

QUALITY PAPER

Improving periodic maintenance performance: a grouping and heuristic approach

Improving
periodic
maintenance
performance

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Abstract

Purpose – This paper proposes a heuristic, data-driven approach to the rapid performance evaluation of periodic maintenance on complex production plants. Through grouping, maintenance interval (MI)-based evaluation and performance assessment, potential nonvalue-adding maintenance elements can be identified in the current maintenance structure. The framework reduces management complexity and supports the decision-making process for further maintenance improvement.

Design/methodology/approach – The evaluation framework follows a prescriptive research approach. The framework is structured in three steps, which are further illustrated in the case study. The case study utilizes real-life data to verify the feasibility and effectiveness of the proposed framework.

Findings – Through a case study conducted on 9,538 pieces of equipment from eight offshore oil and gas production platforms, the results show considerable potential for maintenance performance improvement, including up to a 23% reduction in periodic maintenance hours.

Research limitations/implications – The problem of performance evaluation under limited data availability has barely been addressed in the literature on the plant level. The proposed framework aims to provide a quantitative approach to reducing the structural complexity of the periodic maintenance evaluation process and can help maintenance professionals prioritize the focus on maintenance improvement among current strategies.

Originality/value – The proposed framework is especially suitable for initial performance assessment in systems with a complex structure, limited maintenance records and imperfect data, as it reduces management complexity and supports the decision-making process for further maintenance improvement. A similar application has not been identified in the literature.

Keywords Periodic maintenance, Performance measurement, Maintenance strategy, Grouping, Limited data, Offshore

Paper type Research paper

1. Introduction

In today's world, which is full of complex business environments that place high pressure on industries to deliver products of higher quality in a shorter time at lower prices, productivity is key. The success of any business is highly influenced by having either a cost advantage or a value advantage and the ability of the business to compete effectively and be productive

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(Alsyouf, 2007). One of the main strategies that can influence companies' ability to stay competitive is their maintenance strategy for production equipment (Madu, 2000), as optimal maintenance plays an important role in keeping the life cycle cost down and ensuring efficient operations (Waeyenbergh and Pintelon, 2002).

The evaluation of maintenance performance shows great importance for maintenance management. The continuous improvement of the maintenance management process calls for periodic evaluation of maintenance performance and strategy (Márquez, 2007), as a good choice of performance indicators could help to identify and reduce the gap between current and expected maintenance performance (Muchiri *et al.*, 2011). However, it is difficult to perform quantitative analysis for decision-making support in many organizations, especially when the availability of equipment failure data is limited (Seiti *et al.*, 2019). For components with low maintenance frequencies, the period for data gathering before a strategy can be reevaluated might take many years, which also raises difficulties for performance evaluation. To address such issues, this paper proposes an interval-based group evaluation framework for periodic preventive maintenance, i.e. predetermined preventive maintenance that is periodically performed. Routine inspections (RIs) and age-based preventive maintenance (ABPM) are both considered periodic preventive maintenance since both types are carried out following a fixed time period (Shafiee, 2015). The proposed framework provides a maintenance performance overview for complex production systems and suggests qualitative actions for performance improvement regarding (1) optimal periodic maintenance frequency defined in maintenance strategies, (2) compliance with maintenance frequency in execution and (3) the effectiveness of periodic maintenance. The framework takes imperfect maintenance into consideration and can be applied with limited and flawed data.

The remainder of this paper is structured as follows. Section 2 describes the research approach of this paper. Section 3 provides a comprehensive literature review on the evaluation and optimization of periodic maintenance performance, followed by a problem statement developed from the literature review. Section 4 introduces the concept of periodic maintenance performance evaluation. In Section 5, a case study is conducted on various components based on real-life data from an offshore site. Discussions, conclusions and future work are presented in Section 6–7.

2. Research approach

The research presented in this paper primarily follows a prescriptive and quantitative approach. A literature review was conducted regarding both evaluation and optimization methods for periodic maintenance intervals (MIs) at the beginning of this research. The concept design process was conducted based on the concept synthesis model (Andreasen *et al.*, 2015). Design goals and associated evaluation standards were first formulated for the ideal solution space. The ideation process was then carried out during multiple workshops, where ideas were selected, synthesized and grouped into concept proposals. The proposal that promised the best results was selected and redeveloped into the final concept. The conceptualization process was dynamic and iterative. For the quantitative aspect, the periodic maintenance performance of 9,538 pieces of components was evaluated in a case study. Historical periodic maintenance data on this equipment were obtained from the case company's computerized maintenance management system (CMMS), covering over 32,000 periodic maintenance work hours over the past nine years. The data were cleaned, reorganized and presented as a data model in business intelligence (BI) software for better understanding and illustration. MATLAB script was written to execute the evaluation process described in this paper. The findings were evaluated through semi-structured interviews and meetings with company maintenance experts.

The research was conducted in collaboration with a major offshore oil and gas exploration and production company. So far, the evaluation framework has been tested through a study

with the case company. However, the framework is believed to be generally applicable for maintenance improvement on not only offshore oil and gas platforms but other large production sites as well.

3. Literature review

Maintenance intervals and maintenance tasks are the two key factors in defining periodic maintenance strategies. This literature review will mainly focus on MIs. The evaluation of periodic MIs often comes in the form of a proposal with an optimal interval. While such optimization gives details on how maintenance performance can be improved in the future, it also shows how much the current performance deviates from the proposed scenario. Therefore, evaluation and optimization aspects are both covered in this literature review. The left half of [Table 1](#) lists the main approaches applied to evaluate periodic MIs in the literature ([Section 3.1](#)): reliability and cost analysis, graphical analysis and the other three less common approaches. The right half of [Table 1](#) summarizes their coverage of three aspects: component grouping, imperfect maintenance and limited failure data ([Section 3.2](#)).

3.1 Approaches to interval evaluation/optimization

3.1.1 Reliability and cost analysis. The quantitative optimization of periodic MIs has been researched in recent years. In principle, shorter MIs assure lower failure rates, while longer MIs reduce maintenance costs and may lead to higher failure rates. Since the nature of finding the optimal periodic maintenance interval is essentially the search for the best balance point between system availability and cost, most identified studies utilize reliability/failure analysis and cost modeling as the main approach. For instance, [Ahn and Kim \(2011\)](#) developed a procedure to choose between two maintenance policies based on equipment availability, maintenance cost and their priorities. On top of reliability and cost analysis, [Abbasinejad et al. \(2021\)](#) applied expected utility theory and proposed an ABPM policy to determine the optimal maintenance interval for equipment with variable and constant failure rates, respectively. It is worth mentioning that for certain critical components, reliability and cost analysis results suggest the use of condition monitoring, which further reduces failure rate and increases productivity comparing to periodic maintenance ([Townsend et al., 2016](#); [Townsend and Badar, 2018](#)). As for routine inspections, [Guo et al. \(2015\)](#) provided an analytical approach to optimize inspection intervals to achieve minimum maintenance costs, taking both short- and long-term cost rates into account. Other studies applying reliability and cost analysis are listed in [Table 1](#).

3.1.2 Graphical analysis. Research on graphic-based maintenance measurement solutions mainly aims to provide fast and intuitive analysis of maintenance performance and support the decision-making process for maintenance management. Based on the hazard plotting method ([Nelson, 1969](#)), a data-based graphical tool, Graphical Analysis for Maintenance Management (GAMM), is proposed to visualize the maintenance sequence versus the cumulated run time ([Martínez et al., 2013](#)). The Graphical Analysis for Operation Management Method (GAOM) takes both maintenance and production data into consideration ([Viveros Gunckel et al., 2017](#)), while Graphical Analysis for Overall Effectiveness Management (GAOEM) further integrates graphic interaction between reliability and production indicators ([Viveros Gunckel et al., 2018](#)). These tools use two-dimensional graphic illustrations for each equipment or system, making these methods more suitable for application to critical equipment with higher maintenance frequency. Other graphical-based methods have also been applied to support the evaluation of MIs, such as total time on test (TTT) plots ([Rao and Prasad, 2001](#)).

3.1.3 Bayesian analysis, voting and additional action estimation. While reliability, cost and graphical analysis are the most common methods applied to determine periodic MIs, other

Table 1.
List of literature:
evaluation and
optimization of
periodic MIs

Author(s)	Main approach for interval evaluation/optimization					Aspects considered	
	Reliability and cost analysis	Graphical analysis	Voting	Bayesian analysis	Additional action estimation	Applicable for component groups	Imperfect maintenance considered
Ahn and Kim (2011)	X						
Abbasinejad <i>et al.</i> (2021)	X						
Guo <i>et al.</i> (2015)	X						
Townsend <i>et al.</i> (2016)	X						
Townsend and Badar (2018)	X						
Yang <i>et al.</i> (2017)	X					X ^{SD}	
Talukder and Knapp (2002)	X					X ^{SD}	
Vu <i>et al.</i> (2014)	X					X ^{SD}	
Wang <i>et al.</i> (2010)	X					X ^{SD}	
Vu <i>et al.</i> (2013)	X					X	
Shafiee and Finkelstein (2015)	X						
Fan <i>et al.</i> (2021)	X					X ^{SD}	X
Xiao <i>et al.</i> (2020)	X					X ^{SD}	X
Martinod <i>et al.</i> (2018)	X					X	X
Martinez <i>et al.</i> (2013)		X					
Viveros Gunckel <i>et al.</i> (2017)		X					
Viveros Gunckel <i>et al.</i> (2018)		X					
Rao and Prasad (2001)		X					
de Almeida-Filho <i>et al.</i> (2017)	X		X				X
Han <i>et al.</i> (2019)	X			X		X	X
Piesik <i>et al.</i> (2020)					X		X
Note(s): X ^{SD} : grouping based on system structural dependency							

approaches have also been observed. [Han et al. \(2019\)](#) presented an integrated framework to determine periodic MIs for offshore safety barriers, using a Bayesian approach to identify preliminary maintenance thresholds for periodic maintenance. [de Almeida-Filho et al. \(2017\)](#) developed a quartile-based voting approach for group decision-making by aggregating the preferences among decision-makers and seeking the best compromise point between conflicting criteria. [Piesik et al. \(2020\)](#) used a qualitative classification method to estimate the impact of risks under different system criticality and suggested additional actions based on the classification results.

3.2 Aspects of interval evaluation/optimization

3.2.1 Group evaluation/optimization. In most cases, it is not practical for a maintenance planner to plan or schedule periodic maintenance for each component individually, especially when the components are not critical ([Wang et al., 2010](#)). Such issues have been addressed through studies on group maintenance for multi-component systems. Group maintenance policies for multi-component systems can be categorized into two kinds: block-based group maintenance and age-based group maintenance. For block-based group maintenance, all components share a common maintenance interval and are maintained sequentially ([Yang et al., 2017](#)). Block-based group maintenance is particularly suitable for a group of identical components without structural dependencies, such as blade components from a wind turbine system, while age-based group maintenance is more applicable when components come in different types and have multiple MIs.

For age-based group maintenance, MIs are first calculated for individual components. These components are then grouped according to the proximity of interval length when maintenance policies are made ([Shafiee and Finkelstein, 2015](#)) or based on the proximity of calendar dates during scheduling to reduce overhaul time ([Talukder and Knapp, 2002](#); [Vu et al., 2014](#)). [Wang et al. \(2010\)](#) used the delay time concept to identify inspection intervals for individual components in a multi-component system, which was further utilized to form a group inspection model. [Vu et al. \(2013\)](#) discussed the grouping of maintenance jobs in complex systems with redundancy. In that context, the repair jobs for noncritical components were kept on hold and grouped with upcoming preventive maintenance to reduce maintenance costs. Most reviewed grouping approaches share the common assumption that the structure of the multi-component system is known.

On the other hand, when the structure of a multi-component system is unknown, grouping methods did not get enough attention in the literature reviewed. [Shafiee and Finkelstein \(2015\)](#) proposed a model for component degradation and cost to find the optimal replacement age for both system and component levels, with a discussion of grouping strategies for components with similar optimal periodic MIs. [Martinod et al. \(2018\)](#) suggest a component grouping method based on their similarity of degradation rate, maintenance cost and lifetime.

3.2.2 Imperfect maintenance. The literature mentioned so far only considered the effect of preventive maintenance to be perfect, meaning the component under maintenance is assumed to be replaced or restored to a full health condition (good as new). Although imperfect maintenance has been extensively studied for both preventive and corrective maintenance ([Shafiee and Chukova, 2013](#)), only a few studies were found that considered imperfect maintenance together with component grouping for periodic maintenance evaluation. [Fan et al. \(2021\)](#) presented a group maintenance optimization model with consideration of stochastic dependency in subsea Xmas tree systems. The authors considered two binary states for the possible outcomes of periodic maintenance: perfect (good as new) and the same as the previous condition (bad as old). [Xiao et al. \(2020\)](#) introduced an interval optimization method for multi-component systems and assumed imperfect outcomes from periodic maintenance by introducing an age reduction factor. [Martinod et al. \(2018\)](#) proposed a

stochastic model to provide maintenance plans for each component while taking the effect of imperfect maintenance actions into account.

3.2.3 Limited failure data. Most of the identified interval evaluation research targets specific applications with known failure distribution parameters or sufficient failure data or uses numerical examples as verification. The issue of missing or insufficient failure data was barely addressed in the studies related to interval evaluation. From the literature review, two methods can be extracted for handling limited failure data. The first method is to include more data samples by clustering the same types of components. [Han et al. \(2019\)](#) clustered all pressure release valves from an offshore installation into one group in which the number of periodic tests and failures was counted by calendar year. The second method is to introduce other knowledge to support the evaluation process. Such knowledge can be in explicit forms, such as legal regulations and vendor recommendations ([Piesik et al., 2020](#)), or more tacit and experientially grounded based on the opinions of maintenance experts ([de Almeida-Filho et al., 2017](#)).

3.3 Research question

While most studies have applied reliability analysis to periodic maintenance interval optimization, it is commonly assumed that failure data or failure distribution parameters for components are known. However, in practice, certain scenarios, especially the application of conservative maintenance strategies, can reduce the availability of failure data ([de Jonge and Scarf, 2020](#)). The presumption of data availability becomes less feasible when (1) the failure distribution parameters for a certain type of component are not available or (2) components rarely fail in the history and therefore do not provide enough samples for reliability calculation. Both cases are particularly common for noncritical components in complex systems. Consequently, the evaluation results become less reliable when the data are insufficient or imperfect.

In addition, many studies on the development or evaluation of periodic maintenance strategies focus on one piece or one group of specific equipment ([Almomani et al., 2012](#)), whereas research on maintenance evaluation across multiple equipment classes is very limited. Most of the components are not critical enough to be analyzed on a case-by-case basis, and their variety across multiple dimensions raises challenges for performance evaluation and improvement. Therefore, there is a research gap in obtaining performance overviews for various groups of equipment with limited failure data.

Taking all these aspects into consideration, the remainder of this paper intends to answer the following research question: “How can periodic maintenance performance for aggregated equipment in groups be evaluated with limited failure data available?” Based on the research question, a concept for a periodic maintenance performance evaluation framework is developed.

4. Concept

The evaluation framework presented in this paper provides a systematic and efficient approach to creating an overview of a historical maintenance picture among various types of equipment ([Figure 1](#)). As a first step, the grouping of similar components increases data

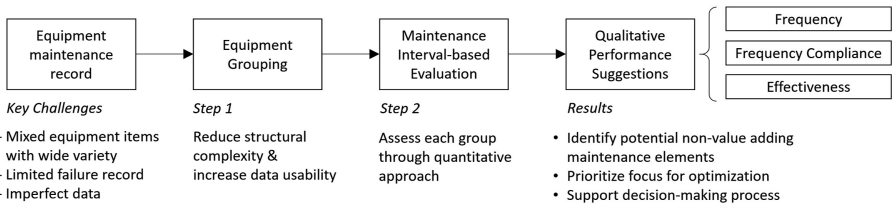


Figure 1.
Process overview of the periodic maintenance evaluation framework

availability, thereby enabling the analysis of components with low maintenance frequency. With the minimum periodic maintenance interval considered the basic evaluation unit, the performance of periodic maintenance is evaluated for each group. Finally, preliminary suggestions are offered on which periodic maintenance strategies should be improved in a qualitative manner. The approach is generic and can be adapted across different industries without changing hardware or data structure.

4.1 Step 1: component grouping

The concept of component grouping introduced in this step is inspired by product platform theory, which is based on the principle that utilizing grouping methodologies to standardize product families will eventually help solve the issue of product development and management complexity (Harlou, 2006). Such grouping ideology has recently been utilized to standardize maintenance jobs under high structural complexity and limited data availability (Agergaard *et al.*, 2021). For equipment in relation to preventive maintenance, grouping criteria have been proposed based on shared intervals (Shafiee and Finkelstein, 2015), criticality (Li *et al.*, 2018), equipment function, maintenance action (Soleymani *et al.*, 2020), reliability and cost (Martinod *et al.*, 2018). By further integrating these methods, this paper proposes a component grouping approach to enable group maintenance evaluation of components in complex production systems.

In this paper, the grouping method aims to segment components that have worked and been maintained in a similar way and therefore reduce the complexity of the maintenance architecture. Therefore, three main viewpoints are defined to understand the components: equipment family, operating context and historical maintenance action. The equipment family viewpoint discusses the component itself, e.g. the type of component, size of the component, etc., and shall be defined at the beginning of the analysis. The operating context viewpoint is for a grouping of the components that worked in the same way and under the same condition. It also can cover other aspects, such as the function of components in its system. The last viewpoint defined is that of historical maintenance actions. This perspective ensures that components that undergo similar maintenance activities will be grouped together. Grouping will only take place after all these viewpoints are specified. Considering all viewpoints gives organizations the possibility of grouping similar components to be evaluated with higher data validity and lower architectural complexity. The level of detail in each viewpoint depends on the level of analysis. One of the main purposes of component grouping is to increase data validity and therefore enable the analysis of equipment with low maintenance frequency, which should be considered when defining the required level of detail in each viewpoint.

4.2 Step 2: maintenance interval-based evaluation

4.2.1 Maintenance interval. A periodic maintenance job can be life-extending (e.g. lubrication of a gearbox) or nonlife-extending (e.g. a function check of an emergency shutdown valve). Considering that this information might be missing from the historical maintenance record, this paper assumes that in either case, a general inspection of the component is always included when the component is being periodically maintained. These general inspections are expected to discover visually detectable failures, preventing equipment health conditions from further degrading, which can consequently lead to production loss, maintenance costs or safety incidents. For a given component, the minimum time interval of such general inspections from periodic maintenance is defined as the MI.

For each MI, the following possible failure detection scenarios (FDSs) are considered:

- (1) *Scenario 1: No failure detected.* The health condition degrades, but no detectable failure develops before the next PM.

- (2) *Scenario 2: Failure detected by periodic maintenance activities.* A failure develops to a level that can be detected by periodic maintenance, but it is not severe enough to be noticed by other methods (such as casual observation or production loss).
- (3) *Scenario 3: Failure detected by undesired events.* A failure develops to a noticeable level and consequently triggers a failure notification by one of the undesired failure detection methods. The component is later repaired by corrective maintenance.

Periodic maintenance is performed at the end of each MI. Here, imperfect maintenance is understood through the following possible scenarios:

- (1) *Scenario A:* A perfect life-extending maintenance was conducted, after which the component's health is fully restored (good as new).
- (2) *Scenario B:* The maintenance conducted was life-extending but imperfect, or nonlife-extending. The component's health partially improves or remains the same (bad as old).
- (3) *Scenario C:* The maintenance conducted was imperfect, after which the health condition of the component degrades due to improper operation during execution.

Note that in Scenarios B and C, it is assumed that any detectable potential failures will be notified during maintenance and repaired after a short time. This means that the minimum component health after periodic maintenance actions should always be better than the detectable failure level. The degradation of equipment health over time can be plotted on a potential failure (P-F) curve (Ochella *et al.*, 2021). In Figure 2, a few examples of random combinations between Scenarios 1–3 and Scenarios A–C are shown in P-F curves.

In addition to FDS, other information can also be obtained from the historical maintenance time record for each MI segment. The time difference between the actual start times of two adjacent periodic maintenance operations is defined as the periodic maintenance actual interval. The time lapsed from the actual start time of the latest periodic maintenance operation to the first failure notified by undesired events is defined as the failure notification time. An illustration of FDSs, periodic maintenance actual intervals and failure notification times is shown in Figure 3. MIs containing this information are considered basic elements to be evaluated for the corresponding component groups.

4.2.2 Periodic maintenance strategy positioning. Maintenance decisions are often made based on tacit knowledge from human experience in the industry (Agergaard *et al.*, 2021). However, it has yet to be determined whether the current practice yields an optimal maintenance outcome. Therefore, it is important to determine which and how periodic maintenance strategies could be adjusted to improve performance.

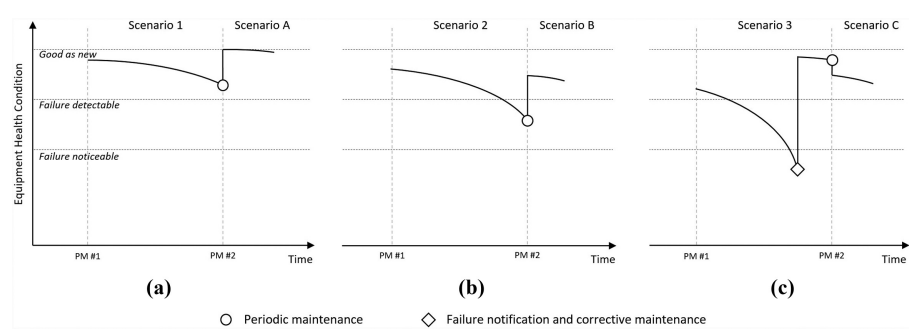


Figure 2.
Examples of random combinations between Scenarios 1–3 and Scenarios A–C: (a) Scenario 1 + A, (b) Scenario 2 + B and (c) Scenario 3 + C

The proposed approach focuses on the initial evaluation of periodic maintenance with a wide coverage of equipment variety. Frequency and thoroughness are considered the two most critical dimensions of periodic maintenance and are thus defined as maintenance configuration parameters on a generic level. In Figure 4, strategy positioning represents where a periodic maintenance strategy is located in these two dimensions, and execution positioning represents the actual positioning of the strategy after maintenance execution. Depending on the compliance situation, the positioning of the executed maintenance work might deviate from the defined strategy. Low frequency and thoroughness lead to lower preventive maintenance costs but also cause a decrease in equipment reliability; a balance point needs to be found. Evaluation of strategy positioning and deviation indicates whether the current status is optimal.

4.2.3 Evaluation criteria. To reflect frequency in execution positioning (f_e), frequency deviation (Δf) and process in execution positioning (P_e), five evaluation criteria are defined based on the information obtained from MIs. Note that process deviation is, in most cases, not included in maintenance data and requires inspection on-site; therefore, it is not considered in this research. The five criteria are as follows:

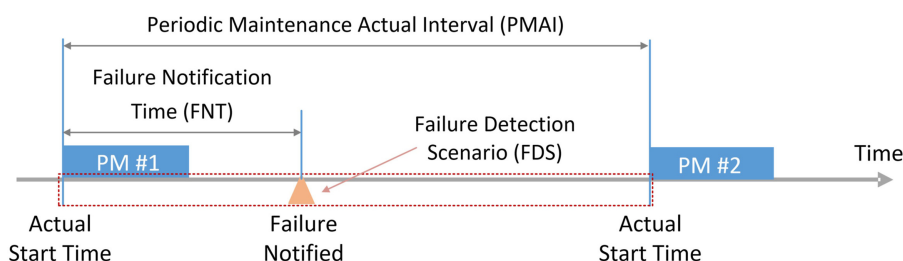


Figure 3.
Example of an MI
segment

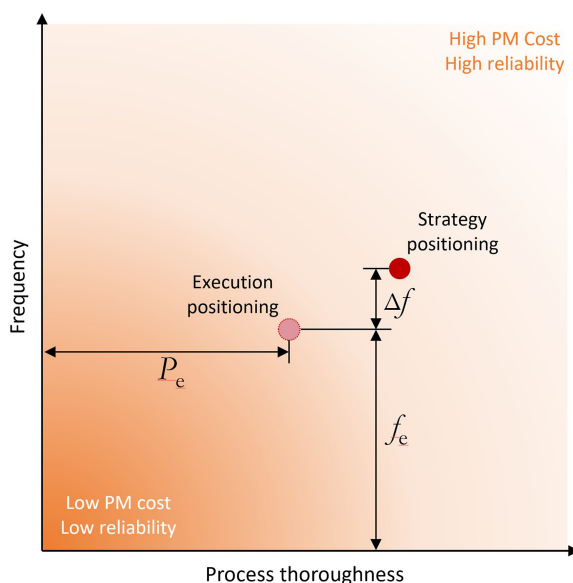


Figure 4.
Periodic maintenance
strategy positioning

- (1) *No failure rate*: Percentage of MIs that have no failures notified.
- (2) *On-time rate*: Percentage of periodic maintenance actual intervals that are compliant with the defined maintenance cycle.
- (3) *Skip rate*: Percentage of MIs that are long enough to contain several intended maintenance cycles, indicating one or more periodic maintenance operations have been skipped.
- (4) *Undesired failure detection scenario (FDS) rate*: Percentage of FDSs that belong to the category of failure detected by other undesired events.
- (5) *Average failure notification time (FNT) position*: Average position of failure notification time in MI, i.e. at which phase of MI the failure was notified, represented as a percentage.

Figure 5 shows the links between data from MIs, evaluation criteria and suggestions obtained from the evaluation. The next step further explains how these criteria contribute to suggestions for maintenance improvement.

4.3 Step 3: maintenance performance assessment

Maintenance performance is assessed by the three aspects shown in Figure 5: planned frequency, execution compliance and process effectiveness. Based on the results obtained from the evaluation criteria in Step 2, qualitative suggestions are given for each aspect.

No failure rate indicates whether the frequency of periodic maintenance is adequate. The target value of the no failure rate shall be set differently depending on the component groups. A very high no failure rate can be considered a preliminary indication of overmaintenance, where reducing the minimum frequency of periodic maintenance can be suggested as a potential solution. A low no failure rate can be attributed to several causes, including poor execution compliance and low preventive maintenance process effectiveness; therefore, the need to shorten the frequency cannot be determined solely based on this criterion.

The on-time rate and skip rate show the execution time compliance status of periodic maintenance. As the frequency of inspection affects the time window to mitigate or eliminate failure (Clark, 2019), a long delay in periodic maintenance operations is likelier to cause severe consequences. Therefore, skipping periodic maintenance execution is considered a special case of maintenance delay and shall have standards separate from the on-time rate. The compliance of frequency should be reviewed if either of the criteria fails to meet the target. From another point of view, if the no failure rate is still high when periodic maintenance

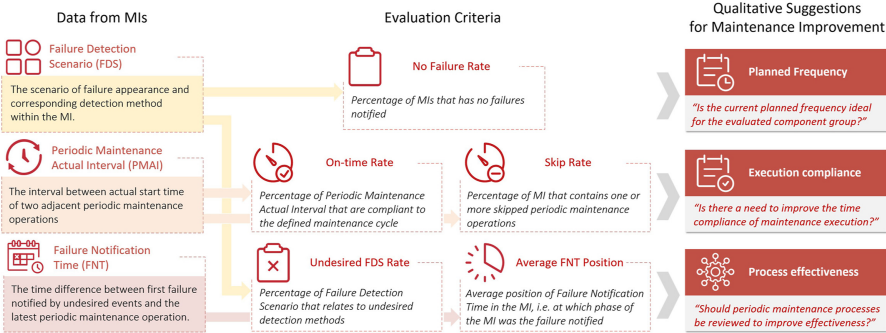


Figure 5.
Overview of the
maintenance interval
evaluation process

executions are frequently delayed or skipped, there is a higher chance that the component group is being over-maintained.

The undesired failure detection scenario rate and average failure notification time position reflects the effectiveness of periodic maintenance. If most failures are discovered by undesired events and/or notified in the early phase of MI, the effectiveness of periodic maintenance appears to be low, in which case a review of the process (and its compliance) is suggested. If the average failure notification time position is close to the end of MI, then reducing periodic maintenance frequency becomes an option.

5. Case study

The proposed framework was validated through a case study of one of the offshore oil and gas production fields of the case company. The field contains eight offshore installations and has more than 50 producing wells. A total of 71,005 historical maintenance records of 9,538 pieces of equipment from 2010 to February 2019 were obtained and processed. The maintenance records contain only basic information on periodic maintenance and failures. Available data fields from historical maintenance are shown by examples presented in Table 2. Note that the data presented have been anonymized.

The minimum MIs of components vary from 14 days to more than two years. Not all of the components have records available throughout the entire time scope, and many of them have not failed historically. Under these conditions, regular reliability and cost analysis methods become less applicable and require case-by-case investigation; thus, they are not suitable for initial performance evaluation. This case study aims to illustrate how the proposed evaluation framework can be utilized to evaluate thousands of components with the limited failure information available.

5.1 Step 1: component grouping

In the case study, equipment types are built based on the existing categorization method in the company's maintenance guidelines, but with a focus on reducing the total number of equipment types by grouping the current variants with similar general inspection procedures. Six equipment types are defined, including emergency shutdown valves (ESDVs), pressure safety valves (PSVs), ordinary manual valves (OMVs), pumps, instrumentation devices and metering devices.

The operating context of components is covered by three viewpoints: platform type, system group and component criticality. First, two platform types, manned and satellite, are defined to distinguish the maintenance accessibility of components. Maintaining components installed on satellite platforms requires extra travel and, consequently, a higher operational cost. Moreover, the absence of on-site maintenance personnel also makes casual observation of early-phase functional failure less possible on satellite platforms. Then, with the notion that a system consists of a certain number of system elements that can be viewed as systems themselves (Walden *et al.*, 2015), the working conditions of components, along with some unsettled functionality differences, are further distinguished by system groups. The term "system" in this context refers to the functional systems defined by the case company, which is also the scope of current preventive maintenance strategies. Each system group can be scoped for multiple systems that share enough structural similarities or for one single system where the equipment is special enough to be evaluated alone. Finally, a risk-based criterion, component criticality, is introduced to determine the importance of components according to the consequence and likelihood of failure (American Petroleum Institute, 2009). One of the three criticality classifications, high, medium or low, is assigned to each component. Different evaluation standards should apply for each criticality level to achieve a better cost-benefit balance.

Table 2.
Examples of retrieved
historical maintenance
records

Record number	Component type	Component ID	Record type	Starting date	System	Criticality	Planned frequency	Work hours	Failure detection method
00,001	Pump	1-P-2001	Periodic maintenance	05/07/2017	SG2	Low	1 year	1.2	–
00,002	Pump	1-P-2001	Failure	24/08/2017	SG2	Low	–	–	Undesired
00,003	Pump	1-P-2001	Periodic maintenance	17/09/2018	SG2	Low	1 year	1.2	–
00,004	Pump	1-P-3001	Periodic maintenance	02/07/2011	SG3	Medium	1 year	0.7	–
00,005	Pump	1-P-3001	Periodic maintenance	01/07/2012	SG3	Medium	1 year	0.8	–
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
71,005	Valve	8FCV-5003	Periodic maintenance	14/11/2018	SG5	High	3 months	0.2	–

Considering the large number of components included in the scope, the grouping should be kept at a generic level. Therefore, the viewpoint of historical maintenance action here focuses on planned maintenance frequency. Research suggests that higher maintenance frequency leads to a greater effective mean time between failures (Li, 2016), but meanwhile, the corresponding periodic maintenance cost also increases. Qualitative results are expected from the evaluation to verify whether the current interval of periodic maintenance is adequate. In special cases, components with maintenance frequency changes over time are considered different individuals, with available maintenance records divided by corresponding frequencies. In the case study, components with a minimum frequency of more than two years are left out for the rest of the study, since these components are often regulated by other factors, such as legal requirements.

An illustration of the equipment grouping methodology is shown in Figure 6.

5.2 Step 2: maintenance interval-based evaluation

A total of 330 component groups are formed and evaluated by the proposed method. As shown on the right side of Figure 6, each component group contains a certain number of MIs, which are compared to the five established evaluation criteria mentioned in Section 4.2.3. In this case, the value chosen for each criterion is shown in Table 3. No suggestions are given when the performance for a given criterion is within the desired range (marked as “Good”). An increase or decrease in frequency is suggested when the no failure rate lies outside of the desired range. For execution compliance and process effectiveness, a review shall be suggested if either criterion is not met. To ensure the accuracy of the analysis, the result can also be marked as not available (N/A) when the valid data points for a certain criterion are too few. Data processing and calculation processes are realized using MATLAB scripts.

5.3 Step 3: maintenance performance assessment

Assessment results cover three dimensions of periodic maintenance: planned frequency, execution compliance and process effectiveness. The evaluation results provide valuable insights into the current periodic maintenance performance as well as indications of which and how periodic maintenance could be improved in the future.

The results of periodic maintenance frequency evaluations vary between different equipment types and criticality levels. For instance, the frequency of most pumps with medium criticality appears to be quite low, while most instrumentation devices may have too frequent maintenance. Results from frequency evaluation can also be interpreted as

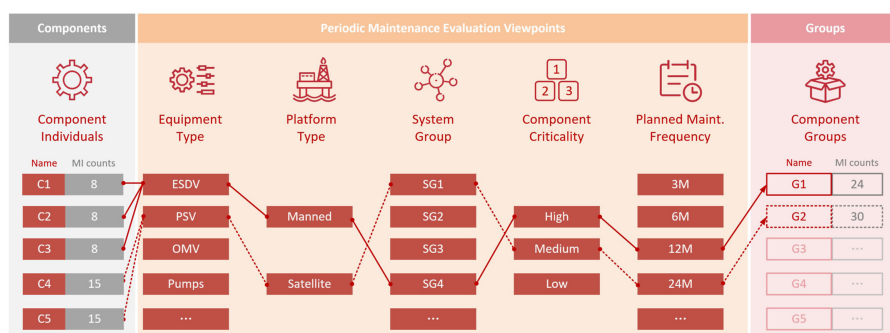


Figure 6.
Illustration of the
component grouping
process

qualitative suggestions of how future maintenance can be shaped to achieve better cost efficiency. Assuming that all proposals for higher or lower frequency will result in doubled or halved periodic maintenance work hours, respectively, the estimated savings potential on periodic maintenance work hours is up to 23%. The reduction of undesired corrective maintenance will lead to a further increase in cost efficiency.

Furthermore, the execution compliance and process effectiveness evaluation provide opportunities for discovering potential issues in current maintenance strategies. When a review is suggested for a component group, it promotes the priority of the attention level on the corresponding strategy. This means that a review of these strategies offers a better chance of improving periodic maintenance performance.

6. Discussion

The case study provides an application of the proposed framework to an offshore production plant with real-life data. As opposed to the identified literature on periodic maintenance evaluation and optimization, this framework focuses on interval-based group maintenance evaluation at the preliminary level. The grouping of components reduces complexity for initial performance evaluation and enables analysis on a large scale. Using MIs instead of components as the basic unit of evaluation allows components with low maintenance frequency or limited data to be included. The case study shows how the framework can be adapted to the industry.

Due to the wide scope of the evaluation and very limited data availability, the evaluation results are preliminary and do not clearly show the exact causes of problems. It should be noted that more precise conclusions on maintenance performance still require sophisticated reliability analysis. Furthermore, maintenance frequency and tasks might be limited by other constraints, such as maintenance downtime, shutdown requirements, available manpower and safety requirements. To reduce maintenance downtime, it is common practice to group preventive maintenance jobs that require shutdown in the scheduling phase. Grouping jobs on adjacent dates might have a negative impact on execution time compliance and introduce over-maintenance for certain components, but on the other hand, it reduces downtime and associated cost. Grouping on scheduling phases and high-priority corrective maintenance jobs will change the number of available on-site maintenance personnel, which in turn affects periodic maintenance performance. Periodic maintenance tasks associated with legal

Table 3.
List of values chosen
for evaluation criteria
and suggestions for
corresponding results

Suggestion aspects	Criteria	Performance suggestions	
Planned frequency	No failure rate (high criticality)	Good (90– 99%)	Reduce frequency (>99%) Increase frequency (<90%)
	No failure rate (medium criticality)	Good (80– 95%)	Reduce frequency (>95%) Increase frequency (<80%)
	No failure rate (low criticality)	Good (50– 80%)	Reduce frequency (>80%) Increase frequency (<50%)
Execution compliance	On-time rate	Good (≥70%)	Review suggested (<70%)
	Skip rate	Good (≤20%)	Review suggested (>20%)
Process effectiveness	Undesired failure detection scenario rate	Good (≤80%)	Review suggested (>80%)
	Average failure notification time position	Good (≥40%)	Review suggested (<40%)

requirements need to be identified and evaluated separately. These factors also need to be considered before making maintenance decisions.

Therefore, the proposed framework does not function as a decision-making tool to find exact, optimal strategies; rather, it functions as a decision support tool to prioritize strategies with potential performance issues. It helps maintenance experts gain a preliminary performance overview on all equipment, so the scope of analysis for the next step can be narrowed down to the strategies that need the most attention. The framework can be combined with other reliability and cost analysis tools for a more detailed evaluation. Decisions on changing periodic maintenance strategies should then be made carefully by maintenance experts.

7. Conclusion

This paper presents a periodic maintenance performance evaluation framework that systematically groups and evaluates large amounts of components across systems. The framework provides a fast and comprehensive overview of historical periodic maintenance performance and highlights the component groups that might have performance issues. In relation to the research question,

How can periodic maintenance performance for aggregated equipment in groups be evaluated with limited failure data available?,

it can be concluded that the proposed framework is an effective evaluation tool for various types of equipment in large numbers. The gain is especially large when data availability is limited. The results of the evaluation open up discussion between different stakeholders and help to support the decision-making process for maintenance management. The main advantages of the proposed framework are summarized as follows.

- (1) *Highly adaptive*: Only basic information from historical maintenance data is required. The framework can be utilized for the preliminary assessment of periodic maintenance performance for various industries.
- (2) *Works with imperfect data*: This method also works with components that have irregular execution records of periodic maintenance. Failure records with missing detection methods only exclude corresponding MIs from the evaluation, while the components can still be evaluated by groups.
- (3) *Reduces management complexity*: The component grouping method maintains a balance between analysis accuracy and efficiency, making it possible to carry out the evaluation of various components in large amounts.
- (4) *Prioritizes focus for maintenance improvement*: The suggestions for frequency and process aspects provide indications of component groups that might have performance issues. By utilizing this evaluation framework as a decision support tool, maintenance experts can prioritize the component groups that potentially benefit more from strategy optimization and thus increase efficiency for maintenance management.
- (5) *High analysis efficiency*: The evaluation process can be performed using scripts and can be repeated when new maintenance data are ready.

Future research should focus on integrating other factors that have impacts on periodic maintenance performance, such as maintenance downtime, shutdown requirements and manpower. Costs associated with these factors can also be taken into account for performance evaluation.

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