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Analyses on guidelines of reliability-centered maintenance and the challenges in applying for green hydrogen technologies

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Green hydrogen offers a promising pathway for reducing carbon emissions and renewable energy integration. However, its production via water electrolysis faces major reliability, safety, and cost challenges, which are identified by sudden failures of components, associated repair, and maintenance expenses as well as unexpected operational downtime. To improve reliability and safety of hydrogen systems, planned maintenance is critical in mitigating performance degradation, extending lifespan and reducing economic loss. Reliability-centered maintenance (RCM) offers a structured approach to optimally integrate corrective and preventive maintenance strategies, aiming to enhance reliability and ensure cost-effective operation. The maintenance task selection decision logic is the noble feature of RCM analysis which varies in different standards and guidelines. Therefore, this study explores the application of maintenance task selection logic step embedded in RCM framework for green hydrogen technologies, with particular interest in electrolyzers by reviewing available standards and guidelines. Besides, this study sheds light on the challenges of applying the existing task selection logic and discusses initiatives from managerial perspective to customize the current RCM to be applied in green hydrogen sector.

Keywords: Green hydrogen, electrolyzer, reliability centered maintenance, preventive maintenance, reliability.

1. Introduction

Green hydrogen is considered a potential alternative to the conventional fossil fuels due to its carbon-neutral production pathway and diverse applications, for example, fuel for road transportation, maritime, and industrial processes, and feedstock for synthesizing sustainable chemicals like green ammonia and green methanol (Hydrogen Council 2020; Kang 2021). Despite the advantages, its unique properties such as minimum ignition energy (0.017 mJ (Ono et al. 2007)), wide flammability range (4% - 75% in air (McCarty 1981)), and material degradation, commonly known as hydrogen embrittlement (HE) (Dwivedi and Vishwakarma 2018), unfold several safety and reliability concerns. Besides, the production of green hydrogen via water electrolysis, is currently the most expensive production technique, having the cost range between 2.2 – 8.2 € per kg of hydrogen (Ajanovic et al. 2022). Reliability issues such as unexpected production shutdown due to accidents or component failure, and associated expenses in maintenance and repairs are some of the major contributors. Tuhi et al. reviewed the hydrogen incident and accident database 2.1 (HIAD 2.1) and highlighted that many past accidents in water electrolysis plants were largely attributable to inadequate maintenance practices (Tuhi et al. 2024). Besides, the lessons documented in the database underscore the importance of implementing proper maintenance and inspection strategies. The ability to measure deviations from normal operating parameters permits appropriate personnel (e.g., reliability engineers, maintenance planners) to plan and schedule adjustments that will prevent further degradation of the component, thereby eliminating failure and associated downtime (Mobley 2002). This is highly relevant to a component handling hazardous element like hydrogen since any event leading to hydrogen release can have severe consequences on human, environment and property.

Maintenance is typically classified into corrective maintenance (CM) and preventive maintenance (PM), where CM is performed after a failure has occurred and PM is conducted in advance to avoid to the failure (Ahmad and Kamaruddin 2012). Selecting an appropriate maintenance task for components handling hydrogen is crucial because components differ in their criticality, and the chosen maintenance frequency and scope must be aligned with the overall lifetime cost (Selvik and Aven 2011; Patil et al. 2022). In this regard, reliability centered maintenance (RCM) is a widely accepted and proven methodology that offers an efficient framework for maintenance planning (Selvik and Aven 2011). The central step of RCM is selecting the appropriate maintenance strategy for each component, since the identification of critical components, failure modes, and consequences can be addressed while performing reliability analysis. Also, reliability analysis can be conducted to validate RCM task selection and intervals, identify over or under maintenance, and refine failure mode criticality, thereby establishing a closed loop continuous improvement process.

RCM has been largely adopted in various sectors such as aviation, nuclear power plant, chemical, power distribution, and oil and gas (Zhou et al. 2016; Catelani et al. 2020; Chen et al. 2023; Fischer et al. 2012; Fonseca 2000; Patil and Bewoor 2022; Riswanto et al. 2019; Tucci et al. 2006; Keynia et al. 2022). As a result, there exist several international standards and guidelines proposed by expert personnel/ organizations regarding the framework of applying RCM and maintenance task selection logic for each critical component. However, only a single study, Baglee and Knowles (Baglee and Knowles 2012), is found related to hydrogen domain which discussed the state of the art in fuel cell condition monitoring and maintenance utilizing RCM and radio-frequency identification (RFID) technologies and suggested an optimal structure for an integrated, cost effective maintenance management system.

Given the limited application of RCM and the presence of multiple guidelines with differing maintenance task selection logic, this study examines the suitability of applying existing maintenance task selection logic embedded in the RCM frameworks to the emerging green hydrogen domain. This is accomplished through a comprehensive review of existing RCM standards and guidelines, recognizing that each source applies its own task selection logic. This work examines all available resources to evaluate how suitable existing selection logics are for the green hydrogen sector. Besides, differences in existing maintenance task selection logic are identified, which may ultimately lead to the development of a selection process tailored specifically to green hydrogen technologies, if required. This study also identifies the key challenges associated with applying existing RCM maintenance task selection logic and proposes managerial actions to address these challenges when implementing the RCM framework for green hydrogen technologies.

The article is structured as follows: RCM is briefly described in section 2. The procedure adopted to analyze RCM guidelines is explained in section 3. Section 4 presents a comparison between the guidelines, discusses the challenges of applying current maintenance task selection logic and proposes managerial actions. Finally, conclusion is presented in section 5.

2. Reliability centered maintenance

According to the IEC 60300 (2009) standard (International electrotechnical commission 2009), RCM is defined as a method for identifying and selecting failure management policies to efficiently and effectively achieve the required safety, availability and economic operation. It involves a systematic evaluation of system functions, potential failure modes, and a priority-based assessment of safety and economic considerations to identify applicable and effective maintenance tasks (Rausand 1998). Rather than applying PM and CM independently, RCM integrates these approaches to leverage their respective strengths, thereby maximizing component reliability while minimizing lifecycle costs. RCM analysis is typically conducted in a step-by-step manner, and current practices describe similar basic element, which include:

- Initiation and planning
- Identify functional failures
- Critical item selection
- Failure modes, effects and criticality analysis (FMECA) for each critical item
- Maintenance task selection
- In service data collection and updating

The RCM analysis begins with initiating and planning, which includes defining system boundaries and functions. Next, functional failures are assessed, and critical components are identified based on impact on environment, health and safety (EHS), production availability, and material loss. FMECA is then performed for each critical component to determine dominant failure modes, their consequences and criticality. This step ensures resources are allocated to the most critical failure modes, as applying RCM to every failure mode is not cost effective. The subsequent step involves selecting suitable maintenance tasks for the critical failure modes using a logical approach. This step is considered the most distinctive feature of RCM compared to other maintenance planning techniques. The principle is to decide whether a PM task is applicable and effective for each critical failure mode or whether it is more appropriate to allow the component to run to failure and then perform CM. Finally, decisions are refined using operational experience once the RCM is implemented. Fig.1. depicts a simplified flowchart of the RCM process adopted from (Rausand 1998). Though RCM is conducted in operation, it is necessary to plan from the design phase to maximize benefit and collect feedback from the analysis.

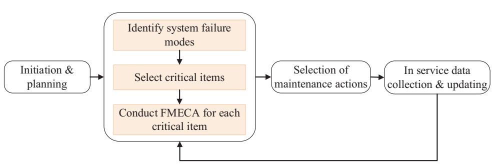

Fig. 1. Block diagram of RCM methodology (adapted from (Rausand 1998))

3. Procedure of RCM guideline analysis

The procedure adopted in this paper is organized in three steps, as shown in Fig.2. Firstly, standards, guidelines and peer reviewed articles discussing RCM analysis are selected. While selecting the resources, priority is given to those provided by globally recognized certification bodies, such as international electrotechnical commission (IEC), the national aeronautics and space administration (NASA) and American bureau of shipping (ABS). The selected standards and guidelines are listed below.

- Guidance notes on reliability-centered maintenance by ABS (2018) (American Bureau of Shipping 2018)
- IEC 60300-3-11: Application guide reliability centered maintenance (2009) (International electrotechnical commission 2009)
- NASA reliability centered maintenance guide for facilities and collateral equipment (2008) (NASA 2008)
- Reliability centered maintenance framework by Rausand (Rausand 1998)

Two other standards - SAE-JA1011(1999): Evaluation Criteria for RCM Processes and SAE-JA1012 (2002): A Guide to the RCM Standard are not publicly available, hence, cannot be included in this work. Afterwards, a comprehensive review of the maintenance task selection decision logics presented in these selected resources is conducted. Finally, the suitability of the maintenance task selection logic in case of green hydrogen technologies is assessed by identifying the challenges of applying these in-practice selection logics.

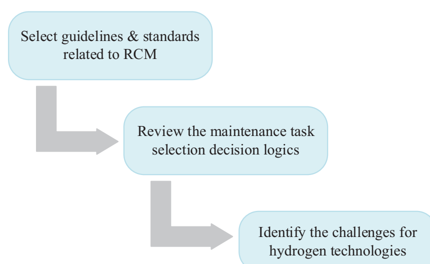

Fig. 2. Procedure of RCM guidelines analysis

4. Comparisons and discussions

In this section, findings by reviewing the maintenance task selection logic are presented. Also, this section discusses the challenges of applying current maintenance task selection logic and suggests managerial actions in customizing RCM strategies for green hydrogen technologies.

4.1. *Maintenance task selection logic of existing guidelines*

The maintenance task selection logic discussed in all the selected resources are presented here.

4.1.1. *ABS Guidance notes on RCM*

The ABS guidance notes on RCM categorizes maintenance tasks into proactive tasks, one-time changes, servicing tasks, and routine inspections. Here, the proactive tasks are further divided into four categories: planned PM, condition monitoring/ predictive maintenance, combination of PM and condition monitoring (referred to as combination task), and failure finding tasks. The decision logic presented here considers the risk ranking conducted through risk matrix and the availability of an applicable and effective maintenance tasks. Table1 presents the task selection logic proposed in this guideline.

4.1.2. *IEC 60300*

In IEC 60300 (2009), maintenance tasks are divided into PM and CM. The tasks identified as PM are condition monitoring, scheduled restoration, scheduled replacement and failure finding. The alternative actions mentioned in the standard include redesigning and modification of existing components, changing operating and maintenance procedures and additional operator training. The maintenance task selection process proposed by this standard depends on whether the failure is evident or hidden. Each branch of the decision logic tree concludes with several possible maintenance options. The best option is determined by evaluating both the cost of implementation and the operational impact that the selected option will have on the overall maintenance activities. Table 2 presents the task selection logic proposed in this standard.

4.1.3. *NASA RCM guide*

In this guide, four types of maintenance actions are recommended: reactive, preventive, predictive testing and inspection (PT&I), and proactive. It also outlines criteria for selecting the appropriate maintenance strategy based on the characteristics of components. For instance,

Table 1: Task selection logic in ABS guidance notes on RCM

Maintenance task	Conditions
One-time change	'Failure mode is in the highest risk categories' **OR** 'The failure mode is not in the highest/lowest risk categories' **AND** 'Applicable and effective CM approach is unavailable' **AND** 'Applicable and effective one time change approach is available'
Run to failure	Failure mode is in the lowest risk category
Condition monitoring	'Failure mode risk is not in the highest/ lowest risk categories' **AND** 'Applicable and effective condition monitoring approach is available'
Redesign	'Failure mode risk is not in the highest/ lowest risk categories' **AND** 'Applicable and effective condition monitoring approach and one-time change task is not available'
Planned maintenance	'Failure mode risk is not in the highest/ lowest risk categories' **AND** 'Applicable and effective condition monitoring is not available' **AND** 'Applicable and effective planned maintenance is available'
Combination of PM & condition monitoring task	'Failure mode risk is not in the highest/ lowest risk categories' **AND** 'Applicable and effective condition monitoring & planned maintenance approach are not available' **AND** 'Applicable and effective combination task is available'
Failure finding task	'Failure mode risk is not in the highest/ lowest risk categories' **AND** 'Applicable and effective condition monitoring, planned maintenance & combination tasks are not available' **AND** 'Applicable and effective failure finding task is available'

reactive maintenance is suitable for small, non-critical, redundant, and unlikely to fail components. PM applies to components subject to wear and with a predictable failure pattern. PT&I is recommended for items experiencing random or PM-induced failures and nor prone to wear. Proactive maintenance is used to reduce or failure probability through root cause analysis, FMECA, age exploration and commissioning.

The decision logic outlined in this guideline is primarily based on the failure's impact on EHS and the availability of an effective PT&I method an interval-based approach. Table 3 illustrates the task selection logic proposed here.

Table 2: Task selection logic in IEC 60300

Maintenance task	Conditions
• Condition monitoring • Scheduled replacement • Scheduled restoration • Alternative actions	'Evident failure' **AND** 'Evident adverse effect on EHS'
• Condition monitoring • Scheduled replacement • Scheduled restoration • No PM • Alternative actions	'Evident failure' **AND** 'No evident adverse effect on economic/ operational'
• Condition monitoring • Scheduled replacement • Scheduled restoration • Failure finding • No PM • Alternative actions	'Hidden failure' **AND** 'No hidden adverse effect on economic/ operational'
• Condition monitoring • Scheduled replacement • Scheduled restoration • Failure finding • Alternative actions	'Hidden failure' **AND** 'Hidden adverse effect on EHS'

4.1.4. *RCM framework suggested by Rausand*

This article (Rausand 1998) is one of the earliest works presenting a structured approach to RCM. This work provides a framework for utilizing operating experience in a more systematic way. Two maintenance actions are considered: PM and CM.

Table 3: Task selection logic in NASA RCM guide

Maintenance task	Conditions
Reactive	No adverse effect on EHS, energy efficiency and no collateral economic loss
Preventive	'No adverse effect on EHS' **AND** 'Effective PT&I technology not available' **AND** 'Effective interval approach is available'
Predictive testing & inspection	'Adverse effect on EHS' **AND** 'Effective PT&I approach is available'
Proactive	'Adverse effect on EHS' **AND** 'Effective PT&I approach is not available' **AND** 'Effective interval approach is not available'

The decision logic presented here depends on the availability of a failure alerting indicator, failure rate characteristics, and type of failure mode (hidden or evident). The suggested PM tasks are scheduled on-condition tasks, scheduled overhaul, scheduled replacement, scheduled function test and run to failure. Table 4 discusses the task selection logic discussed in this literature.

Table 4: Task selection logic in (Rausand 1998)

Maintenance task	Conditions
Scheduled on-condition task	'Failure alerting indicator is available' **AND** 'Reasonable consistent age interval exists between the time of potential failure and the time of functional failure'
Scheduled overhaul	'Failure alerting indicator does not exist' **AND** 'The failure rate is increasing' **AND** 'Overhaul is feasible'
Scheduled replacement	'Failure alerting measurable indicator does not exist' **AND** 'The failure rate is increasing' **AND** 'Overhaul is not feasible'
Scheduled function test	'Failure alerting measurable indicator does not exist' **AND** 'The failure rate is not increasing' **AND** 'The function is hidden'
No PM activity found/ corrective maintenance	'Failure alerting measurable indicator does not exist' **AND** 'The failure rate is not increasing' **AND** 'The function is not hidden'

Although each selected guideline has its reasonable selection logic for determining maintenance actions, it is evident that the RCM task selection depends on the type of risk involved, the availability of suitable PM approaches, and type of failure modes (e.g., evident or hidden). Besides, the reviewed sources share a common view: PM is recommended when viable condition monitoring, failure identification and inspection methods are available. On the other hand, CM and failure finding tasks should be used when such approaches are not feasible. Besides, all the resources assumed that a components failure time can be assumed correctly which aids in scheduling maintenance task before failure as PM task.

4.2. Challenges from existing task selection logic in green hydrogen technologies

The consensus between the existing guidelines introduces several challenges for green hydrogen technologies and the following particulars discusses challenges to convenient adoption of the existing RCM guidelines in green hydrogen applications. These have been formulated based on the comparison of the existing task selection logic, as previously presented.

Novelty in technologies: Effective PT&I, condition monitoring methods, and relevant data, as well as failure identification approaches are still lacking for the green hydrogen technologies. Currently there are two methods applied for condition monitoring of electrolyzers: measurement of polarization curves and electrochemical impedance spectroscopy (EIS), each comes with own limitations (Souza et al. 2023). In case of conducting inspection, some studies (Giannini et al. 2023; Campari et al. 2023; Collina et al. 2023) have identified the limitations of using risk-based inspection for hydrogen technologies and (Campari et al. 2022) thoroughly explained the modifications needed. In the absence of effective monitoring and inspection approaches, the existing task selection logic recommends failure-finding or CM for electrolyzers. Consequently, following the current logic does not support the selection of PM or condition-monitoring tasks, despite these being the most appropriate maintenance strategies for electrolyzers.

Lack of historical data: Because electrolyzers are still in development stage, limited historical failure and maintenance data make it difficult to define appropriate maintenance intervals. Therefore, scheduled maintenance tasks recommended in existing guidelines such as planned maintenance (in ABS guidance), scheduled replacement or restoration (in IEC 60300), and scheduled on-condition tasks, overhauls, replacements, or function tests (in (Rausand 1998)), are difficult to implement. As a result, the task selection logic that leads to these options must be re-evaluated for green hydrogen technologies, or explicit provisions for decision-making under limited historical data must be incorporated into the selection logic.

Inherent properties of hydrogen: Material degradation due to HE and the resulting catastrophic failure of electrolyzers can occur, as evidenced by (Tuhi et al. 2024). Monitoring HE is particularly challenging, as it requires specialized and costly testing methods (Tuhi et al. 2024). Under the current task selection logic, the lack of proven monitoring approaches for hidden failures like HE leads to the selection of a risk-acceptance option. Moreover, existing guidelines assume that failure modes follow predictable degradation patterns, an assumption that does not adequately account for the probability of catastrophic failures.

Dynamic operational mode: Water electrolysis plants typically operate with intermittent energy supply, resulting in dynamic operational conditions that can alter the criticality of failure modes. Such variability affects the existing task selection logic, which is based on the assumption that failure modes behave consistently within a defined operating context. Consequently, maintenance tasks that are appropriate under one operational mode may be unsuitable under another, leading to ambiguous outcomes and the need for mode-specific maintenance tasks.

High cost: The task selection logic discussed in IEC 60300 (2009) concludes with several maintenance options and specifies that the most appropriate choice should be determined through an economic evaluation. As a result, substantial effort is required to thoroughly evaluate the economic implications of all maintenance tasks when applying RCM for hydrogen technologies – an undertaking that is particularly challenging due to the novelty of hydrogen technologies and the lack of historical data. Moreover, this added analytical complexity further contributes to the already high production costs of green hydrogen.

4.3. ***Customizing RCM strategies for green hydrogen technologies***

Several managerial actions can support the effective application of RCM to hydrogen technologies, particularly electrolyzers, as outlined below.

- Making early investment in robust data collection and developing advanced monitoring approaches for hydrogen technologies should be viewed as a long-term innovation investment for reliability improvement rather than a routine maintenance cost.

- The results of the RCM analysis, especially hidden failure and maintenance tasks, should be systematically integrated into existing reliability models to ensure realistic, risk-informed decision making. Besides, a governance process can be established where feedback from operation and reliability models is used to continuously refine RCM assumptions, failure mode criticality, and maintenance strategies, ensuring adaptability for emerging green hydrogen technologies.
- Opportunistic maintenance (OM) can be considered in the RCM framework tailored for hydrogen technologies. OM involves conducting any PM task during a corrective one on a failed component where suitable maintenance resources are already on location which enables repair/ replacement of components without additional downtime (Thomas et al. 2008). Hence, incorporating OM into the RCM framework could be particularly valuable for maintenance practitioners and may help reduce the high operational costs of green hydrogen.

5. Conclusion

This study reviewed the guidelines and international standard related to RCM and investigated the suitability of maintenance task selection processes for green hydrogen technologies. The analysis revealed that existing maintenance task selection logics depend heavily on the availability of predictive maintenance/ condition monitoring approaches, inspection methods, and reliable procedures for determining maintenance intervals. However, application of existing guidelines for green hydrogen technologies, especially electrolyzers, face several challenges stemming from emerging technologies involved, limited historical maintenance data, inherent characteristics of hydrogen, unique operational modes, and high cost. Due to these challenges, the maintenance tasks suggested by current task selection logic may result in ambiguous decisions and need customization. These challenges must be carefully addressed by management when implementing RCM framework for hydrogen technologies. Developing a customized decision logic that reflects the unique failure characteristics (HE and catastrophic failure) and dynamic operation of electrolyzers and establishing robust processes for collecting failure and maintenance data should be given importance. In addition, exploring the integration of OM into a tailored RCM framework may offer significant benefits by reducing operational costs and improving overall reliability.

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