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COMPARATIVE ANALYSIS OF RCM AND FMEA IN THE CONTEXT OF ECO-MAINTENANCE SUSTAINABILITY AND CIRCULAR ECONOMY

BY

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Abstract. Environmental challenges, particularly those relating to waste disposal from industrial processes, are increasing around the world and therefore require the adoption of sustainable maintenance techniques. The notion of eco-maintenance is the application of environmentally conscious approaches in equipment maintenance to reduce waste, conserve resources, and extend the useful life of the machinery, practices consistent with sustainability and circular economy. This research compares two maintenance systems, namely Reliability Centered Maintenance (RCM) and Failure Mode, Effects, and Criticality Analysis (FMECA) under eco-maintenance philosophy. While FMECA enables anticipation of potential failure modes and their prevention by prioritizing risks through Risk Priority Number (RPN), it can be time-consuming and complex. RCM offers maintenance strategies that lead to reduced consumption of resources while maximizing the useful life of the equipment, although extra cost will be incurred in the initial stages.

Keywords: eco-maintenance, sustainability, circular economy, Reliability Centered Maintenance (RCM), Failure Mode, Effects, and Criticality Analysis (FMECA).

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1. Introduction

The industrial sector has, in recent years, begun to face increasing pressure from regulatory authorities to adopt more efficient and environmentally responsible operational strategies (Garetti and Taisch, 2012). These pressures have emerged alongside the rapid expansion of manufacturing activities at a global level, which has led to significant increases in energy consumption, resource depletion, and, at the same time, the generation of vast amounts of waste, placing considerable strain on natural ecosystems (Herrmann *et al.*, 2014). As a result of these pressures, as well as the growing need for humanity to bring about positive changes to ecosystems, environmental sustainability has become one of the most pressing concerns in current industrial practice (United Nations, 2015). Considering these sustainability concerns, eco-maintenance, as a pillar of sustainability, has emerged as a direct and promising response to these challenges.

Eco-maintenance represents a shift in thinking regarding how industrial organizations approach the maintenance of machinery and equipment (Jasiulewicz-Kaczmarek, 2013a). To preserve or even restore ecosystems, industrial equipment and machinery must have a longer lifespan and be maintained more efficiently. Thus, eco-maintenance integrates environmental considerations into the planning and execution of maintenance activities. Minimizing waste, reducing energy consumption, and extending the lifespan of equipment are closely linked to the principles of the circular economy, which promotes waste elimination through the continuous use of resources, the extension of product life cycles, and the recovery and regeneration of materials at the end of their useful life (Geissdoerfer *et al*., 2017). Maintenance management as a strategy to maintain equipment availability and ensure that costs associated with operations are optimized has been well discussed in various studies (Verzea *et al*., 1999). There has been a transition from the use of corrective to preventive and predictive maintenance strategies by various industries.

Choosing the right maintenance methodology has become an important strategic decision in today's context. The most used methods in industrial maintenance are *Reliability-Centered Maintenance* (RCM) and *Failure Mode, Effects, and Criticality Analysis* (FMECA). To reduce resource consumption and improve reliability by focusing on preventive and predictive actions, RCM is an effective approach. This method is systematic, focuses on functions, and aims to identify the most efficient maintenance strategies (Moubray, 1997).

On the other hand, if a structured analytical method is needed to identify possible failure modes in a system, FMECA provides this type of analysis. It is also used to evaluate and measure the level of criticality through the *Risk Priority Number* (RPN) (Stamatis, 2003).

Even though both methods have many advantages when studied separately, a direct comparison between RCM and FMECA is still missing. This study is developed in the context of eco-maintenance, sustainability, and circular economy principles, to fill an important gap that is not well covered in existing research. This gap makes it more difficult for industrial managers and researchers to find clear, evidence-based guidance when choosing and combining maintenance strategies that support sustainability goals.

This paper aims to provide a comparative analysis of RCM and FMECA from the perspective of eco-maintenance and circular economy principles. The study is based on a solid review of the existing literature and seeks to develop both theoretical perspectives, which form the foundation of this work, as well as practical recommendations in the field of industrial maintenance. Earlier studies have pointed out the presence of clear themes connecting ecology, maintenance, and sustainability (Nica *et al.*, 2025a) which forms the theoretical foundation for this current comparison study.

The remainder of this paper is structured as follows: Section 2 presents a review of the relevant literature. Section 3 describes the methodological approach. Section 4 presents the comparative analysis. Section 5 proposes an integrated framework. Section 6 discusses the findings, and Section 7 presents the conclusions.

2. Literature Review

2.1. Sustainability and Environmental Challenges in Industrial Maintenance

In the scientific literature, the relationship between industrial activity and environmental degradation has been widely documented. Mass production and manufacturing processes account for a significant share of global energy consumption and greenhouse gas emissions (Garetti and Taisch, 2012). Maintenance activities aim to reduce excessive resource consumption and limit waste generation. Researchers have argued, and continue to argue, that traditional maintenance methods are not compatible with sustainability objectives (Franciosi *et al*., 2018). These methods prioritize operational continuity at the expense of environmental considerations. This approach conflicts with the goals established by important international initiatives. These include the United Nations Sustainable Development Goals (SDGs) and the European Green Deal (United Nations, 2015) (European Commission, 2019).

In response to these issues, an increasing number of studies have begun to explore the integration of environmental principles into industrial maintenance practices. In this context, scientific research highlights that maintenance is no longer just a technical function, but also a strategic tool (Franciosi *et al*., 2020) (Iung and Levrat, 2014). When used in this way, maintenance can significantly

reduce environmental impact, help conserve natural resources, and support long-term industrial sustainability.

2.2. Eco-Maintenance and the Circular Economy

The concept of eco-maintenance involves maintaining the performance and reliability of technical systems while minimizing the impact of maintenance processes on the environment as much as possible. Among the key characteristics of eco-maintenance are maintaining system performance and reliability, minimizing the use of natural resources, reducing waste generation, and limiting energy and material consumption (Jasiulewicz-Kaczmarek, 2013b). The idea of eco-maintenance was introduced to integrate environmental responsibility throughout the life cycle of maintenance processes (Stuchlý and Jasiulewicz-Kaczmarek, 2014). The circular economy is an economic concept that aims to redesign industrial systems by eliminating waste and ensuring that the value of products and equipment is preserved for as long as possible (Geissdoerfer *et al*., 2017).

It is important to highlight the strong connection between sustainability and eco-maintenance, which means that the circular economy is built on sustainability principles as its foundation (Cappelletti and Menato, 2023). Therefore, both the circular economy and eco-maintenance play an essential role in achieving a regenerative and circular economic model (Sassanelli *et al*., 2021), mainly by extending the lifespan of equipment and supporting their reuse and recycling.

2.3. Reliability Centered Maintenance (RCM)

The methodology known as *Reliability-Centered Maintenance* was first introduced in the civil aviation industry in the second half of the 1960s and has since been widely adopted across many other sectors (Moubray, 1997). Condition-based maintenance involves a detailed analysis of the roles and functions performed by specific equipment, as well as the possible ways in which this equipment may fail. RCM aims to determine the most appropriate maintenance approach for each piece of equipment based on its level of importance (Nowlan and Heap, 1978).

From a sustainable development perspective, Reliability-Centered Maintenance offers several advantages (Rausand and Vatn, 2008). First, since it is not strictly time-scheduled, it helps reduce unnecessary costs related to spare parts and lubrication products. Second, by applying preventive maintenance principles, it allows organizations to avoid unexpected equipment failures and emergency situations.

2.4. Failure Mode, Effects, and Criticality Analysis (FMECA)

Failure Mode, Effects, and Criticality Analysis (FMECA) represent a well-structured and logical bottom-up approach (Stamatis, 2003) aimed at identifying all possible failure modes that may occur within the analyzed system. FMEA also provides the possibility to determine the impact of these failures on system performance and to assess their criticality by quantifying the associated risks. The practical use of FMECA involves carrying out the analysis using an established worksheet that is referred to as the AMDEC sheet (fiche AMDEC). Using this worksheet entails documenting the modes of failure of each part, along with their possible causes and consequences on the system, together with the severity, occurrence, and detection ratings that enable the determination of RPN (Verzea and Luca, 2013). A commonly used method for risk quantification within FMECA is the *Risk Priority Number* (RPN). This technique uses a formula based on three components: severity, probability of occurrence, and detectability (Liu *et al*., 2013).

Regarding the implementation of FMECA in the context of eco-maintenance operations (Hartini and Ciptomulyono, 2022), it can be argued that this approach offers significant potential for preventing environmental risks generated by maintenance activities (Roszak *et al*., 2015). However, like any analytical method, FMECA also has certain limitations. First, the analysis process can be quite time-consuming. Moreover, the RPN method has been criticized for its subjectivity (Spreafico *et al*., 2017).

3. Methodology

For the current research work, the qualitative approach was used, whereby systematic literature review is applied (Tranfield *et al*., 2003). The selected methodology for research was a systematic literature review, since it is believed to be the best means of achieving the research objective of conducting a comparative study of RCM and FMECA in terms of eco-maintenance, sustainability, and circular economy. The methodology used here is an extension of bibliometric studies previously conducted in the area (Nica *et al*., 2025a).

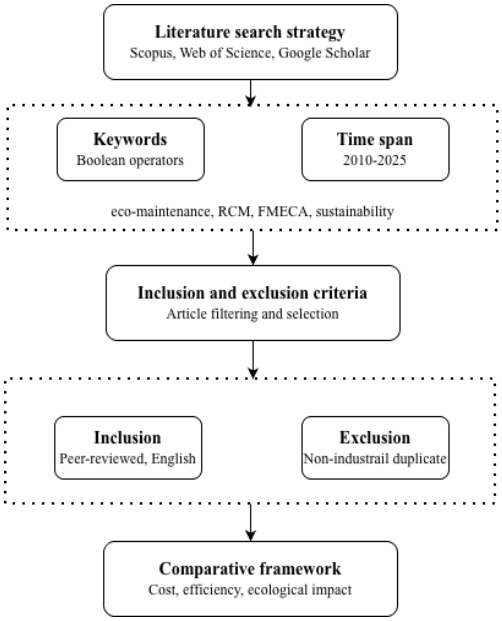


Fig. 1 – Research Methodology Framework.

3.1. Literature Search Strategy

As regards the current review, searches were conducted through several academic databases including Scopus, Web of Science, and Google Scholar. Searches were conducted using certain keywords like "eco-maintenance," "reliability centered maintenance," "failure mode effects and criticality analysis," "FMECA circular economy," "RCM sustainability," and "industrial maintenance environmental impact." To make searches more efficient and relevant, Boolean operators are preferred. The period under consideration is within the last fifteen years (2010-2025).

3.2. Inclusion and Exclusion Criteria

Inclusion criteria were as follows: (i) related to one or more topics of interest from this research paper; (ii) published in any peer-reviewed journal/conference proceedings; and (iii) available in English. Exclusion criteria were as follows: (i) application in non-industrial setting only; (ii) no clarity regarding methodology; or (iii) repetition in different database sources.

3.3. Comparative Framework

The comparative analysis between RCM and FMECA was conducted by considering the following three criteria:

• Operating Cost: which considers costs incurred when both techniques were applied as well as the economic impact resulting from their implementation.

• Maintenance Efficiency: which evaluates the potential of both techniques to increase equipment reliability, ensure its uninterrupted functioning, and extend its lifespan.

• Ecological Impact: which describes the contribution of each technique in reducing waste generation and preserving energy resources.

4. Comparative Analysis of RCM and FMECA

The section below offers a systematic comparison between the three evaluation criteria identified within the methodology.

4.1. Operational Cost

At the outset, it can be understood that RCM involves a large investment (Moubray, 1997).The implementation of RCM involves large investment at the start stage for collecting data, training staff, and making special maintenance plans. Nonetheless, it is evident that there are clear economic advantages from implementing RCM. By enabling a transition from time-based maintenance to condition-based maintenance and thereby avoiding maintenance operations that are not needed, the implementation of RCM results in saving costs because of lesser spending on spare parts and downtime (Rausand and Vatn, 2008).

It should be noted that FMECA concentrates more on risk analysis. Though it utilizes the same resources, FMECA produces a list of possible risks, prioritized according to their significance, thereby creating the basis for maintenance from the perspective of budget planning. The role played by FMECA in reducing expenses is confined only to eliminating high-risk areas without any mention of maintenance expenses.

4.2. Maintenance Effectiveness

It can be achieved using the holistic methodology used by RCM. The method uses a structured approach in identifying the functionality requirement of the equipment and relies on the use of predictive maintenance measures such as vibration monitoring, thermography, and oil analysis, which allow it to identify potential failure points, and hence increase the availability of the equipment and their life cycle.

On the other hand, FMECA increases maintenance effectiveness in terms of its preventive approach in highlighting the most important causes of failure. Nevertheless, FMECA does not give any guidance in terms of how the maintenance process should be conducted after highlighting these areas of concern. This means that an effective maintenance schedule needs to be developed after the process.

4.3. Environmental Impact

There are different approaches that RCM uses to achieve environmental sustainability. The first one is the condition-based maintenance approach. This has the effect of lowering the usage of maintenance resources as well as waste production. Predictive maintenance, on the other hand, helps to avoid any damage that may arise from the malfunction of the system, including leaking, power overload, and emergency disposal of faulty equipment (Jasiulewicz-Kaczmarek and Gola, 2019). In general terms, sustainable use of the environment is achieved since equipment will be used for long without need for new purchases or mining of fresh materials.

The prevention by FMECA of failures that might prove to be very disastrous based on the outcome of such failures is what may help achieve environmental aims. The tool meant to avoid failure leading to emission of harmful products to the environment or loss of energy will prove invaluable in cases when the machinery breaks down to cause environmental problems. Yet the environmental impact of FMECA is said to be reactive.

4.4. Summary Comparison

The following table synthesizes the comparative findings across all evaluation dimensions:

Table 1

Comparative Summary of RCM and FMECA in the Eco-Maintenance Context

Dimension	RCM	FMECA
Operation cost	High: initial investments; substantial savings due to preventive maintenance	Implementation cost is moderate; cost savings through failure prevention
Maintenance Effectiveness	High: comprehensive asset management approach with realistic policy formation based on it	Moderate avoiding major environmental failures
Environmental Impact	High: less resource consumption and wastage due to longevity	Moderate: avoiding major environmental failures
Implementation Complexity	High: involves extensive data and expertise	High: requires intensive analysis; RPN scores subjective in nature
Circular Economy Alignment	Strong: promotes longevity and material savings	Moderate: helps avoid waste through failure prevention
Best Suited For	Big firms possessing different assets and sustainability objectives	Companies seeking risk reduction and failure prevention

The differences and similarities between the RCM and FMECA approach are outlined in Table 1 with respect to six aspects such as costs, efficiency of maintenance, impact on the environment, implementation complexity, circularity, and applicability for best use. All six aspects are briefly defined and utilized for illustrating important attributes of both strategies concerning their application in the field of eco-maintenance. Even though the RCM strategy proves to be superior to FMECA in terms of reduced costs over time, complete management of resources, assets, and conservation through efficient equipment usage, FMECA is more affordable and possesses an effective risk management approach.

5. Proposed Integrated Eco-Maintenance Framework (IEMF)

Regarding this issue, a comparative study reveals that RCM and FMECA are not rival approaches.

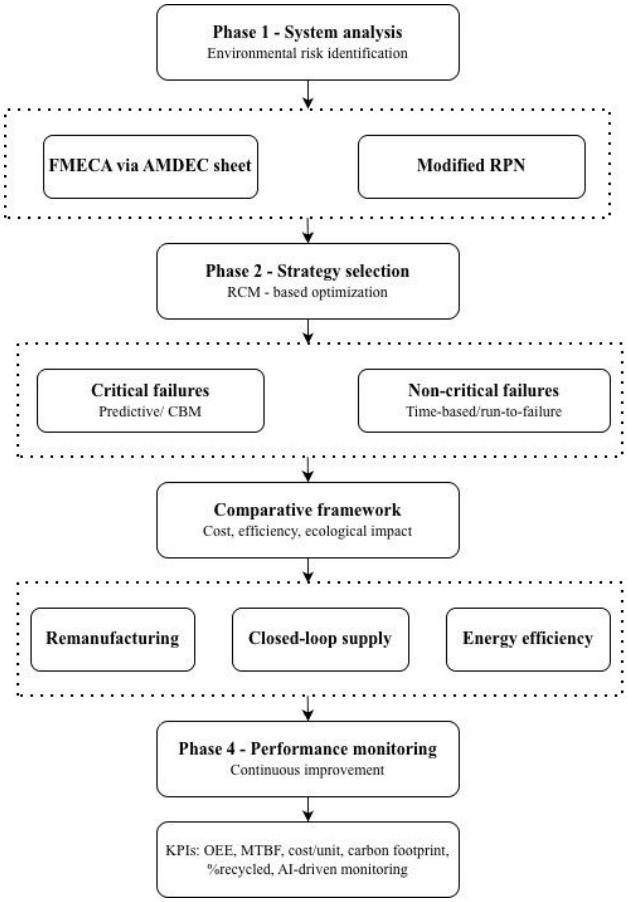


Fig. 2 – Integrated Eco-Maintenance Framework (IEMF).

On the contrary, it would be appropriate to argue that the two approaches complement each other by utilizing their individual strengths. For this reason, the adoption of eco-maintenance framework or IEMF is suggested.

5.1. Phase 1 – System Analysis and Environmental Risk Identification

For the first step, the process focuses primarily on FMECA because this will ensure a thorough understanding of the failure risks involved. The maintenance staff will identify potential failure modes, analyze the consequences, and determine the criticality of the failure modes using a slightly modified version of RPN (Roszak *et al*., 2015), where the new element added will be environmental impact in addition to severity, occurrence, and detectability.

5.2. Phase 2 – Maintenance Strategy Selection and Optimization

The second phase follows a decision-making approach similar to what is followed in RCM to identify the best maintenance strategy for the item using the information developed through the risk prioritization process in phase 1 (SAE International, 2009). A predictive or condition-based maintenance strategy is adopted in case of critical failure modes while a time based or run to failure maintenance strategy can be adopted in case of non-critical failure modes if there are no environmental impacts involved. The optimization of maintenance strategy via a methodology approach such as lean, has been known to result in remarkable gains in terms of efficiency and effectiveness (Youssouf *et al*., 2014). This further justifies the choice of CBM as the maintenance strategy for key equipment at the IEMF.

5.3. Phase 3 – Circular Economy Integration

Thirdly, this stage relates to the topic of the circular economy due to the consideration of the issues of material savings and extending the life cycles of maintenance process realization. The actions carried out on this stage include: the assessment of reparable and remanufactured components before replacement; organizing closed loop material supply chain for gathering of spare components and consumable resources; performing energy efficient maintenance procedures (Kirchherr *et al*., 2017).

5.4. Phase 4 – Performance Monitoring and Continuous Improvement

In the fourth phase, an effective system for performance measurement is adopted to evaluate the effectiveness of the maintenance integration strategy used. Some of the key performance indicators recommended include (Muchiri *et al*., 2011):

• Overall Equipment Effectiveness (OEE)
• Mean Time Between Failures (MTBF)
• Maintenance cost per unit of production
• Carbon footprint of maintenance activities
• Percentage of recovered/recycled parts to total spares consumed (Franciosi *et al.,* 2020).

AI-driven monitoring tools could contribute to the ongoing evaluation step in the suggested model (Nica *et al*., 2025b).

5.5. Framework Applicability and Managerial Implications

Adaptability is another feature of the IEMF that will make it adaptable for use in diverse industries irrespective of whether the industry is heavy or light industry. The concept of adaptability will facilitate the adoption of the IEMF and modifications in the framework based on the requirements of the organization. Regarding industrial management, IEMF acts as an organizational framework that may assist industrial managers in dealing with the challenging task of decision-making in sustainable maintenance management.

6. Discussion

6.1. Theoretical Implications

As can be seen from the comparative analysis, neither of these two methods proves to be fully efficient when used separately to overcome the sustainability issues of industrial maintenance at present. In this context, it turns out that the conclusions made by researchers coincide with the situation that is described in scientific literature, because one approach does not necessarily work under complicated circumstances (Franciosi *et al.*, 2018).

Speaking of theory, it is necessary to underline the fact that the environmental factor, while considering the choice of maintenance methodology, is rather underestimated compared to operational and economic factors (Sénéchal, 2017). This situation can be explained by the necessity to include the ideas related to the circular economy into the maintenance planning process.

6.2. Practical Implications

The following recommendations can be made for companies that have only used either the RCM or FMECA approaches. From the analysis, it can be stated that the risk assessment capabilities of the FMECA approach combined with the optimization capabilities of the RCM approach would provide sufficient resources to achieve better results.

An additional recommendation can be made for using the four-factor

score rating system along with the current three-factor score rating system for all companies using the FMECA approach. The latter approach is quite economical.

6.3. Limitations

In the case of any literature-based research methodology, there will always be some limitations that arise from the nature of such designs. First, it raises the issue of publication bias, where only selected articles will be included for the purposes of analysis. Secondly, the IEMF is still untested, since it has not been implemented in real life circumstances. Further advancements of the model can be facilitated through the incorporation of artificial intelligence technology, which has proved to be useful for eco-maintenance purposes (Nica *et al*., 2025b).

7. Conclusions

The paper has conducted a thorough comparative analysis between the two approaches namely Reliability Centered Maintenance and Failure Mode, Effects, and Criticality Analysis in the context of eco-maintenance, sustainability, and circular economy approaches. From the findings of the analysis, it can be noted that even though both these maintenance management approaches have unique and useful advantages related to environmentally friendly maintenance management processes, none of them by themselves are adequate to meet the various needs of such a process.

From the point of view of system sustainability, the RCM method would be considered a superior method because it applies a condition-based and predictive maintenance technique to minimize resource consumption, extend service lives, and mitigate the potential negative environmental effects caused by unexpected failures. From the standpoint of circular economy, the RCM model would yield more advantages because it plays a direct role in minimizing resource consumption and waste production by increasing the life cycles of equipment. However, one limitation associated with the RCM model would be its significant financial investment requirement at the early stages of implementation. In terms of failure risk prevention and identification, FMECA is inferior to RCM because it lacks a holistic maintenance management strategy. Nevertheless, FMECA provides a rigorous approach to evaluating the risks associated with potential failures. Because of this strength, FMECA would play a critical role in preventing serious environmental incidents by addressing their root causes. The introduction of environmental consequences as the fourth criterion for assessing RPN could serve as an effective way to integrate the two approaches to eco-maintenance management.

In conclusion, the proposed IEMF framework, combining strengths of both maintenance approaches, operates through the process of four stages, namely risk assessment, selection of maintenance approaches, implementation of

the circular economy, and evaluation of performance. Due to a holistic perspective used in the implementation of the concepts of the circular economy, the IEMF framework serves as an instrument that enables organizations to achieve excellence in maintenance operations, reduce maintenance expenses, and take care of the environment.

Several areas for further investigation arise from the results obtained during the present research. On the one hand, practitioners can utilize the proposed IEMF framework as an effective support tool while selecting and combining the maintenance strategies according to their sustainability goals. On the other hand, many possibilities remain open for researchers who may explore various aspects of the present study. First, one should consider the application of an empirical study to analyze the practical implementation of the proposed IEMF framework. Second, researchers can perform a quantitative analysis of environmental impacts made by the chosen maintenance approaches used by a firm. Third, one could develop a more detailed FMECA scoring system regarding environmental implications.

In general, the transition to sustainability and the circular economy demands a reconsideration of the strategy applied by companies in maintenance activities. The integration of RCM and FMECA within the eco-maintenance framework discussed above could be considered as one of the key challenges that would allow achieving consistency between the current maintenance practices and modern requirements.

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ANALIZĂ COMPARATIVĂ A RCM ȘI FMEA ÎN CONTEXTUL ECO-MENTENANȚEI, SUSTENABILITĂȚII ȘI ECONOMIEI CIRCULARE

(Rezumat)

Provocările de mediu, în special cele legate de eliminarea deșeurilor provenite din procesele industriale, sunt în creștere la nivel global și necesită adoptarea unor tehnici de mentenanță sustenabilă. Noțiunea de eco-mentenanță reprezintă aplicarea unor abordări orientate către protecția mediului în activitățile de întreținere a echipamentelor, cu scopul de a reduce deșeurile, de a conserva resursele și de a prelungi durata de viață utilă a utilajelor, practici aliniate principiilor sustenabilității și economiei circulare. Această cercetare compară două sisteme de mentenanță – Reliability Centered Maintenance (RCM) și Failure Mode, Effects, and Criticality Analysis (FMECA) – din perspectiva filozofiei de eco-mentenanță. În timp ce FMECA permite anticiparea modurilor potențiale de defectare și prevenirea acestora prin prioritizarea riscurilor folosind Risk Priority Number (RPN), metoda poate fi consumatoare de timp și complexă.

RCM oferă strategii de mentenanță care reduc consumul de resurse și maximizează durata de viață a echipamentelor, deși implică costuri suplimentare în etapele inițiale.