for the maximum von Mises stress response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Heel Radius	2	454.7	227.4	0.61	0.585
Thickness	2	25580	12790	34.58	0.003
Error (pooled A×B interaction)	4	1479.6	369.9	-	-
Total	8	27514.3	-	-	-

Table 5. ANOVA results for the total displacement response.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Heel Radius	2	14.37	7.185	2.43	0.204
Thickness	2	562.2	281.097	94.94	< 0.001
Error (pooled A×B interaction)	4	11.84	2.961	-	-
Total	8	588.4	-	-	-

At a 95% confidence level, the ANOVA in Table 4 confirms that thickness is a statistically significant factor for the stress response ($P = 0.003 < 0.05$), whereas heel radius is not significant on its own ($P = 0.585 > 0.05$). H_0 is therefore rejected for thickness and accepted for heel radius with respect to the stress response. It should be noted that, because the Error term in Tables 4 and 5 pools the Heel Radius × Thickness interaction (see Section 2), the interaction between the two factors discussed above, most evident in the opposite stress trend of the 40 mm-thick designs, is identified from the response pattern in Table 2 rather than from a separate significance test.

An analogous ANOVA performed on the total displacement response, shown in Table 5, yielded $P < 0.001$ for thickness and $P = 0.204$ for heel radius, again showing that thickness is the sole statistically dominant factor governing both stress and stiffness, while heel radius does not produce a statistically detectable change in deflection on its own. This finding is consistent with elementary beam-bending theory, since the second moment of area of a rectangular cross-section scales with the cube of thickness ($I \propto h^3$), giving thickness a much stronger leverage on both bending stress and deflection than the fillet radius alone. Similar dominance of a single control factor identified through combined Taguchi–ANOVA analysis has also been reported in other precision-manufacturing optimization studies, for example in the selection of spindle speed, feed rate, and depth of cut for CNC machining of metallic components, reinforcing the robustness of this statistical approach across different manufacturing domains [5], [16].

From a design standpoint, these statistical results imply that engineers seeking to improve the safety margin of a fork tine should prioritize increasing base thickness over enlarging the heel radius, since thickness delivers a far greater and more predictable reduction in stress per unit of design change. Heel radius should nonetheless not be disregarded: although not statistically significant in isolation, its interaction with thickness, evident in the throat-thinning behavior observed for the 40 mm-thick designs, means that radius selection must always be evaluated jointly with the local wall thickness rather than as an independent design choice.

Design 9 (D9) achieved the lowest stress (159.0 MPa) and the highest Factor of Safety (2.61) among all variations, but this came at the cost of the heaviest fork mass (116 kg), an overdesign that penalizes hydraulic lifting efficiency and material cost without a proportional safety benefit. Conversely, the 40 mm-thick designs (D1–D3) failed to reach the industry-recommended Factor of Safety of 2.0. Balancing structural safety against mass efficiency, Design 6 (D6), combining an 85 mm heel radius with a 50 mm thickness, was selected as the optimal configuration. D6 limits the maximum stress to 208.5 MPa and raises the Factor of Safety to 1.99, close to the 2.0 industry benchmark and clearly safer than the factory-standard design D5 (FoS 1.84), while adding only 1 kg of mass relative to D5 (97 kg versus 96 kg). This result demonstrates that a modest, well-placed increase in heel radius, when combined with an adequately thick base section, can deliver a substantial safety improvement without a significant weight penalty.

These results are consistent with the broader literature on structural optimization of L-shaped and cantilevered steel components. Bozkurt et al. showed that localized geometry refinement at high-stress structural parts of a diesel forklift truck can meaningfully lower peak stress without a wholesale redesign of the component [1], while Li et al. demonstrated that the fillet geometry of cold-formed steel L-shaped built-up columns strongly governs their impact and load-bearing performance, echoing the sensitivity of the heel region observed in the present study [12]. The throat-thinning effect identified for the 40 mm-thick designs also aligns with fatigue and stress-concentration principles reported for threaded and filleted components, where increasing a local radius without sufficient surrounding material can paradoxically raise, rather than lower, the peak stress [2]. Compared with the factory-standard design D5, the proposed D6 configuration offers a more favorable balance between the stress-reduction benefits of a larger heel radius and the stiffness benefits of adequate wall thickness, and it does so using the same AISI 4140 material and the same overall envelope dimensions, meaning that D6 could be adopted as a drop-in replacement without requiring new tooling, raw-material specifications, or assembly procedures.

From a manufacturing standpoint, it is worth noting that the same Taguchi-based optimization logic used here, minimizing a critical response through a small, statistically efficient set of experimental trials, has also proven effective outside structural design, for instance in optimizing spindle speed, feed rate, and depth of cut to reduce machining time in CNC milling of metallic bipolar plates for fuel-cell applications [16]. This cross-domain

consistency supports the use of the L9 orthogonal array as a general-purpose, resource-efficient tool for engineering optimization problems in which two or three control factors must be balanced against a critical performance response, whether that response is structural stress, as in this study, or manufacturing cycle time, as in CNC machining process optimization.

4. Conclusions

This study applied a Taguchi 3^2 factorial design combined with static Finite Element Analysis to optimize the heel radius and base thickness of a 3-ton capacity forklift fork tine made of AISI 4140 alloy steel. The numerical model was validated against analytical cantilever-beam calculations with an error below 1% and a mesh-independence study performed on the baseline design, confirming the reliability of the meshing and boundary-condition setup used for the parametric study. Heel radius alone did not significantly affect stress ($P = 0.585$) or displacement ($P = 0.204$) in the ANOVA, and on thin cross-sections a larger radius could even raise stress through a throat-thinning effect caused by the reduction of the net cross-sectional area at the heel. Base thickness, in contrast, was confirmed as the dominant, statistically significant parameter ($P = 0.003$ for stress and $P < 0.001$ for displacement) governing both the strength and stiffness of the fork tine, a result consistent with the cubic dependence of the section's second moment of area on thickness.

Among the nine design variations tested, Design 6 (85 mm heel radius, 50 mm thickness) was identified as the optimal configuration, reducing the maximum stress to 208.5 MPa and raising the Factor of Safety to 1.99, an improvement over the factory-standard design (FoS 1.84) achieved with a mass increase of only about 1 kg. These findings confirm that AISI 4140 fork tines with the D6 geometry are structurally safe for static operation and can be recommended as a fabrication standard for 3-ton class forklifts. For future work, it is recommended that (1) the D6 design be validated experimentally through physical fatigue and tensile testing of a fabricated prototype; (2) the analysis be extended to dynamic loading scenarios, such as sudden braking or travel over uneven surfaces, to better represent real operating conditions [15]; and (3) alternative alloy systems be evaluated against AISI 4140 to explore whether a lower-density material can achieve an equivalent or higher yield strength, further improving the mass efficiency of the optimized fork tine.

Acknowledgments: The authors thank the Department of Mechanical Engineering, Jakarta State Polytechnic, and the double-degree program partner, St. John's University, Taiwan, for administrative and technical support during this research.

References

1. Ö. Y. Bozkurt, İ. C. Dai, and Ö. Özbek, "The Finite Element Analysis and Geometry Improvements of Some Structural Parts of a Diesel Forklift Truck," *Periodicals of Engineering and Natural Sciences*, vol. 5, no. 2, pp. 202–209, 2017, doi: 10.21533/pen.v5i2.118.
2. J. R. M. dos Santos, M. F. Fernandes, V. M. O. Velloso, and H. J. C. Voorwald, "Fatigue Analysis of Threaded Components with Cd and Zn-Ni Anticorrosive Coatings," *Metals*, vol. 11, no. 9, p. 1455, 2021, doi: 10.3390/met11091455.
3. J. Wu, "Finite element analysis and simulation of cargo fork dynamics," *Journal of Physics: Conference Series*, vol. 2419, no. 1, p. 012072, 2023, doi: 10.1088/1742-6596/2419/1/012072.
4. Y. Sun, L. Wang, B. Zhu, Y. Wang, and Y. Zhang, "The structure design and performance analysis of the transportation fork in hot stamping production line," pp. 1953–1956, 2015.
5. H. Wu, H. Li, X. Wang, J. Yang, R. Jiang, X. Deng, and J. Wang, "Research on multi-objective optimization design for high-precision turning-milling machine tool bed based on Taguchi method-FEA," *Scientific Reports*, vol. 15, p. 27307, 2025, doi: 10.1038/s41598-025-13263-1.
6. M. S. Mahdieh, F. Nazari, and F. A. Ghilaim, "Design of forks and lifting system of a 10-ton forklift truck by FEM simulation," *Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering*, vol. 16, no. 2, pp. 59–67, 2024, doi: 10.71939/jsme.2024.1092071.

7. R. Kurniawan and A. P. Budijono, "Analisis Gaya dan Mekanisme Angkut Forklift Toyota 8FBMT50 Berdaya Angkat 5 Ton dengan Sistem Hidrolik," *Jurnal Teknik Mesin (JTM)*, vol. 6, no. 1, pp. 51–59, 2018.
8. A. Ishak, K. Siregar, G. Valkov, and V. Nikolov, "Failure Mode and Effect Analysis (Fuzzy FMEA) Implementation for Forklift Risk Management in Manufacturing Company PT. XYZ," *IOP Conference Series: Materials Science and Engineering*, vol. 528, no. 1, p. 012027, 2019, doi: 10.1088/1757-899X/528/1/012027.
9. K. N. Khebude, "Design and Analysis of Mechanical Forklift," *International Journal of Scientific Research and Engineering Development*, vol. 3, no. 2, pp. 685–690, 2020.
10. M. Kumaran, N. Muthuram, and S. Hari Chealvan, "Redefining forklift longevity: a study on fork design optimization and lifecycle enhancement," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 19, no. 9, pp. 6171–6187, 2025, doi: 10.1007/s12008-024-02195-1.
11. A. Jalal, M. Farooq, I. Anwer, N. Hayat, A. Munir, I. Zahid, N. S. Akbar, M. Hamza, M. Nouman, and F. Riaz, "Design and development of a low-cost, eco-friendly forklift for sustainable logistics management," *Frontiers in Built Environment*, vol. 10, p. 1506495, 2025, doi: 10.3389/fbuil.2024.1506495.
12. M. Li, J. Sun, Y. Hu, L. Jiang, S. Zhou, G. Dai, and N. Wu, "Lateral Impact Performance of Cold-Formed Steel L-Shaped Built-Up Columns," *Materials*, vol. 18, no. 19, p. 4548, 2025, doi: 10.3390/ma18194548.
13. S. N. Pokharkar, A. Dumbre, S. Bhagat, R. Pawar, and P. Borude, "Design and Analysis of New Flexible and Safe Forklifts," *International Journal for Science and Advance Research in Technology (IJSART)*, vol. 8, no. 5, pp. 404–410, 2022.
14. S. Fu, H. Chen, H. Ren, T. Lin, C. Miao, and Q. Chen, "Potential Energy Recovery System for Electric Heavy Forklift Based on Double Hydraulic Motor-Generators," *Applied Sciences*, vol. 10, no. 11, p. 3996, 2020, doi: 10.3390/app10113996.
15. Y. Y. Huang and L. Horvath, "Measurement and Analysis of Industrial Forklifts Vibration Levels for Unit Load Testing Purposes," *Applied Sciences*, vol. 11, no. 7, p. 2901, 2021, doi: 10.3390/app11072901.
16. F. Mulyana, R. Maladzi, B. Matsaany, N. Yudisha, M. P. Rifi, F. I. Rahman, B. Ramadhan, and Z. M. C. Alam, "Optimization of Bipolar Plate Machining Process Using the Taguchi Method on CNC 3-Axis," *Recent in Engineering Science and Technology*, vol. 4, no. 01, pp. 44–50, 2026, doi: 10.59511/riestech.v4i01.140.



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ISSN 2985-704X

