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# GRAPE: A Grid for Ranking and Analysis of Priority Environmental indicators in maintenance activities

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**Abstract**— The increasing environmental impact of industrial operations has emphasized the need for sustainable practices in maintenance activities. This paper introduces GRAPE (Grid for Ranking and Analysis of Priority Environmental indicators), a systematic evaluation framework designed to identify, classify, and prioritize environmental indicators associated with maintenance processes. By integrating environmental, operational, and transportation-related impacts, the GRAPE framework assesses indicators using three key criteria: importance, measurability, and urgency. The result is a quantifiable Environmental Impact Priority Level (EIPL), facilitating targeted decision-making and preventive strategies. A case study on distributed maintenance demonstrates the applicability of GRAPE, highlighting high-priority indicators and suggesting optimization actions such as route planning, stock sizing, and water treatment. The GRAPE grid offers a practical tool for aligning maintenance strategies with environmental sustainability goals..

**Keywords**— Maintenance, analysis framework, environmental indicator, performance indicator, pollution.

## I. INTRODUCTION

Maintenance is defined as an approach that focuses on the analysis of repair, monitoring, or replacement activities, using resources such as operators, spare parts, and tools [9]. It enables rapid and effective interventions, the use of tailored information systems, and rigorous monitoring of operations. Maintenance also reduces random downtime, optimizes supply chain control, manages human and material resources efficiently, and benefits from external expertise and flexibility [4]. However, recent

environmental constraints demand increased attention to the environmental impact of implemented systems. Environmental impact assessment is defined as a multidisciplinary, multi-step procedure ensuring that environmental considerations are factored into decisions related to potentially impactful activities. Environmental impact studies analyze the effects of maintenance operations on the environment and measure the environmental acceptability of maintenance systems. It is crucial to first identify maintenance practices likely to impact the environment, then classify indicators for evaluating this impact, and finally apply them to a case study.

This work is structured as follows: a state of the art is given in section 2, followed by the description of the problem to be addressed, in section 3. In Section 4 the proposed evaluation grid for indicators is build. It is then used in section 5 to assess the environmental impact of maintenance, and is applied for priority assessment in section 6, before some discussions and conclusions.

## II. STATE OF THE ART

A first, comprehensive bibliographic study was conducted recently [19]. Findings, from 76 papers, were categorized into four groups, as shown in Table 1, each representing a specific aspect contributing to environmental impact analysis. Indeed, maintenance involves multiple resources: the availability of operators and tools; the potential need for spare parts required to restore service, as well as their transportation to a centralized maintenance workshop. In the specific case of distributed maintenance [24], where the central maintenance workshop handles defective equipment from multiple sites,

transportation-related actions are significant and must be considered in the environmental analysis. Consequently, assessing the environmental impact of maintenance means analyzing the environmental effects of maintenance operations on one hand, and the transportation constraints for delivering spare parts to the central workshop on the other. To conduct a rigorous evaluation, it is essential to quantify these impacts using measurable quantities: environmental impact indicators.

TABLE I. RELEVANT ARTICLES BY CATEGORY

Study Section	Nb of relevant results
Distributed maintenance operations	9
Assessment of the environmental impact of maintenance	13
Assessment of environmental impacts related to transport	24
Environmental impact indicators	30

The preliminary analysis carried out in [19] highlights the relevance and adaptability of environmental impact assessment indicators. Furthermore, it proposes the possibility of integrating environmental constraints into maintenance policies with the objective of potentially reducing the environmental impact in maintenance activities.

### III. THE ADDRESSED PROBLEM AND PARTICULARITIES OF MAINTENANCE ACTIVITIES

Maintenance ensures the availability and reliability of industrial production equipment. Consequently, the study of the environmental impact of maintenance can be approached through an analysis of the impacts of maintenance activities on the one hand and the mobility function on the other. Based on the information gathered, as outlined in bibliographical study summarized in Table 1, the results are categorized into two distinct groups

#### A. Assessment of environmental effects related to Maintenance actions

The concept of distributed maintenance is based on knowledge of network maintenance and organization [24]. The resulting system architecture includes a set of processes (human, material and informational), internal or external to the production site, qualified to execute a defined set of operations. Figure 1 represents the inputs needed and the produced outputs in maintenance activities.

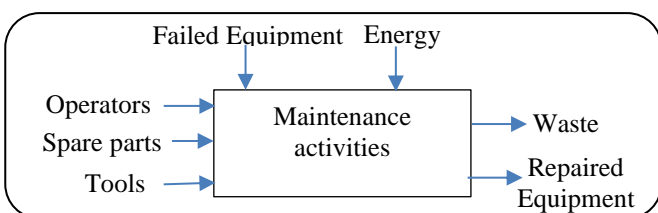


Fig.1 Inputs and outputs of maintenance activity

Maintenance activity requires efficient and competent operators [2][12][21]. It is necessary to minimize the sojourn time, to achieve an optimal dimensioning of the storage areas. What can generate a significant impact on the environment is the use of polluting products and the energy consumption of the tools necessary for the repair of failed equipment. We can also mention, in the case of non-repairable equipment, the quantities of waste that this can generate.

It can be noted that the environmental impact of maintenance activities can be expressed in terms of: cost, time, quality, pollution (soil and/or water and/or air).

#### B. Assessment of environmental effects related to transport

In maintenance activities and more particularly distributed maintenance, mobility, whether for operators or equipment to be repaired, represents an important element. This approach is termed "distributed" because maintenance agents can operate across multiple sites and also transport spare parts and their work equipment as represented in Figure 2 [14][17][18][24]. To perform this task, the use of transport vehicles is essential, making it crucial to study their environmental impact [4]. Transportation contributes to a wide range of environmental effects [5][22]. Given the diversity and complexity of these impacts, perspectives on their assessment vary. An environmental impact indicator for transportation aims to track the evolution of transport-induced air pollution over time and space, compare technological solutions, evaluate transportation modes, identify highly polluting components within the transport system under consideration, and assist in regulatory decision-making.

As previously highlighted, research on environmental impact assessments continues to grow, and transportation is no exception [10] [20]. Within the maintenance context, mobility is a key factor for impact evaluation, as this aspect significantly contributes to environmental pollution. This is primarily due to energy consumption, the emission of toxic waste into the atmosphere, and other forms of pollution.

From the literature review, ten key impact categories related to atmospheric pollutants from transportation were identified and listed in [19].

It can be noted that the environmental impact of transport activities can be expressed in terms of: cost, time, quality, air pollution [4][5][13].

#### C. Environmental Impact Assessment in Maintenance: Tools and Indicators

To propose a grid for evaluating priorities, it is necessary to identify the essential indicators needed [23][3][11][23]. Table 2 presents all the indicators. Exploring environmental impact indicators for maintenance evaluation necessitates studying performance indicators to establish the framework for environmental impact assessments [16]. The importance of quantifying maintenance pushes decision-makers to select and use relevant indicators to assess their service's operational

status and justify past, current, and future actions and expenditures.

Traditional maintenance definitions emphasize "good performance," often focusing on machine availability [1][7][8]. While "good performance" may implicitly include environmental considerations (e.g., energy and material efficiency, minimized pollution), environmental aspects are typically underemphasized or absent. A more comprehensive approach requires explicitly incorporating environmental metrics into performance evaluations to align maintenance practices with sustainability goals.

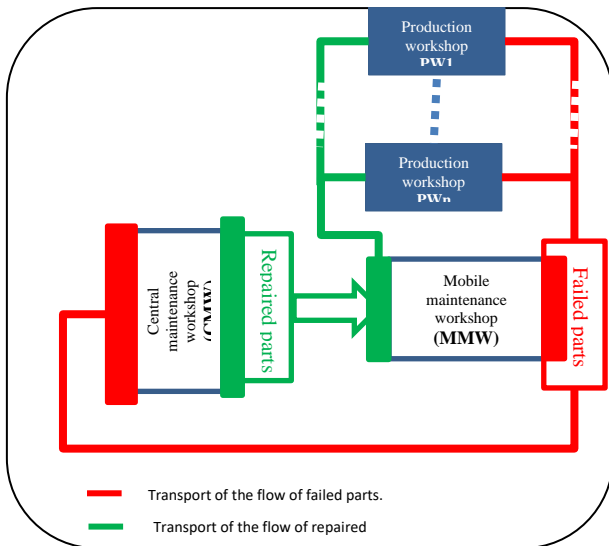


Fig.2 Distributed maintenance: Relationships between the different sites

#### IV. PROCEDURE GRAPE – BUILDING THE GRID

After analyzing the bibliographic study conducted in [19], it is necessary to explore the selection criteria for indicators related to our maintenance system. Indeed, the choice of indicators for evaluating a given system can be based on the following steps:

- a) **Problem Decomposition:** The goal is to break the measurement subject into smaller, more specific parts to obtain quantifiable and measurable data. For maintenance, the quality and availability of equipment can be monitored using MTTF (Mean Time To Failure).
- b) **Indicator Parameterization:** This involves setting a measurement scale (defining minimum and maximum thresholds), determining the optimization direction to clarify whether the indicator value should be maximized or minimized, and defining criteria for obtaining values (e.g., through a formula or algorithm execution).
- c) **Indicator Evaluation:** This step includes calculating the indicator's performance, defining its weight (indicating how the

indicator's performance contributes to system performance), and setting goals and targets for the indicator.

- d) **Indicator Classification:** This involves prioritizing indicators based on their importance and urgency.
- e) **Indicator Selection:** The aim is to choose the most suitable indicators for evaluating system performance.

By definition, an indicator must be quantifiable and measurable. It should also provide specific information that meets expectations and offers insights into potential optimization paths.

To develop our evaluation system, we drew inspiration from FMECA (Failure Modes, Effects, and Criticality Analysis) [6][15][25]. We identified a similarity between criticality (in FMECA) and the performance of the indicators we aim to evaluate. Our evaluation system will thus be based on a Grid for Ranking and Analysis of Priority Environmental indicators named GRAPE.

The GRAPE elements related to maintenance have been defined as follows:

- a) **Functions:** These include transport functions (of spare parts and tools) and maintenance functions (replacing parts and repairing defective components).
- b) **Impact Modes:** These encompass six impact groups—cost, time, quality, water, soil, and air.
- c) **Impact Effects** (linked to the impact modes): Examples include reduced profitability, increased fuel consumption, decreased/increased service time, etc.
- d) **Associated Indicators:** These include indicators like greenhouse gas emissions, waste volume produced, and consumption of non-renewable materials.
- e) **Preventive Actions:** Prevention can involve optimizing the routes of mobile maintenance workshops. These are measures implemented from the outset to prevent potential impacts. In other words, this means anticipating system pollution modes to be prepared to address them or to reduce them proactively.
- f) **Indicator Evaluation:** This element of GRAPE represents the core of the information sought regarding indicators. It includes the criteria used to judge the priority level assigned to each function, based on the following four main criteria:

Table 2- List of essential indicators for maintenance action

Objectives	Actions	Indicators
Global Performance	Transportation	Average duration of transportation operations; Fuel consumption; Overall breakdown rate; Dispute rate per driver; Frequency of work-related accidents; Vehicle load rate; Service level per driver (effective time and distance); Failure rate per truck; Average repair time per truck; Distance traveled; Real-time vehicle traceability; Repair cost per vehicle; Logistics reliability; Average operation duration; Compliance with intervention deadlines
	Environmental	Carbon footprint; Photochemical pollution; Greenhouse gas emissions; Ozone layer depletion; Ecosystem impacts; Health impacts; Toxicity; Acidification; Eutrophication; Potential global warming; Ecosystem damage due to ecotoxic emissions
Maintenance actions	Performance Indicators	<ul style="list-style-type: none"> <li>• <u>Operating Costs</u>: Labor, resource consumption, asset downtime</li> <li>• <u>Expenditures</u>: Outsourcing, spare parts consumption, activity type (method, preventive, corrective, commissioning, budget monitoring)</li> <li>• <u>Performance Metrics</u>: Equipment availability (synthetic efficiency, MTBF), equipment downtime (losses, MTTR), corrective activity indicators, allocation per equipment (factory, workshop, production line, maintainable subassemblies, main components), reliability calculations, dashboards (PMP - percentage of planned maintenance, schedule compliance, downtime, backlogs)</li> </ul>
	Environmental	<ul style="list-style-type: none"> <li>• Waste volume generated</li> <li>• Consumption of non-renewable materials, water, regulated substances, and electricity</li> <li>• Use of recycled or reused materials</li> <li>• Air, water, and soil pollution</li> <li>• Greenhouse gas emissions</li> <li>• Occupied natural space</li> </ul>

- **Importance Criterion (I)**: Refers to the indicator’s influence and effectiveness concerning the target evaluation. Since this concerns environmental factors, an indicator becomes more relevant if its impact on the associated pollution mode is significant. Different values can be assigned, as shown in Table 3-a.
- **Measurability Criterion (M)**: Defines the indicator’s capacity to be measured. Ideally, an environmental impact

indicator should be numerically assessable. Purely qualitative indicators may not be suitable for this type of study. Measurability here reflects how easy it is to measure the indicator (e.g., ease of calculation, execution in an algorithm). Its values are listed in Table 3-b.

**Urgency Criterion (U)**: Indicates the urgency level of the indicator in evaluating the overall process, considering time constraints for optimizing the associated impact. This is outlined in Table 3-c.

Table 3 – Priority Evaluation Criteria

Table 3-a : Importance (I)	Table 3-b : Measurability (M)	Table 3-c : Urgency (U)	Value
Very low	Impossible	Very low	1
Low	Low	Low	2
Medium	Medium	Medium	3
High	High	High	4
Very high	Very high	Major	5

V. ENVIRONMENTAL IMPACT ASSESSMENT BY GRAPE

The performance is reflected by the Environmental Impact Priority Level “EIPL” which represents the priority that we wish to calculate on the environmental impact of a maintenance action. By analogy with the calculation of criticality in an FMEA grid, this EIPL priority level of an indicator represents the product of the 3 criteria; Importance, Measurability and Urgency as follows:

$$EIPL = I \times M \times U \quad (1)$$

The conclusions on the performance of a given indicator can thus be listed in Table 4. Thus, the most interesting indicators will therefore be those which have the best performance index.

Table 4. Conclusion on the performance of the indicator

Performance	EIPL Data Interval	Conclusion - Action
Very high	100 < EIPL ≤ 125	Major impact indicator: to be monitored
High	75 < EIPL ≤ 100	Important indicator
Medium	50 < EIPL ≤ 75	Notable effectiveness indicator
Low	25 < EIPL ≤ 50	Questionable usefulness/impact
Very low	1 < EIPL ≤ 25	Very low value indicator

VI. EXAMPLE OF APPLICATION AND DISCUSSION

Table 5 illustrates the implementation of the GRAPE analysis grid on the distributed maintenance. For both functions, transport and maintenance, we list the impact modes and their effects, and chose to represent only one indicator per mode of impact, for which we give the values of I, M and U criteria and the environmental impact EIPL. Note that some modes of impact are not represented to facilitate the reading of the grid. The assignment of values for each indicator is based on the one hand on the ability to have quantitative measurements and on the other hand on the urgency to implement. As an example, for the transport function the costs are very important and are quantifiable as well as the urgency that can be associated. As for

the maintenance indicators, if we are interested in water pollution it is therefore an emergency to do the necessary treatments knowing that it is a measurable and it is an important criterion.

After analysis, we retain the indicators and preventive measures whose priority is strictly higher than 50 (average priority), i.e. optimization of routes and vehicle loads, optimal positioning of the central maintenance workshop, optimal scheduling of operations, optimal sizing of stocks and second life. Some other preventive measures, although assessed as priorities, will be considered later, such as: vehicle autonomy and water treatment.

## VII. CONCLUSION

This paper proposed GRAPE, an analytical grid for evaluating and prioritizing environmental indicators in maintenance activities. By adapting principles from FMECA, GRAPE provides a structured approach to assess indicators based on their importance, measurability, and urgency, yielding a quantifiable EIPL score. Application of the method to a distributed maintenance case study confirmed its effectiveness in highlighting critical environmental impacts and guiding preventive actions. Notably, transport cost, accident frequency, and water pollution emerged as high-priority concerns. GRAPE thus enables informed decision-making for environmentally conscious maintenance planning. Future research will explore the integration of dynamic data sources and the adaptation of GRAPE to other industrial domains.

However, there is room for improvement, particularly within the context of distributed maintenance:

- Integration of environmental constraints into the operational principles of distributed maintenance: Distributed maintenance consists of three main elements: the central maintenance workshop, the mobile maintenance workshop, and the various geographically distributed sites. Environmental parameters can be integrated into each of these elements. This could include the optimal selection of transport vehicles for spare parts based on their capacities and environmental impact, optimization of vehicle intervention schedules to reduce travel distances, and comparison of vehicle types that could be used (electric or thermal vehicles). Additionally, a more in-depth study of technical and environmental performance indicators would enable the synchronization of all aspects of distributed maintenance with the associated environmental data.
- Application to a case study conducted in [9] on the geographical positioning of the central maintenance workshop: Determining the optimal location of the central maintenance workshop, the capacity of vehicles, and the scheduling of preventive maintenance operations could prove interesting. The objective would be to pursue the same goals while considering environmental indicators this time, in order to compare the two calculation methods and assess the contribution of integrating environmental requirements into the distributed maintenance process.

Table 5 Implementation of GRAPE for priority assessment

Fonction	Impact Mode	Impact Effect	Associated indicator	Evaluation of Indicators				Preventive Actions
				I	M	U	EIPL = I*M*U	
Transport	Cost	Increased fuel consumption	Transport cost	5	5	5	125	Search for optimal routes
	Time	Increased transport times	Average delivery time	4	5	4	80	Optimal positioning of the central workshop
	Quality	Increased number of accidents	Frequency of accidents	5	5	5	125	Autonomous vehicles
	Air	Increased amount of CO <sub>2</sub> emitted	Quantity of CO <sub>2</sub> emitted per year	5	3	4	60	Load optimization
Maintenance	Cost	Decreased profitability	Operation costs	5	4	5	100	Optimal scheduling
	Time	Increased maintenance times	Average repair time	4	5	4	80	Optimal sizing of stocks
	Quality	Reduced equipment life	Reliability	5	3	4	60	Second life
	water	Increased PH of wastewater	PH of wastewater	5	5	5	125	Water treatment
	Ground	Increased concentration of heavy metals	Quantity of waste buried	4	5	2	40	Recycling
	Air	Reduced life of refrigeration equipment due to fluorinated gas leaks	Quantity of fluorinated gas emitted	4	2	3	24	Regular inspection of equipment

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## REFERENCES

- [1] A. Abdi, S. Taghipour, "Sustainable asset management: A repair-replacement decision model considering environmental impacts, maintenance quality, and risk." *Computers & Industrial Engineering* 136 (2019): 117-134.
- [2] T. Bangemann, X. Rebeuf, D. Reboul, A. Schulze, J. Szymanski, J.P. Thomesse, and N. Zerhouni, "PROTEUS—Creating distributed maintenance systems through an integration platform." *Computers in industry* 57.6 (2006): 539-551.
- [3] R. Bannai, S.D. Puspitasari, H. Yokota, E. Kato, Y. Kawabata, "Evaluation of sustainability indicators in maintenance management of port mooring facilities." *Life-Cycle Civil Engineering: Innovation, Theory and Practice*. CRC Press, 2021. 465-470.
- [4] J. Borcken, "Evaluation of environmental indicators for transport with ELECTRE III." *Actes du Seminaire PIE* (2005).
- [5] J. Borcken, "Strategic Environmental Indicators for Transport and their Evaluation-Qualitative Decision Aiding for SEA." *Proceedings of the SEA 2005* (2005).
- [6] M. Catelani, I. Ciani, and M. Venzi, "Failure modes, mechanisms and effect analysis on temperature redundant sensor stage." *Reliability Engineering & System Safety*, 180, 425-433, (2018).
- [7] R. A. Djeunang Mezafack, M. Di Mascolo, Z. Simeu-Abazi, and S. Akbari Haghighi, "Performance evaluation of centralized maintenance workshop in the circular economy context," *MOSIM 2020-13th International Conference on Modeling, Optimization and Simulation*, Agadir, Morocco, Nov. 2020.
- [8] R. A. Djeunang Mezafack, M. Di Mascolo, and Z. Simeu-Abazi, "Systematic literature review of repair shops: focus on sustainability," *International Journal of Production Research*, 60(23), 7093-7112, Nov. 2021
- [9] R. A. Djeunang Mezafack, Z. Simeu-Abazi, and M. Di Mascolo, "Optimization of Distributed Maintenance: Design, Scheduling and Capacitated Routing Problem.," *IFAC-PapersOnLine*, Volume 55, Issue 19, 2022, Pages 139-144.
- [10] R. A. Djeunang Mezafack, Z. Simeu-Abazi, M. Di Mascolo, "Mastering Carbon Footprint in the Context of Distributed Maintenance", *ICCAD 2022*.
- [11] C. Franciosi, B. Lung, S. Miranda, S. Riemma, "Maintenance for sustainability in the industry 4.0 context: A scoping literature review." *IFAC-PapersOnLine* 51.11 (2018): 903-908.
- [12] Z. Hajej, N. Rezg, and A. Gharbi, "Joint optimization of production and maintenance planning with an environmental impact study." *The International Journal of Advanced Manufacturing Technology* 93 (2017): 1269-1282
- [13] K. Hamilton, and G. Atkinson, "Air pollution and green accounts." *Energy Policy* 24.7 (1996): 675-684.
- [14] C.M. Hoffmann, and R. Joan-Arinyo, "Distributed maintenance of multiple product views." *Computer-Aided Design* 32.7 (2000): 421-431.
- [15] IEC 60812:2018 Failure modes and effects analysis (FMEA and FMECA)
- [16] M. Jasiulewicz-Kaczmarek, A. Gola, "Maintenance 4.0 technologies for sustainable manufacturing-an overview." *IFAC-PapersOnLine* 52.10 (2019): 91-96.
- [17] R. Joumard, and H. Gudmundsson, "Indicators of environmental sustainability in transport: an interdisciplinary approach to methods." *European Commission*, 2010.
- [18] R. Joumard, H. Gudmundsson, and L. Folkeson, "Framework for assessing indicators of environmental impacts in the transport sector." *Transportation research record* 2242.1 (2011): 55-63.
- [19] M. Kouakep Tchouma, R.A. Djeunang Mezafack, M. Di Mascolo, Z. Simeu-Abazi, "Environmental impact of operations carried out in the context of distributed maintenance: a literature review", in: *2023 International Conference on Control, Automation and Diagnosis (ICCAD)*, IEEE, Rome, Italy
- [20] K. Minarovičová, "Environmental impact of ETICS maintenance." *International Conference on Advanced Building Construction and Materials*. 2015.
- [21] D. Necula, N. Vasile, and M. F. Stan, "Maintenance-a solution to reduce the environmental impact of electrical machines." *Electrical and Electronic Engineering* 1.2 (2011): 55-59.
- [22] F. Rainer. "Environmental external costs of transport", *Springer Science & Business Media*, 2001.
- [23] H. Rødseth, "Development of Indicators for Maintenance Management within Integrated Planning." (2017).
- [24] Z. Simeu-Abazi, A. Alali Alhouaij, "Optimisation of distributed maintenance: Modelling and application to the multi-factory production", *Reliability Engineering & System Safety – Volume 96, Issue 11, Pages 1564-1575, November 2011*.
- [25] N. Williard, S. Mathew, "A failure modes, mechanisms, and effects analysis (FMMEA) of lithium-ion batteries", *Microelectronics Reliability*, Volume 52, Issue 8, 2012,