An Investigation of Sustainable Maintenance Performance Indicators: Identification, Expert Validation and Portfolio of Future Research

**AEF SAIHI**, **MOHAMED BEN-DAYA**, AND **RAMI AS'AD**
Department of Industrial Engineering, American University of Sharjah, Sharjah, United Arab Emirates
Corresponding author: Afef Saihi (g00079250@aus.edu)

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**ABSTRACT** The full integration of sustainability considerations into maintenance practices requires a close monitoring of maintenance impact through appropriate key performance indicators (KPIs) that take into account various sustainability aspects. However, there is a lack of a comprehensive framework of KPIs covering all the sustainability dimensions, and the few attempts to address this need are specific to certain industries and lack validation by experts in the field. Therefore, the aim of this research is to develop and validate a comprehensive and multidimensional framework of sustainability performance indicators for the assessment of maintenance impacts on the triple-bottom-line. To that end, an exhaustive list of general indicators is collected based on both international organizations standard-sets and published literature. Subsequently, this list is projected on the maintenance area to establish the pertinent indicators. Then, a validation phase is performed with a highly qualified expert panel through semi-structured questionnaires and follow-up discussions. The validated list of sustainable maintenance KPIs includes 63 indicators amongst which 34 belong to the environmental pillar and are split between various categories such as resource use, residuals, environmental compliance, etc. The social pillar comprises of 15 indicators related to occupational health and safety, training and development and customer satisfaction dimensions. Finally, the economic pillar includes 14 indicators split between economic performance and investment categories. The findings of this research provide guidance to practitioners in the field and set the foundations for conducting promising future works. A rich portfolio of future research based on the obtained results is proposed.

**INDEX TERMS** Maintenance, sustainability, direct impacts, indirect impacts, performance indicators, expert validation.

I. INTRODUCTION
Over the last decade, sustainability aspects have gained an ever-growing importance. Organizations are pushed to rethink their responsibilities and revisit their priorities by incorporating environmental and social aspects, in addition to the economic performance, into their decision-making process. Companies nowadays are facing various challenges to remain competitive in a global market. In fact, embracing sustainability considerations in the various business aspects has become a crucial necessity. Broadly speaking, sustainability is defined as the development “that meets the needs of present without compromising the ability of future generations to meet their own needs” [1], [2]. Sustainability thinking helps businesses reduce risk, conserve critical and non-renewable resources, increase material and energy efficiency, and innovate by developing environmentally friendly products and services [3]. There is a growing concern about environmental degradation that is forcing many industries to carry out environmentally conscious decisions at all stages from product design, manufacturing, service up to end-of-life activities.

To achieve sustainability objectives, its related goals need to be reflected in the firm’s strategies and cascaded down to all business functions. Maintenance is a critical activity performed throughout the product’s lifecycle in order to retain its functionality and prolong its availability. It was always viewed, in the past, as an activity that merely aims to maintain
and restore the functionalities of an equipment to the desired performance level [4], [5]. However, nowadays, this view has started to evolve by considering maintenance as an activity that has an impact on all dimensions of sustainability due to its contribution to the enhancement of socioeconomic wellbeing, the minimization of environmental impacts and the reduction of life cycle costs. No one can deny, for instance, the pivotal role of maintenance in the reduction of total costs, the promotion of safety and the minimization of energy consumption among others [6]. Therefore, the goal of maintenance processes in the sustainability era is not merely to prevent, check and repair equipment and systems and ensure they run smoothly; but it encompasses the increased profitability and the total lifecycle costs optimization while offering an opportunity for decreasing the influence on natural environment and increasing the efficiency of resource utilization without disturbing safety and social wellbeing [7].

The economic and technical impacts of maintenance on sustainability are fairly discussed in the literature. They include the consequences of facility/machine downtime due to breakdowns and their associated costs related to lost production, quality issues, and compromised performance, among others. However, the other pillars of sustainability, namely environmental and social, are also impacted by maintenance. As a matter of fact, the lack of maintenance can lead to several environmental problems such as increased energy consumption and greenhouse gases (GHG) emissions, and ineffective use of resources [8].

The full integration of sustainability aspects into maintenance management practices requires close monitoring of maintenance impacts on the triple bottom line (TBL) through appropriate key performance indicators (KPIs) that span the three sustainability pillars. However, the performance indicators currently used by organizations merely focus on technical and economic aspects and are not oriented for sustainable performance assessment and decision making [9]. The assessment of maintenance impacts on sustainability calls for the identification and subsequently the adoption of relevant indicators that help evaluate current and future outcomes. The quantification of the performed maintenance activities impacts via such indicators results in more informed decisions concerning the effectiveness and efficiency of such activities. It is noted that indicators on the performance levels along the three pillars need to be combined into a single framework and results need to be presented to decision makers [10]. The availability of such indicators provides a mean to monitor sustainability performance over time, derive the future goals, determine the improvement potentials, benchmark against other organizations, align with stringent government regulations concerning sustainable business practices, and assist with sustainability reports. Despite the relevance of the topic of maintenance impacts on sustainability, very limited studies addressed the performance evaluation dimension and attempted to develop key performance indicators (KPIs) that are deemed useful for sustainable maintenance evaluation. Furthermore, the currently developed maintenance indicators rarely address the social and environmental impacts. The few studies that did develop such indicators focused on a specific type of industry or paid attention to the environmental sustainability pillar only [11], [12], [13]. Additionally, these few attempts lack validation by experts in the field rendering the suitability/applicability of those indicators a questionable matter.

The aim of this research is to bridge these gaps through proposing a comprehensive, general, multidimensional and hierarchical framework of sustainability performance indicators. This is followed by projecting the general directory on the maintenance area. The aim is to generate a complete framework that can be used by any industry for the selection of suitable and significant indicators towards measuring and evaluating maintenance impacts on sustainability. Furthermore, to address the lack of validation problem in the literature, semi-structured surveys and follow-up discussions are conducted with highly qualified experts in the field. This helped bring the list of indicators to a manageable size by selecting the most suitable indicators for sustainable maintenance assessment. This contributes to addressing the identified research gaps and to opening several new promising avenues for research in this area. To fulfill the aim of this study, the following objectives are defined: (i) put-together a comprehensive list of sustainability KPIs based on both international organizations standard sets and a thorough review of the relevant literature; (ii) select from the general list of sustainability KPIs those that are relevant to maintenance; (iii) perform indicators purification and validation with experts in the field through surveys and follow-up discussions.

The remainder of this paper is organized as follows. Section 2 presents a comprehensive review of the relevant literature and lists the identified research gaps. Section 3 describes the methodological steps adopted to fulfill the aim of this study. Section 4 is devoted for the reporting and discussion of the results. Section 5 proposes a portfolio of future research directions based on this study’s findings. Finally, Section 6 summarizes the paper and presents some concluding remarks.

II. RELATED LITERATURE

This section focuses on examining the state of research addressing sustainability performance indicators in general and looking into the sustainable maintenance related indicators. The aim is to investigate the aforementioned objectives and clearly identify the associated research gaps.

A. GENERAL PERFORMANCE INDICATORS FOR SUSTAINABILITY ASSESSMENT

Incorporating sustainability dimensions into the different business activities and processes has created the need to propose measures/indicators that assess where do they stand from a sustainability perspective, evaluate system’s performance and measure progress over time. This key need led
to the emergence of sustainability indicators as a widely accepted tool [14]. In essence, sustainability indicators provide an effective way to ensure the industries and their various stakeholders are behaving responsibly [15]. Thus, an increasing number of initiatives and organizations have begun developing sustainability indicators and using them to provide assurance that particular activities are sustainable and to help companies take the right decisions when required [16]. As such, various sets of indicators have been developed in the literature and different organizations have established relevant standards such as Global Reporting Initiative (GRI standard), General Motors (GM) metrics for sustainable manufacturing, Organization for Economic Co-operation and Development (OECD) Core Environmental Indicators (CEI), Institution of Chemical Engineers (IChemE) sustainability metrics, Lowell Center Sustainable Production (LCSP) indicator framework, National Institute of Standards and Technology (NIST), European Environmental Agency Core Set of Indicators (EEA-CSI), Ford product sustainability index (PSI), United Nations-Indicators of Sustainable Development (UN-CSD), among others [17]. Table 1 summarizes the most common sustainability indicator sets along with the sustainability dimensions covered by each. These sets of indicators have been developed by organizations to address the various levels of sustainable decision making [18]. They span the process/product level (e.g., Ford PSI), corporate/organization level (e.g., GRI), nation/region level (e.g., UN-CSD), global level (OECD) [19]. It argued that most of the research works on sustainability assessment focused on the product level or have been centered around certain activities and processes and there is a lack in developing comprehensive frameworks that cover all the sustainability dimensions. A major challenge for decision makers is the selection criteria for KPIs, both quantitative and qualitative, pertinent to their specific industries and line of business, and how to interpret them in support of their decision-making process [20]. Therefore, this brings out the need for a systematic and comprehensive conceptual framework of indicators that spans the sustainable activity pillars regardless of the type of industry or performed activity. Among the aforementioned standard sets, only three organizations (GRI, LCSP and NIST) provide indicators that are general in nature, tackle sustainability performance at the organization level, and include the three pillars of sustainability [17]. Among these three indicators sets, GRI indicators are the most comprehensive and the most widely used for sustainable performance reporting by organizations [27], [28], [29].

**B. PERFORMANCE INDICATORS FOR SUSTAINABLE MAINTENANCE EVALUATION**

Decision making in maintenance has long been based on performance indicators; however, these indicators are mostly developed taking into consideration only technical and economic aspects while overlooking the environmental and social dimensions [30]. As noted earlier, performance indicators are an effective way of summarizing performance information in a clear qualitative or quantitative form and conveying it to the target users and concerned stakeholders to aid them in taking the right decisions. This naturally is also applicable to maintenance decision makers given the relevance of the maintenance impacts on sustainability and the high extent to which it affects its various dimensions. In this context, [11] discussed the maintenance decision support systems weaknesses in terms of assessing the sustainability performance and argued that social and environmental impacts of maintenance are not sufficiently addressed by the current indicators. Along the same lines, [12], [13], [31] pointed out that despite the increasing interest among researchers in the maintenance impacts on sustainability during the last decade, only few recent studies have addressed its performance evaluation aspects. Theses studies proposed some indicators for measuring and evaluating sustainability performance and how it is impacted by the maintenance activities carried out. [31] developed an initial framework for assessing sustainable maintenance performance by including measures at the corporate, tactical and functional levels in the specific context of the automotive industry. Moreover, in an attempt to increase decision-makers awareness concerning environmental impacts of maintenance related activities, [9] presented a framework of sustainability indicators, but they only focused on the environmental dimension of sustainability. [17] conducted a comprehensive review of maintenance impacts on sustainability and generated a list of indicators used to assess these impacts. Their study was purely dedicated for manufacturing industries with no formal validation of the framework of indicators. Similarly, [32] proposed an interpretive structural model of KPIs for the evaluation of sustainable maintenance practices for the rubber industry. In a recent study, [33] developed and validated a sustainable cleaner maintenance performance measurement framework. However, the work was dedicated for the car manufacturing industry, addressed only the sustainable aspects of the maintenance activities and did not account for the indirect impacts on the maintained engineered objects.

| Indicator set | Number of indicators | Included pillars | Reference |
|---------------|---------------------|-----------------|-----------|
| GRI           | 79                  | ✓               | ✓         | ✓         | [21]      |
| IChemE        | 22                  | ✓               | ✓         | ✓         | [22]      |
| GM metrics    | 33                  | ✓               | ✓         | ✓         | [23]      |
| Ford PSI      | 8                   | ✓               | ✓         | ✓         | [19]      |
| LCSP          | 22                  | ✓               | ✓         | ✓         | [24]      |
| UN-CSD        | 96                  | ✓               | ✓         | ✓         | [25]      |
| OECD-CEI      | 46                  | ✓               | ✓         | ✓         | [19]      |
| NIST          | 170                 | ✓               | ✓         | ✓         | [18]      |
| EEA-CSI       | 37                  | ✓               | ✓         | ✓         | [26]      |
C. RESEARCH GAPS
Having surveyed the relevant literature, the following gaps have been identified.

- Although some efforts have targeted the identification of maintenance related KPIs, a comprehensive and general list of indicators that provides sufficient guidance for practitioners to integrate sustainability aspects into their decision making is yet to be developed.
- As noted by [19], most of the research works addressing sustainability assessment focused on the product
level or have been centered around certain activities and processes, and there is a lack in developing a comprehensive framework that covers all the sustainability dimensions regardless of the type of industry or the performed activities.

- Most of the research works in this area addressed the direct impacts generated by the maintenance activities on sustainability and only very few ones considered the indirect impacts reflected on the maintained engineered objects’ behavior.
- The few attempts seeking to partially address these gaps lack validation by experts in the field.

### III. METHODOLOGICAL STEPS

To achieve the aim of this study and fulfill its objectives, various research strategies are adopted, and qualitative techniques of data collection are used. Three consecutive phases of research are conducted including: (1) determining the list of general sustainability indicators, (2) selecting the sustainability indicators relevant to maintenance, and (3) conducting maintenance indicators purification with experts in the field. Figure 1 consists of three blocks and depicts the steps involved in each stage of research along with an outline of the existing dependencies amongst them. A detailed explanation of the various steps involved in each phase are provided in the subsequent sections. It shall be noted that the three stages of research are dependent, and their outputs serve as foundation to conduct the consecutive stage. Table 2 presents the mapping between the different research objectives, methodological choices and corresponding research strategies.

### IV. GENERAL SUSTAINABILITY INDICATORS

The first research objective aims to identify the various general sustainability indicators by referring to international standard sets and the relevant literature. The first block in Figure 1 describes the adopted procedure. First, inclusion and exclusion criteria, that are in line with the objectives of this research, were defined to select the international standard sets. In essence, the included indicators should involve the three pillars of sustainability, address sustainability
TABLE 4. Definitions of direct versus indirect impacts of maintenance on sustainability.

| Type of impact | Author’s definition                                                                                                                                 |
|----------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| Direct         | Direct impacts of maintenance on sustainability include the various consequences engendered by the execution of maintenance related tasks/operations and/or their management on different aspects of sustainability. The energy consumed, emissions released, waste generated, effect on health and safety that are associated with performing maintenance tasks are a few examples of these direct impacts. |
| Indirect       | Indirect impacts of maintenance on sustainability encompass the various effects of maintenance related activities on the behavior and performance level of the maintained engineered objects with respect to the three pillars of sustainability. Increased/decreased GHG emissions and energy consumption and the ineffective/effective use of materials by poorly/well maintained machines are a few examples of these indirect impacts. |

performance at the organization level (i.e., exclude the indicators related to global and national levels), and are general in nature (i.e., not related to a specific industry or type of business). Among the different indicator sets mentioned in section 2.1, only GRI, LCSP and NIST conform with the inclusion criteria. Given that GRI indicators are the most comprehensive and widely used by organizations [27], [28], [29], they are selected as the starting point to generate the initial list of general sustainability indicators.

Second, the published literature also constitutes a significant source to solicit the indicators highlighted by other researchers in the field and map them to the GRI indicators. The adopted search keywords are (“sustainability indicators”) OR (“sustainability metrics”) OR (“sustainability KPI”) OR (“sustainability performance”) OR (“Indicators for Sustainab”) OR (“sustainability criteria”). The initial screening of the literature revealed that most of the research in this area has been conducted during the last decade. Therefore, Scopus database is selected to search for articles published after the year 2010 which yielded 1497 articles. The filtering process underwent many steps; an initial screening based on titles and abstracts of the articles, then another deep screening based on their content. Only the papers that are pertinent to the scope of this research and entail answers to the first research question are selected. Subsequently, a backward search is conducted to scan the references of the already selected articles and check if they are related to the scope of this research. This systematic procedure generated 43 relevant papers.

The indicators collection process started with the initial list provided by the GRI indicator set. Then, the various indicators highlighted in the selected research articles are extracted and examined. If the assessed indicator matches with one of the GRI indicators, no new entry is created, and the corresponding article is mapped accordingly. However, if it does not match any of the GRI indicators, a new entry is created in the list and the corresponding article is mapped. Afterwards, the levels of detail are created and fine-tuned several times to group the related indicators and associate them to the appropriate dimensions within each pillar.

A structured hierarchy is established providing a comprehensive and hierarchical view of the various indicators and their relative classes. Table 3 summarizes the categories and subcategories identified within each sustainability pillar along with the number of indicators representing each and the 43 references used to extract them.

V. SUSTAINABILITY INDICATORS RELEVANT TO MAINTENANCE

The output of the previous phase serves as input for this step of research which aims to investigate the second research question and determine the most-suitable indicators to assess the maintenance sustainable performance as presented in the second block of Figure 1. To begin with, the solicited general sustainability indicators are projected on the maintenance domain to select the ones relevant for this area and that can serve to measure its impacts on sustainability. Both direct and indirect impacts of maintenance on sustainability are taken into account during the projection stage. Thereafter, similar to the previous research strategy, relevant articles from the published literature are selected, their indicators are derived and explored, distinct new entries are created in the list, and references are mapped accordingly. The used search keywords are “maintenance” AND (“sustainability” OR “energy” OR “TBL” OR “Triple Bottom Line” OR “environment” OR “ecological” OR “green” OR “carbon” OR “emission” OR “social” OR “safety”) AND (“indicator” OR “metric” OR “KPI” OR “performance” OR “criteria” OR “framework” OR “measur” OR “aspect”). Scopus search using these keywords yielded 217 articles that are published after 2010. The same refining procedure detailed in Section 3.1 is applied, with exclusion of the non-relevant works and the optimization and modeling works where the latter works were reviewed in a recent article [8]. Finally, 21 articles are selected and considered relevant to the objective of this study. Once again, the indicators highlighted in the selected works are thoroughly examined, compared with the projected list, and accordingly new entries are created if needed, and the references mapped to the list. It shall be noted that the conventional technical indicators such as Overall Equipment Effectiveness (OEE), Mean Time Between failure (MTBF), Mean Time To Repair (MTTR), etc. are not included in the list. This is due to the fact that organizations, wishing to assess the level of sustainability of their maintenance activities, should already have a mechanism
### TABLE 5. A preliminary list of identified indicators and the associated decision after experts’ evaluation.

| Environmental pillar | Resource use | Material use | Pillar - Category - Subcategory - Indicator | Group responses | Decision on the indicator post expert evaluation |
|----------------------|--------------|--------------|--------------------------------------------|----------------|-----------------------------------------------|
|                       |              |              | **Average** | **Median** | **SD** |                                      |
| Environmental pillar |              |              |                          |               |       |                                      |
| Resource use          |              |              |                          |               |       |                                      |
| Resource use          |              | Material use | MU1 Total weight or volume of material used by maintenance activities with specification of the used material type (virgin, reused, recycled, remanufactured) | 3.50 | 4.00 | 0.84 | Delete as its average is lower than the cut-off value and it exists in the denominator of the ratio MU1 |
|                       |              | Material use | MU2 % increase in the use of biodegradable components | 4.00 | 4.00 | 0.89 | Keep as is |
|                       |              | Material use | MU3 % of recycled/reused/remanufactured material used for maintenance activities | 4.17 | 5.00 | 0.98 | Keep as is |
|                       |              | Material use | MU4 Total weight or volume of material used for maintained systems functions (raw materials, semi-manufactured goods, auxiliary materials, etc.), renewable or non-renewable with specification of the used material type | 3.50 | 4.00 | 0.84 | Delete as its average is lower than the cut-off value and it exists in the denominator of the ratio MU1 |
|                       |              | Material use | MU5 Total energy consumption ratio-direct: amount of material used by maintenance activities / organization specific metric (e.g., Production volume, number of employees, etc.) | 4.00 | 4.00 | 0.89 | Keep as is |
|                       |              | Material use | MU6 Total energy consumption ratio-indirect: amount of material used by maintained systems functions / organization specific metric | 3.83 | 3.00 | 0.98 | Keep as is |
|                       |              | Material use | MU7 Total consumption of lubricants and cleaners used for maintenance by type (biodegradable, non-biodegradable) and percent usage of each type | 4.50 | 4.00 | 1.54 | Change it to a ratio and follow-up with the expert to review his rating in light of the new changes. Updated to: Ratio of the total consumption of lubricants and cleaners used for maintenance activities by organization-specific metric. |
|                       |              | Material use | MU8 % increase in the use of biodegradable lubricants and cleaners | 4.33 | 5.00 | 0.82 | Keep as is |
|                       |              | Material use | MU9 Usage of chemicals and environmentally risky material for maintenance work | 4.67 | 5.00 | 0.52 | Keep and change it to a ratio. Updated to: Ratio of the chemicals and environmentally risky material used for maintenance activities by organization-specific metric |
| Energy use            |              |              |                          |               |       |                                      |
|                       |              |              | EU1 Total energy consumption by maintenance activities within the organization (fuel, electricity, heating, cooling, steam) through assets owned and controlled by the organization | 4.50 | 5.00 | 0.84 | Delete as it is reflected in the ratio EU1 |
|                       |              |              | EU2 Total energy consumption by maintenance activities outside the organization (transportation, distribution, etc.) | 4.17 | 5.00 | 0.98 | Delete as it is reflected in the ratio EU2 |
|                       |              |              | EU3 Total energy consumption by maintained systems functions | 4.33 | 4.00 | 0.52 | Delete as it is reflected in the ratio EU3 |
|                       |              |              | EU4 Energy intensity ratio-direct (within): Total energy consumption by maintenance activities within the organization through assets owned and controlled by the organization / organization-specific metric | 4.50 | 5.00 | 0.84 | Keep and split into 2 ratios EU4 and EU4 to reflect the within and outside organization consumptions |
|                       |              |              | EU5 Energy intensity ratio-direct (outside): Total energy consumption by maintenance activities / organization-specific metric | 4.17 | 5.00 | 0.98 | Created based on EU1 and experts suggestions |
|                       |              |              | EU6 % reduction of energy consumption by maintained systems due to maintenance activities | 4.00 | 4.00 | 0.89 | Keep as is |
|                       |              |              | EU7 % reduction of energy consumption by maintenance activities due to reduction initiated by maintenance processes | 4.83 | 5.00 | 0.41 | Keep as is |
|                       |              |              | EU8 Actual energy consumed / theoretical energy needed for maintenance processes | 3.50 | 4.00 | 0.84 | Delete as its average is lower than the cut-off value |
|                       |              |              | EU9 Ratio of actual energy consumed / theoretical energy needed for maintained systems functions | 4.00 | 4.00 | 0.63 | Keep as is |
| Water use             |              |              |                           |               |       |                                      |
|                       |              |              | WE1 Volume of water withdrawn for maintenance activities breakdown by source | 3.33 | 3.00 | 0.52 | Delete as its average is lower than the cut-off value |
|                       |              |              | WE2 Volume of water withdrawn for maintained systems breakdown by source | 3.17 | 4.00 | 0.98 | Keep as is |
| Land use              |              |              |                           |               |       |                                      |
|                       |              |              | LU1 Land used by maintenance infrastructure with specification of the type (fertile, non-fertile) | 2.83 | 3.00 | 0.75 | Delete as its average is lower than the cut-off value |
|                       |              |              | LU2 Maintenance waste effect on land quality (e.g., land contamination) | 4.17 | 5.00 | 0.98 | Keep as is |
|                       |              |              | LU3 Maintained systems waste effect on land quality | 4.33 | 4.00 | 0.82 | Keep as is |
| Residuals             |              |              |                           |               |       |                                      |
| Effluents and waste   |              |              |                           |               |       |                                      |
|                       |              |              | EW1 Amount of waste generated by maintenance activities specified by waste type and disposal method (solid, liquid, hazardous, non-hazardous, recyclable, disposable, reusable…) | 4.50 | 5.00 | 0.84 | Keep and change to a ratio. Updated to: Ratio of the amount of waste generated by maintenance activities by organization-specific metric |
|                       |              |              | EW2 Amount of waste generated by defective maintained systems due to lack of proper maintenance | 4.67 | 5.00 | 0.52 | Keep and change to a ratio. Updated to: Ratio of the amount of waste generated by defective maintained systems due to lack of proper maintenance by organization specific metric |
|                       |              |              | EW3 Volume of recorded significant spills derived by maintenance activities specified by type (oil, fuel, spills of waste, spills of chemicals and others), and by destination (soil or water surfaces) | 4.00 | 5.00 | 1.10 | Keep and change to a ratio. Updated to: Ratio of the volume of recorded significant spills derived by maintenance activities by organization specific metric |
|                       |              |              | EW4 Volume of recorded significant spills derived by maintained systems functions specified by type and by destination | 4.17 | 4.00 | 0.98 | Keep and change to a ratio. Updated to: Ratio of the volume of recorded significant spills derived by maintenance systems by organization specific metric |
|                       |              |              | EW5 Amount of wastewater discharged by maintenance activities by type and destination | 3.17 | 4.00 | 0.98 | Delete as its average is lower than the cut-off value |
|                       |              |              | EW6 Transport of hazardous waste generated by maintenance activities | 3.17 | 3.00 | 1.17 | Keep as is |
|                       |              |              | EW7 Transport of hazardous waste generated by maintenance activities | 3.50 | 4.00 | 0.84 | Keep as is |
|                       |              |              | EW8 Hazardous waste rate specified by disposal method (reused, incinerated, landfilled) | 3.83 | 3.00 | 0.98 | Keep as is |
| Emissions and pollution|              |              |                         |               |       |                                      |
|                       |              |              | EP1 Direct GHG emissions (from sources that are owned or controlled by the organization) related to maintenance activities (in metric tons of CO2 equivalent) | 4.33 | 5.00 | 0.82 | Delete as it is reflected in the ratio EP1 |
|                       |              |              | EP2 GHG emissions related to maintained systems functions (in metric tons of CO2 equivalent) | 4.33 | 4.00 | 0.82 | Delete as it is reflected in the ratio EP2 |
|                       |              |              | EP3 Indirect GHG emissions (consequence of the activities of the organization, but occur at sources owned or controlled by another entity) related to maintenance activities (in metric tons of CO2 equivalent) | 4.00 | 4.00 | 0.89 | Delete as it is reflected in the ratio EP3 |
### TABLE 5. (Continued.) A preliminary list of identified indicators and the associated decision after experts’ evaluation.

| Indicator                                                                 | Value       | Decision                                                                 |
|---------------------------------------------------------------------------|-------------|--------------------------------------------------------------------------|
| EP<sub>1</sub>: GHG emissions intensity ratio-direct/within: Total GHG emissions generated by maintenance activities within the organization through assets owned and controlled by the organization / organization-specific metric | 4.50 5.00 0.84 | Keep and split into 2 ratios EP<sub>1</sub> and EP<sub>2</sub> to reflect the within and outside organization emissions |
| EP<sub>2</sub>: GHG emissions intensity ratio-direct/within: Total GHG emissions generated by maintenance activities outside the organization / organization-specific metric | 4.00 4.00 0.89 | Created based on EP<sub>1</sub> and experts suggestions |
| EP<sub>3</sub>: GHG emissions intensity ratio-indirect: Total GHG emissions associated to maintained systems functions / organization-specific metric | 4.00 4.00 0.89 | Keep as is |
| EP<sub>4</sub>: % Reduction in GHG emissions as a direct result of reduction initiatives taken by maintenance processes | 4.67 5.00 0.52 | Maintain as is |
| EP<sub>5</sub>: Emissions of ozone-depleting substances (ODS) due to maintenance activities | 4.33 5.00 1.21 | Keep and change to a ratio. Updated to: Ratio of total emissions of ozone-depleting substances (ODS) due to maintenance activities by organization-specific metric |
| EP<sub>6</sub>: Emissions of ODS due to maintained systems functions | 4.00 4.00 0.63 | Keep and change to a ratio. Updated to: Ratio of total emissions of ODS due to maintained systems functions by organization-specific metric |
| EP<sub>7</sub>: Significant air emissions for each of the following: NOX, SOX, Persistent organic pollutants (POP), Volatile organic compounds (VOC), Hazardous air pollutants (HAP), Particulate matter (PM) related to maintenance activities | 4.17 5.00 0.98 | Keep and change to a ratio. Updated to: Ratio of the air emissions for each of the following: NOX, SOX, POP, VOC, HAP, PM related to maintenance activities by organization-specific metric |
| EP<sub>8</sub>: Significant air emissions for each of the following: NOX, SOX, POP, VOC, Hazardous air pollutants HAP, Particulate matter PM related to maintained systems functions | 3.83 4.00 0.75 | Keep and change to a ratio. Updated to: Ratio of the air emissions for each of the following: NOX, SOX, POP, VOC, HAP, PM related to maintained systems functions by organization-specific metric |
| EP<sub>9</sub>: Noise/odors/dust/smog generated by maintenance activities | 4.00 4.00 0.89 | Keep as is |
| EP<sub>10</sub>: Noise/odors/dust/smog generated by maintained systems functions | 3.17 3.00 0.98 | Delete as its average is lower than the cut-off value |

#### Environmental Compliance

| Compliance with environmental standards and regulations | Value       | Decision                                                                 |
|--------------------------------------------------------|-------------|--------------------------------------------------------------------------|
| CES<sub>1</sub>: Number of complaints, illegal cases and significant fines and sanctions for non-compliance of maintenance activities with environmental laws and regulations | 4.00 4.00 0.89 | Keep as is |
| CES<sub>2</sub>: Number of complaints, illegal cases and significant fines and sanctions for non-compliance of maintained systems functions with environmental laws and regulations due to lack of maintenance | 4.17 4.00 0.98 | Keep as is |
| CES<sub>3</sub>: Environmental management system (e.g., ISO 14001) | 4.00 5.00 1.55 | Rename the indicator to clarify its meaning and follow-up with the expert to review his rating in light of the new changes. Updated to: Implement environmental management system (e.g., ISO 14001) |

#### Social criteria

| Social criteria | Value       | Decision                                                                 |
|-----------------|-------------|--------------------------------------------------------------------------|
| Health and Safety Occupational health and safety | | |
| OHS<sub>1</sub>: The number of maintenance work-related incidents, injuries and maintenance accidents requiring first aid | 4.33 5.00 0.82 | Keep as is |
| OHS<sub>2</sub>: Lost workdays due to maintenance accidents | 4.33 5.00 0.82 | Keep as is |
| OHS<sub>3</sub>: Occupational health and safety management system (e.g., ISO 45001) | 3.83 4.00 1.47 | Rename the indicator to clarify its meaning and follow-up with the expert to review his rating in light of the new changes. Updated to: Implement OHS management system (e.g., ISO 45001) |
| OHS<sub>4</sub>: The number of maintained systems functions work-related incidents, injuries and accidents requiring first aid due to lack of maintenance | 4.50 5.00 0.55 | Keep as is |
| OHS<sub>5</sub>: % of maintenance employees with high risk of diseases or incidents related to the nature of their work | 4.17 5.00 0.98 | Keep as is |
| OHS<sub>6</sub>: Implemented programs for training, counselling, and risk-control to limit the risk of injuries and assist the employees and their families with serious illnesses | 4.67 5.00 0.52 | Keep as is |
| OHS<sub>7</sub>: Personal protective and safety equipment provided for maintenance activities | 4.67 5.00 0.52 | Keep as is |
| OHS<sub>8</sub>: Availability of medical facilities and healthcare resources to provide emergency services if required | 4.33 5.00 0.82 | Keep as is |
| OHS<sub>9</sub>: Improvement rate in safety performance due to the adopted safety measures | 4.33 5.00 0.82 | Keep as is |

#### Physical working environment

| Physical working environment | Value       | Decision                                                                 |
|------------------------------|-------------|--------------------------------------------------------------------------|
| PWE<sub>1</sub>: Maintenance workplace noise level | 3.50 4.00 0.84 | Delete as its average is lower than the cut-off value |
| PWE<sub>2</sub>: Maintenance workplace lighting and ventilation | 3.50 4.00 0.84 | Delete as its average is lower than the cut-off value |

#### Employees

| Employees Hiring and benefits | Value       | Decision                                                                 |
|-------------------------------|-------------|--------------------------------------------------------------------------|
| HB<sub>1</sub>: Total number of maintenance employees | 3.00 3.00 1.10 | Delete as its average is lower than the cut-off value |
| HB<sub>2</sub>: Total number of maintenance employees hired by age group, gender and region | 3.00 3.00 1.10 | Delete as its average is lower than the cut-off value |
| HB<sub>3</sub>: Total number of maintenance employees turnover by age group, gender and region | 2.83 3.00 0.98 | Delete as its average is lower than the cut-off value |
| HB<sub>4</sub>: Benefits provided to maintenance personnel: insurance, minimum wage, etc. | 3.00 3.00 1.10 | Delete as its average is lower than the cut-off value |

#### Training and development

| Training and development | Value       | Decision                                                                 |
|--------------------------|-------------|--------------------------------------------------------------------------|
| TD<sub>1</sub>: Average hours of maintenance-related training per maintenance employee | 3.83 4.00 0.98 | Keep as is |
| TD<sub>2</sub>: Type and scope of maintenance-related training programs (training topics) | 3.00 3.00 1.10 | Keep as is |
| TD<sub>3</sub>: Percentage of total maintenance employees by gender who received a regular performance and career development review | 3.83 4.00 0.75 | Keep as is |
| TD<sub>4</sub>: Percentage of maintenance employees trained in sustainability concepts | 4.50 5.00 0.55 | Keep as is |

#### Employee satisfaction

| Employee satisfaction | Value       | Decision                                                                 |
|-----------------------|-------------|--------------------------------------------------------------------------|
| ES<sub>1</sub>: Reward and appreciation: incentives for maintenance employee performance | 3.17 3.00 0.75 | Delete as its average is lower than the cut-off value |
| ES<sub>2</sub>: Job satisfaction rate of maintenance employees (through questionnaires, surveys) | 3.50 4.00 0.84 | Delete as its average is lower than the cut-off value |
| ES<sub>3</sub>: Job satisfaction rate of maintained systems employees | 2.50 2.00 1.05 | Delete as its average is lower than the cut-off value |
| ES<sub>4</sub>: Complaints rate of maintenance employees | 3.17 3.00 0.98 | Delete as its average is lower than the cut-off value |
| ES<sub>5</sub>: Maintenance employees’ involvement | 3.00 4.00 1.10 | Delete as its average is lower than the cut-off value |

#### Customers

| Customers Customer satisfaction | Value       | Decision                                                                 |
|---------------------------------|-------------|--------------------------------------------------------------------------|
| C<sub>5</sub>: Number of incidents of customer complaints | 3.83 4.00 0.98 | Keep as is |
| C<sub>6</sub>: Number of practices to assess customer satisfaction level | 3.33 4.00 1.03 | Delete as its average is lower than the cut-off value |
in place to evaluate maintenance performance using those conventional technical measures.

The projection on the maintenance area is performed by the authors with supervision and contribution of a senior co-author who has extensive knowledge in the maintenance area along with published books and articles in top journals. Both direct and indirect impacts of maintenance activities on sustainability are taken into consideration while doing the indicators projection. Most of the research works published in the literature addressed mainly the direct impacts. Although limited number of studies considered the indirect impacts, there is a lack of a clear definition that helps researchers and practitioners distinguish between the two types of impacts. Therefore, the authors started by coining definitions for the direct and indirect impacts of maintenance on sustainability as described in Table 4.

Throughout the projection process, the previously solicited general sustainability indicators are independently explored by the researchers with regard to their appropriateness and applicability to the maintenance domain. Thereafter, several rounds of comparison, evaluation and fine-tuning are performed to come up with a tentative list of indicators that is further ameliorated and amended based on the published relevant literature. This resulted in 95 indicators mapped into different structured classes belonging to the three pillars of sustainability. The first column of Table 5 summarizes these indicators, their respective categories and the way they are structured. The supporting related studies that contributed to their creation are presented in Table A.1 provided in the Appendix.

| Economic pillar | Economic Performance and Investment | Compliance with social standards and regulations | Supply chain | Supplier social assessment |
|----------------|------------------------------------|-----------------------------------------------|--------------|--------------------------|
|                |                                   | Compliance with social standards and regulations |              |                          |
|                |                                   | CSST  Number of complaints, illegal cases and significant fines and sanctions for non-compliance of maintenance activities with social laws and regulations | 3.83 4.00 0.98 | Keep as is                |
|                |                                   | CSSM  Number of complaints, illegal cases and significant fines and sanctions for non-compliance of maintenance systems functions with environmental laws and regulations | 4.17 4.00 0.75 | Keep as is                |
|                |                                   | SSA  % of maintenance suppliers and subcontractors screened using social criteria | 3.33 4.00 0.82 | Delete as its average is lower than the cut-off value |

VI. EXPERT VALIDATION OF MAINTENANCE SUSTAINABILITY INDICATORS

Once the entire list of maintenance sustainability indicators is solicited, the next step consists of conducting a purification phase with experts in the field to have a first layer of validation for the indicators. This procedure aims to evaluate the collected indicators in terms of their level of suitability to assess the sustainable performance of maintenance activities. To start this process, a data collection questionnaire is designed to solicit the individual opinions of the experts of the panel. The questionnaire is developed based on the findings of the previous phase of research which is the entire list of maintenance sustainability indicators. It is semi-structured in nature as it contains both closed-ended and open-ended questions. The closed-ended questions allow the panel of experts to rate the level of suitability of the indicators using a 5-point Likert scale: (1) not suitable, (2) less suitable, (3) moderately suitable, (4) suitable, and (5) highly suitable. The open-ended questions allow the experts to provide their comments regarding the provided indicators and their suggestions for improving the list. Prior to the data collection, a pilot test of the questionnaire is conducted by two experts where both design and content are amended as per their recommendations [74].

The experts selection adopted the purposive sampling type based on their level of knowledge and expertise in the field of research. Those with a track record of extensive knowledge and relevant expertise are targeted. Then, individual emails describing the aim of the research and its background are sent to 11 experts, six of them accepted the invitation.
Subsequently, the data collection questionnaire along with more details about the study are sent to these six experts. The quality of the selected sample of experts ensures its representativeness [75]. Table 6 describes the profiles of the experts involved in the study.

The experts responses were analyzed and summarized using measures of central tendency and variability. Follow-up discussions and rating review with some experts were performed when necessary. Subsequently, the hierarchical list of indicators was improved and purified based on the experts’ ratings, suggestions and comments. The cut-off value for an indicator to be considered suitable for measuring maintenance sustainability performance is a mean value of 3.7 along with a low variability among the experts responses [76]. Based on the level of variability, follow-up discussions were initiated with some experts after implementing the necessary suggested modifications in order to give them the opportunity to review their ratings in light of the new changes.

Several suggestions and recommendations are communicated by the panel of experts in order to purify the list of indicators. Some of them felt that few pairs are redundant, some others commented on the level of clarity of some indicators and the way they are named. One of the major comments received criticized some items of the preliminary list of indicators that are measured in their raw format (e.g., total weight or volume, total consumption, total emissions, etc.). They advised that each of these indicators must be a ratio considering the usage rate of the maintained systems or the organization’s level of activity. They also added that most of the indicators, in that current raw format, would be biased and that this ratio logic should be applied to all of them. Based on this major comment, necessary amendments are made through (1) changing the corresponding indicators and following up with the experts to review their ratings if necessary, or (2) deleting the indicator if it is already reflected in one of the existing ratios in the list, or (3) creating a new indicator to cover its various aspects. The second and third columns of Table 5 summarize the group responses metrics and the decision taken for each indicator post expert evaluation and data analysis. The various decisions taken are distinguished and highlighted in different colors and the color code adopted is described in Table 7.

To support data interpretation and decisions taken after the evaluation of the experts’ responses, few examples are given. To begin with, the example of the indicators MU1 and MU4 is provided. The final decision is to delete these indicators for two reasons. Firstly, their group responses averages are lower than the cut-off value. Secondly, given that these indicators are measured in raw format, they should normally be converted to ratios considering the experts’ suggestion, however, they are already reflected in the existing two ratios (MU5 and MU6) in the “Material use” subcategory. Furthermore, the decision on several indicators of the list (such as MU2, EU5, LU2, etc.) is to “keep as is” as their group averages are higher than the cut-off value, the variability among the experts’ responses is low (≤ 1) which reflects the consensus among them on the indicators’ level of relevance, and no reluctance or negative comments are expressed by the experts. The indicators MU7, CES3 and OHS3 qualified for being kept according to the group responses average, however the variability among responses is a bit high and they required some changes as per the experts recommendations. After implementing the necessary changes, follow-up discussions are conducted with the experts to review their responses in light of these modifications which brought the standard deviations to 0.54 for MU7 and CES3 and 0.51 for OHS3. Moreover, some indicators are newly created based on other indicators of the preliminary list and experts suggestions. For instance, EU42 is created based on EU2. It is advised by the experts to change EU1 and EU2 to ratios. EU1 was deleted as it is already reflected in the ratio EU4, however, there was no ratio to replace EU2. Therefore, the ratio EU4 is split into two ratios (i.e., EU41 and EU42) to account for the energy consumption by maintenance activities within and outside the organization. The purification process continued in the same fashion and evaluated all the preliminary indicators. This resulted in a reduced list of 63 indicators that are presented in Table A.2 of the Appendix.

### VII. PORTFOLIO OF FUTURE RESEARCH DIRECTIONS BASED ON THE FINDINGS

This study lays the foundation for a complete portfolio of future research avenues based on the current findings, and offers interesting opportunities for future research. This
research portfolio includes, but not limited to, the following research directions:

- The three pillars of sustainability are mostly considered as isolate elements rather than an integrated system where the various dimensions impact one another. There is a lack of understanding the causal theoretical background associated with sustainable maintenance aspects and a lack of a model to weight both qualitative and quantitative indicators. The findings of this research could be exploited to design and validate a multidimensional concept based on the triple bottom-line approach for sustainable maintenance performance evaluation. This would contribute to better understand the causal background of sustainable maintenance related dimensions and determine the most critical performance indicators.

- In the same context of sustainable maintenance performance evaluation, a methodological framework for the integration of the most influential sustainability indicators into a maintenance balanced scorecard could be proposed along with a detailed and guided approach of putting it into action.

- The identified most critical performance indicators could be integrated in different decision support tools and used to suggest means to enhance sustainable maintenance decision making (e.g., propose maintenance planning models that would form an integral part of the decision-making process while properly taking into consideration environmental and social criteria, proposing new perspectives to integrate sustainability aspects into maintenance strategies, etc.).

- The real challenge for organizations is to develop a manageable set of the most relevant KPIs to measure the impact of their maintenance activities on the three pillars of sustainability. This calls for developing industry-specific reduced and manageable sets of maintenance sustainability performance indicators while ensuring balanced coverage of the implicated sustainability aspects. A framework for the materiality assessment, selection and prioritization of the identified KPIs for particular industries could be proposed.

- Researchers could address the implementability issues and barriers that hinder the incorporation of the identified indicators into sustainable maintenance decision support systems, and explore the potential solutions for that and the role of technology in facilitating this integration.

- Future research could also consider further classification of the identified indicators based on the implicated decision levels (i.e., strategic, tactical, operational) and characterize the relationships between them and their role in driving decision making at the associated level.

- The identified KPIs could be leveraged to conduct longitudinal research for specific organizations to evaluate the improvement over time. This can be complemented with performing detailed case studies proposing a step-by-step approach to develop a roadmap towards attaining more sustainable maintenance activities.

- Some studies address the identification of useful performance indicators and metrics, but do not deal with their measurement and quantification or what sort of data should be collected [77]. Thus, a detailed methodological approach could be proposed towards the quantification and measurement of the sustainability key influencing indicators.

### VIII. CONCLUSION

In order to incorporate sustainability considerations into maintenance practices, there is a pressing need for a diligent monitoring of maintenance impacts on the three pillars of sustainability through appropriate KPIs. The review of the published literature revealed that (1) most of the research works addressed the direct impacts of maintenance on sustainability with very few studies dealing with the indirect impacts, (2) there is a lack of a comprehensive framework of performance indicators that covers all the sustainability dimensions, (3) the very few attempts to develop a comprehensive list of indicators are specific to certain industries and lack validation by experts in the field.

This study contributed to address these identified gaps in research. A comprehensive, multidimensional and hierarchical framework of sustainability performance indicators, serving to aid decision-makers in assessing the performance of their maintenance activities with respect to the three sustainability pillars, is developed and validated by experts in the field. First, an extensive list of general sustainability KPIs is solicited based on both international standard sets and the published literature. Then, this list was projected on the maintenance area to identify the sustainability KPIs that are pertinent to assessing maintenance impacts on sustainability. Afterwards, the validation of these performance indicators is performed with experts in the field through semi-structured questionnaires and follow-up discussions. Finally, this research can serve as a building block for future works, and its findings set the foundations for a rich and promising portfolio of subsequent research.
### APPENDIX

**TABLE A.1.** Supporting references for maintenance sustainability indicators.

| Indicator | [35] | [78] | [79] | [80] | [81] | [82] | [113] | [83] | [84] | [85] | [86] | [87] | [88] | [90] | [91] | [92] | [17] |
|-----------|------|------|------|------|------|------|-------|------|------|------|------|------|------|------|------|------|------|
| MU<sub>1</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>2</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>3</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>4</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>5</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>6</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>7</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>8</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>9</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MU<sub>10</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| WU<sub>1</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| WU<sub>2</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| LW<sub>1</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| LW<sub>2</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| LW<sub>3</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| LW<sub>4</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| LW<sub>5</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| LW<sub>6</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>1</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>2</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>3</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>4</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>5</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>6</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>7</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>8</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>9</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EP<sub>10</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| CES<sub>1</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| CES<sub>2</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| CES<sub>3</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| CES<sub>4</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| SEI<sub>1</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| OHS<sub>1</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| OHS<sub>2</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| OHS<sub>3</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| OHS<sub>4</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| OHS<sub>5</sub> | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

124270
| Indicator | [35] | [78] | [79] | [80] | [81] | [31] | [82] | [13] | [11] | [83] | [32] | [84] | [85] | [86] | [88] | [89] | [90] | [91] | [92] | [77] |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| OHS₁      | ✓    | ✓    |      |      |      | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| OHS₂      | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| OHS₃      | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| OHS₄      | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| PWE₁      | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| PWE₂      | ✓    |      |      | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| HB₁       | ✓    |      |      | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| HB₂       | ✓    |      |      | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| HB₃       | ✓    |      |      | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| HB₄       | ✓    |      |      | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| TD₁       | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| TD₂       | ✓    |      | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| TD₃       | ✓    |      | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| TD₄       | ✓    |      | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ES₁       | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ES₂       | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ES₃       |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ES₄       | ✓    |      |      | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ES₅       | ✓    |      |      | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| CS₁       | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| CS₂       | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| CSS₁      |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| CSS₂      |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| SSA₁      |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₁      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₂      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₃      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₄      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₅      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₆      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₇      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₈      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₉      | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₁₀     | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₁₁     | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₁₂     | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₁₃     | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₁₄     | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| ECP₁₅     | ✓    |      | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |
| IN₁       | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| IN₂       | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| IN₃       | ✓    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
### TABLE A.2. Purified list of maintenance sustainability indicators.

| Environmental pillar | Pillar - Category - Subcategory - Indicator |
|----------------------|---------------------------------------------|
| **Resource use**     |                                             |
| Material use         |                                             |
| MU₂                  |                                             |
| MU₃                  | Refer to Table V for the nomenclature       |
| MU₅                  |                                             |
| MU₆                  |                                             |
| MU₇                  | Ratio of the total consumption of lubricants |
|                     | and cleansers used for maintenance          |
|                     | activities by organization-specific metric  |
| MU₈                  | Refer to Table V for the nomenclature       |
| MU₉                  | Ratio of the chemicals and environmentally  |
|                     | risky material used for maintenance          |
|                     | activities by organization-specific metric  |
| **Energy use**       |                                             |
| EU₄₀                 | Energy intensity ratio-direct (within) Total |
|                     | energy consumption by maintenance           |
|                     | activities **within** the organization       |
|                     | through assets owned and controlled by the  |
|                     | organization / organization-specific metric |
| EU₄₁                 | Energy intensity ratio-direct (outside):     |
|                     | Total energy consumption by maintenance      |
|                     | activities **outside** the organization      |
|                     | / organization-specific metric               |
| EU₅                  |                                            |
| EU₆                  |                                            |
| EU₇                  | Refer to Table V for the nomenclature       |
| EU₈                  |                                            |
| EU₉                  |                                            |
| **Land use**         |                                             |
| LU₁₀                 | Refer to Table V for the nomenclature       |
| LU₁                  |                                            |
| **Residuals**        |                                             |
| **Effluents and Waste** |                                    |
| EW₁                  | Ratio of the amount of waste generated by   |
|                     | maintenance activities by organization-      |
|                     | specific metric                             |
| EW₂                  | Ratio of the amount of waste generated by   |
|                     | defective maintained systems due to lack of |
|                     | proper maintenance by organization specific  |
|                     | metric                                     |
| EW₃                  | Ratio of the volume of recorded significant |
|                     | spills derived by maintenance activities     |
|                     | specified by type (oil, fuel, spills of    |
|                     | waste, spills of chemicals and others), and  |
|                     | by destination (soil or water surfaces) by   |
|                     | organization-specific metric                |
| EW₄                  | Ratio of the volume of recorded significant |
|                     | spills derived by maintenance                |
|                     | systems by organization specific metric      |
| EW₅                  | Refer to Table V for the nomenclature       |
| **Emissions and Pollution** |                                |
| EP₁₀                 | GHG emissions intensity ratio-direct(within):|
|                     | Total GHG emissions generated by maintenance |
|                     | activities **within** the organization       |
|                     | through assets owned and controlled by the  |
|                     | organization / organization-specific metric |
| EP₁₁                 | GHG emissions intensity ratio-direct (outside): |
|                     | Total GHG emissions generated by maintenance |
|                     | activities **outside** the organization      |
|                     | / organization-specific metric               |
| EP₁                  | Refer to Table V for the nomenclature       |
| EP₂                  |                                            |
| EP₃                  | Ratio of total emissions of ozone-depleting |
|                     | substances (ODS) due to maintenance          |
|                     | activities by organization-specific metric   |
| EP₄                  | Ratio of total emissions of ODS due to      |
|                     | maintained systems functions by organization-|
|                     | specific metric                             |
| EP₅                  | Ratio of significant air emissions for each  |
|                     | of the following: NOX, SOX, POP, VOC, HAP,  |
|                     | PM related to maintenance activities by      |
|                     | organization-specific metric                |
| EP₆                  | Ratio of the air emissions for each of the   |
|                     | following: NOX, SOX, POP, VOC, HAP, PM      |
|                     | related to maintained systems functions by   |
|                     | Organization-specific metric                 |
| EP₇                  | Refer to Table V for the nomenclature       |

**Environmental Compliance**

Compliance with environmental standards and regulations.
TABLE A.2. (Continued.) Purified list of maintenance sustainability indicators.

| Supply chain | | | |
|---|---|---|---|
| CES₁ | Refer to Table V for the nomenclature |
| CES₂ | |
| CES₃ | Implement environmental management system (e.g., ISO 14001) |
| Supplier Environmental Assessment | | | |
| SEA₁ | % of maintenance suppliers and subcontractors screened using environmental criteria |
| Social pillar | | | |
| Health and Safety | Occupational Health and Safety | | |
| | OHS₁ | Refer to Table V for the nomenclature |
| | OHS₂ | |
| | OHS₃ | Implement OHS management system (e.g., ISO 45001) |
| | OHS₄ | |
| | OHS₅ | Refer to Table V for the nomenclature |
| | OHS₆ | |
| | OHS₇ | |
| | OHS₈ | |
| | OHS₉ | |
| Employees | Training and Development | | |
| | TD₁ | Refer to Table V for the nomenclature |
| | TD₂ | |
| Customers | Customer Satisfaction | | |
| | CS₁ | Refer to Table V for the nomenclature |
| Social Compliance | Compliance with social standards and regulations | | |
| | CSS₁ | |
| | CSS₂ | |
| Economic pillar | Economic performance and investment | | |
| Economic Performance | | | |
| | ECP₁ | |
| | ECP₂ | |
| | ECP₃ | |
| | ECP₄ | |
| | ECP₅ | |
| | ECP₆ | Refer to Table V for the nomenclature |
| | ECP₇ | |
| | ECP₈ | |
| | ECP₉ | |
| | ECP₁₀ | |
| | ECP₁₁ | |
| | ECP₁₂ | |
| | ECP₁₃ | |
| Investment | | | |
| | JN₁ | Refer to Table V for the nomenclature |
| | JN₂ | |

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**MOHAMED BEN-DAYA** received the Ph.D. degree in operations research from the Georgia Institute of Technology, in 1988. He is currently an Industrial Engineering Professor at the American University of Sharjah. He has published over 100 papers in refereed journals and conference proceedings. He has co-edited several books on maintenance engineering and optimization and coauthored a textbook on maintenance engineering published by Wiley. His research interests include production planning, maintenance and quality control, and supply chain management. He is the Co-Founder and an Associate Editor of the *Journal of Quality in Maintenance Engineering* (Emerald) and also an Associate Editor of *Information Systems and Operational Research* journal.

**AFEF SAIHI** received the Engineering degree in telecommunications from the Higher School of Communication of Tunisia (SUP’COM). She is currently pursuing the Ph.D. degree in engineering systems management (ESM) with the American University of Sharjah. She is also a Graduate Research and a Teaching Assistant. Her research interests include the fields of supply chain management, maintenance management, sustainable performance evaluation, digital transformation, and innovation management. She has published articles in reputable international journals, such as the *International Journal of Production Economics*, the *International Journal of Innovation Science*, the *International Journal of Quality and Reliability Management*, and the *Journal of Quality in Maintenance Engineering*. She also presented her research works in prestigious international conferences.

**RAMI AS’AD** received the B.Sc. and M.Sc. degrees in systems engineering and operations research from the King Fahd University of Petroleum and Minerals, Saudi Arabia, in 2003 and 2006, respectively, and the Ph.D. degree in industrial engineering from Concordia University, Montreal, Canada. He is currently an Associate Professor at the Industrial Engineering Department, American University of Sharjah. His primary research interests include supply chain management and mathematical modeling, where he has published several articles in a wide spectrum of journals, including the *International Journal of Production Economics*, the *International Journal of Production Research*, *Journal of Cleaner Production*, *Computers and Industrial Engineering*, and *Applied Mathematical Modelling*, among others.

* * *