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Revolutionizing Repairability of Industrial Electronics in Oil and Gas Sector: A Mathematical Model for the Index of Repairability (IOR) as a Novel Technique

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Abstract: The oil and gas (O&G) field is the most sought-after industry in the Gulf Cooperation Countries (GCCs) and holds significant importance in the region's economy. Therefore, this sector requires various industrial electrical, and electronics equipment (EEE) products to perform multiple tasks throughout the upstream, downstream, and midstream segments. However, as these EEE products approach their end of life (EoL), the sector faces the challenge of managing failed units. As a result, replacing or recycling failed EEE products can contribute to the growing problem of electronic waste (e-waste), which can have severe environmental consequences. In addition, while some EEE products can be repaired or remanufactured with low reliability, many others cannot be fixed due to various technical reasons. This paper's primary goal is to propose a circular economy strategy and sustainable practices that promote the longevity of industrial EoL electronic products in the O&G sector through remanufacturing. We introduced and implemented a new mathematical score, the Index Of Repairability (IOR), which aims to assess the ease of EEE repairability in the O&G sector and improve their lifespan and durability based on four criteria: design, spare parts availability, software access, and documentation. This novel mathematical metric leverages the analytic hierarchy process (AHP) and set theory. Additionally, original equipment manufacturers (OEMs) can adopt and benefit from this innovative IOR by incorporating eco-design principles and designing more easily repairable industrial products for technicians, thereby reducing the negative impact of e-waste, enhancing stakeholder satisfaction, and minimizing downtime. Furthermore, governmental organizations can implement regulations and incentives to advocate for and mandate the use of the IOR by OEMs, ensuring that the electronics industry prioritizes repairability, remanufacturing, and sustainability.

Keywords: sustainable development; electronic waste; AHP; remanufacturing; index of repairability; industrial equipment; petrochemicals; GCC; oil and gas; circular economy

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1. Introduction

The Gulf Cooperation Council (GCC) is a significant economic partnership comprising six member states—Oman, Qatar, the United Arab Emirates, Bahrain, Saudi Arabia, and Kuwait—to promote integration, coordination, and interconnection between its members [1]. Moreover, the GCC's oil and gas (O&G) sectors are a vital industry that fuels the economies of many countries in the region [2].

Hence, this sector is a multifaceted industry encompassing various sub-sectors, including renewable energy sources. For instance, many O&G companies are investing in solar, wind, and sea power projects to power their remote operations, generating electricity for offshore platforms and other facilities, reducing the need for expensive and polluting diesel generators [3]. Consequently, electrical and electronic equipment (EEE) plays a significant role in producing, processing, and transporting hydrocarbons [4]. In addition, these products are used to regulate and control operations throughout the upstream, downstream, and midstream phases of the production process, ensuring that everything runs smoothly and efficiently. Moreover, EEE products are crucial in maintaining the industry's health, safety, and environmental standards.

However, as these products reach their end of life (EoL), replacement directly occurs under maintenance contracts. Consequently, managing failed EEE units becomes a significant challenge. In other words, replacing or recycling these failed units can contribute to the growing problem of electronic waste (e-waste), a primary environmental concern with severe consequences in the GCC region and beyond [5], with total e-waste production estimated to reach between 947 and 1090 thousand tons by 2040 [6]. On the other hand, repairing and remanufacturing EEE devices can also be unreliable and challenging in some cases because many original equipment manufacturers (OEMs) do not prioritize the repairability of their designed products [7]. In addition, some OEMs also limit access to spare parts, technical documentation, software, and tools, making it difficult for third-party repairers to perform repairs and remanufacturing. Therefore, there is a pressing need for an assessment system that evaluates and encourages the repairability and remanufacturing of EEE products. However, the existing scoring systems, which are primarily oriented toward personal and household electronic appliances, fail to adequately cater to the specific needs of industrial electronics, especially within the oil and gas (O&G) sector.

In this paper, we introduce the Index of Repairability (IOR) alongside maintenance strategies to encourage the remanufacturing and repairability of EEE products in the O&G sector within the GCC region and other related regions. Therefore, this novel mathematical score is a metric that measures the ease of repairability of industrial electronic equipment. As a result, the IOR's main contribution lies in its emphasis on maintenance contracts between stakeholders and OEMs and its potential to influence government intervention, ensuring the electronics industry focuses on repairability, remanufacturing, and sustainability.

The organization of this paper is outlined as follows. Initially, in the O&G field within the GCC region, the implementation and integration of industrial electronics and the use of EEE in Industry 4.0 are explored. Then, Section 3 examines the strategies and challenges associated with managing worn-out EEE units, such as replacement and remanufacturing, highlighting the technical factors that make certain products challenging to repair. Next, in Section 4, six well-known assessment scoring systems from the existing literature are reviewed and analyzed to promote repairability and demonstrate that industrial electronics, particularly in the O&G field, have not been thoroughly explored. Consequently, we propose a new approach using the Index of Repairability, which evaluates the ease of repairability for electronic equipment in the O&G sector. As a result, it serves as a critical tool for maintenance engineers in the GCC region and other geographical areas with significant O&G operations, aiding in their decision making about whether to replace or repair failed EEE products. Hence, a mathematical model was developed for implementing the IOR, utilizing the analytic hierarchy process (AHP) and set theory based on four criteria. This assessment scoring system model involves consultation with industrial electronics repair experts and incorporates graphical charts and logo design elements. Moreover, Section 5 applies the IOR to real-world scenarios, primarily focusing on artificial lift systems (ALSs). Finally, the outcomes and conclusions are drawn.

2. Application of Industrial Electronics in the O&G Field

The O&G field can be segmented into three primary phases: upstream, midstream, and downstream. Each step has its own unique set of activities, challenges, and technologies. Therefore, Industry 4.0 (I 4.0), or the Fourth Industrial Revolution (IR 4.0), has the potential to bring significant benefits to this sector by leveraging advanced technologies such as artificial intelligence (AI), the industrial Internet of Things (IIoT), big data analytics, wireless communication technologies, cyber-physical systems (CPSs), and digital twin (DT) technologies. [8].

In addition to I4.0, the sector relies heavily on EEE products such as robots and automated systems to perform dangerous or repetitive tasks [9,10], facilitate safe and efficient operations, and improve worker safety across all stages. Figure 1 depicts critical applications of Industry 4.0 and EEE devices within the O&G domain.

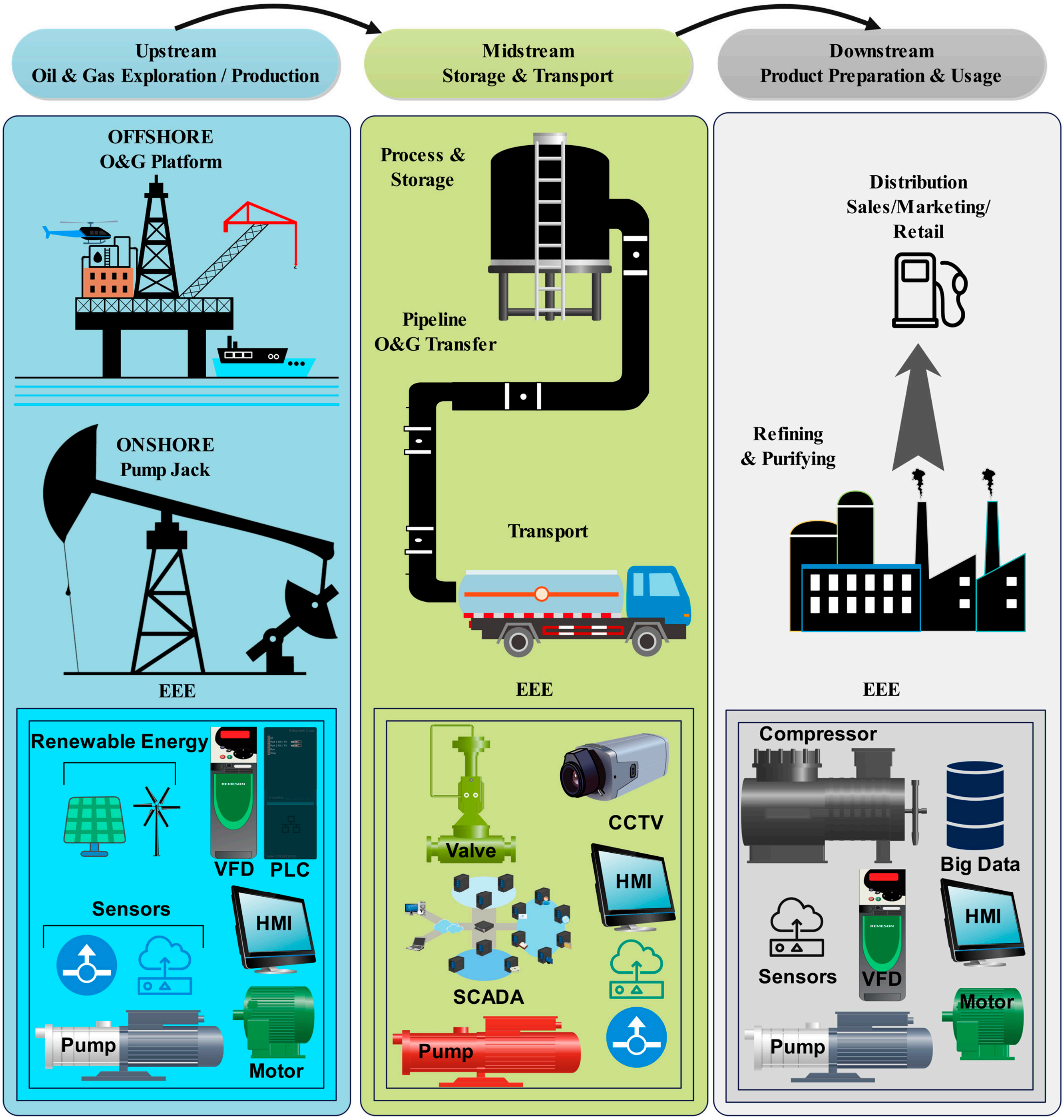

Figure 1. Key applications of Industry 4.0 and EEE devices in the oil and gas sector.

These critical applications are discussed in the following subsections.

2.1. Upstream Exploration

Generally, the upstream stage encompasses exploring, extracting, and producing crude oil and natural gas. This phase includes finding and testing the quality of O&G reserves, drilling wells, and extracting hydrocarbons.

In upstream operations, EEE facilitates the exploration, drilling, and production of O&G reserves, as shown in Figure 1. For instance, advanced drilling rigs come with electric motors, cameras (as shown in Figure 2), variable frequency drives (VFDs), sensors, pumps, and programmable logic controllers (PLCs) that empower and facilitate real-time adjustments of drilling parameters.

Figure 2. Oil rig camera.

Therefore, IoT sensors, AI-powered analytics, and DT technologies are also extensively used to improve reservoir modeling and monitor drilling parameters such as temperature, pressure, and flow rates [4]. These parameters can be displayed on a human–machine interface (HMI), as illustrated in Figure 3.

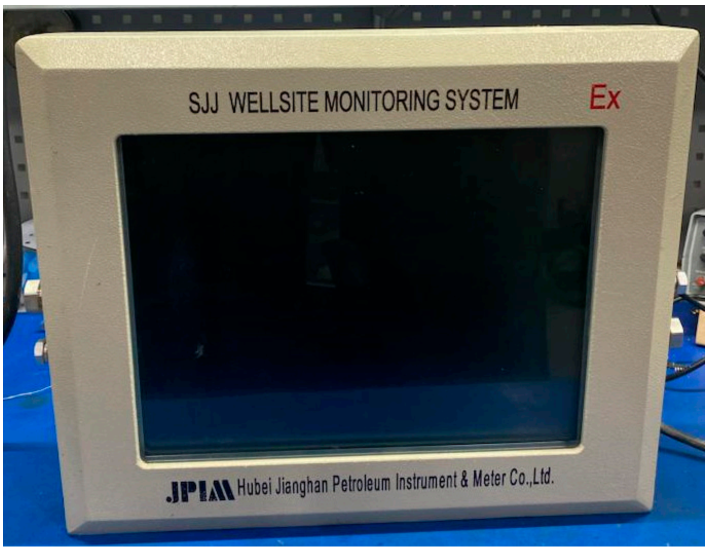

Figure 3. Utilization of a human–machine interface in drilling operations.

Moreover, these devices and technologies help ensure that operations are achieved safely and efficiently, minimizing the risk of accidents and reducing downtime, and then transmitted accurately to a central control room. This room has a distributed control system (DCS) and supervisory control and data acquisition (SCADA) system [11]. These systems monitor and control various processes, equipment, and operations in real time, allowing operators to adjust as needed and identify potential problems to ensure safe and efficient operations. Hence, the DCS is typically used to control and monitor the processes within a facility or plant. In contrast, the SCADA system monitors and controls operations distributed over a larger area, such as pipeline operations or remote well sites.

On the other hand, offshore platforms and onshore facilities require electrical equipment, such as generators, transformers, switchgear, and control systems, to provide access to electric power [12]. Therefore, in addition to traditional power sources, renewable energy sources such as solar power generated using photovoltaic cells and wind power generated using wind turbines supplement the power requirements of offshore platforms and onshore facilities. In addition, some specific EEE devices such as inverters, maximum power point tracking (MPPT) controllers, battery chargers, and batteries are used to regulate and store power [13]. These systems require sophisticated control and monitoring systems, including microgrids and energy storage solutions, to ensure reliable and efficient power delivery.

However, offshore platforms utilize sea power, which uses the kinetic energy of waves and currents to produce electricity, and require specific electrical equipment and systems capable of withstanding harsh environmental conditions, such as saltwater corrosion, high winds, and rough seas [14].

Moreover, artificial lift systems (ALSs) are employed in the O&G upstream industry to increase the flow of hydrocarbons from a production well when the reservoir's natural pressure is insufficient for pushing the fluids to the surface [15]. These systems also utilize several essential EEE products, such as electric motors, which are crucial for powering electrical submersible pumps (ESPs) and progressive cavity pumps (PCPs), to drive the pump and lift fluids to the surface. Furthermore, variable-frequency drives (VFDs) play a significant role in regulating the speed of electric motors in ESPs and other pumping systems, optimizing lift system operations by adjusting motor speeds according to good conditions and production requirements.

Adding to the system's complexity, an ALS employs various sensors and monitoring devices to track parameters such as temperature, pressure, flow rate, and vibration. This monitoring provides valuable information for optimizing system performance and the early detection of potential equipment failures. Simultaneously, control systems such as programmable logic controllers (PLCs) or distributed control systems (DCS) manage the operation of ALSs, automating and coordinating components such as pumps, motors, and valves for efficient and safe production.

In addition, communication devices are another essential element of this system. These facilitate data transmission between different components of the lift system and the control center, allowing the remote monitoring and control of artificial lift systems and quick adjustments and timely maintenance. Therefore, power distribution equipment, which includes components such as transformers, switchgear, and circuit breakers, is vital for delivering electrical power to lift system components.

Last but not least, safety devices such as overcurrent protection, surge protection, and temperature-monitoring mechanisms are employed in ALSs to safeguard EEE products and ensure safe operations. This multifaceted system represents the intricate yet crucial role of each piece of equipment in the smooth functioning of these lift systems.

2.2. Midstream Operations

The midstream phase involves transporting and storing crude oil and natural gas by building pipelines, storage tanks, and transportation infrastructure. This step is critical for moving O&G from production sites to refineries and end-users.

In midstream transportation, I4.0 technologies are used to monitor pipeline integrity, optimize transportation logistics, and detect and respond to potential leaks or other issues. In addition, EEE products such as electric motors, automated pumps, and valves transport

O&G from production sites to refineries and processing plants by controlling the flow of O&G through pipelines and other transportation infrastructure. These systems enable operators to quickly identify and address problems, minimizing the risk of accidents and reducing the time that pipelines are out of commission.

On the other hand, EEE can have a crucial function in storing crude oil and natural gas. For example, SCADA systems can monitor and control storage tanks and pipelines. Therefore, IoT devices can optimize storage by measuring a tank's temperature, humidity, and level and detecting leaks [16]. In addition, power backup systems such as uninterruptible power supplies (UPSs) can also ensure critical EEE products remain operational during power outages or other disruptions. Furthermore, smart sensors and cameras are examples of other EEE devices that can be utilized for remote monitoring, providing operators and managers with real-time data [17].

Transmitters are also utilized in the midstream phase, allowing for communication and data transmission from various sensors and equipment to control centers [4]. Hence, emergency shutdown (ESD) systems are crucial EEE products, as shown in Figure 1, for rapidly detecting and responding to potential leaks or other issues, automatically shutting down equipment and isolating affected areas to prevent further accidents or damage. These devices help safeguard personnel and equipment while minimizing potential environmental harm.

2.3. Downstream Refining

During the downstream phase, crude oil is refined and processed into usable products such as gasoline, diesel, jet fuel, and other products, using catalytic cracking, distillation, and hydrotreating technologies. These refined products are then distributed and marketed to end-users, such as consumers and businesses.

In fact, I4.0 technologies, including AI-powered analytics, DT technology, and CPSs, optimize refining processes, improve product quality, and reduce energy consumption and environmental impacts in downstream refining [18]. For example, a CPS's precise integration of physical and digital systems allows real-time pipeline integrity monitoring and controls refinery processes. However, a DT refers to a virtual model of a physical asset, such as an oil rig or a refinery, which can be used for predictive maintenance, performance optimization, and identifying potential issues before they occur, reducing downtime and maintenance costs [8]. Moreover, big data analytics is being used to process large amounts of data generated with sensors and other devices, providing valuable insights for decision making, improving supply chain management, optimizing production, and reducing waste.

In addition, refineries use industrial EEE products, as presented in Figure 1, such as electric motors, VFDs, and sensors, to operate and manage their equipment, such as pumps, compressors, and heat exchangers. Furthermore, sophisticated control and safety systems are utilized to enhance the efficiency and consistency of the refining process as well as to regulate and mitigate emissions. At the same time, intelligent sensors play a critical role in downstream operations by constantly monitoring product quality and identifying impurities or contaminants in real time.

Hence, to ensure safety in the O&G sector, all EEE products used in these facilities must meet the highest safety standards, including explosion-proof equipment [4]. This is necessary to prevent sparks, electrical arcs, accidents, and explosions to avoid igniting highly combustible crude oil and natural gas.

3. Dealing with Failed EEE in O&G Industry

Due to the O&G industry's significant dependence on industrial electronic equipment, EEE products frequently reach their EoL relatively quickly. However, managing failed EEE products at their EoL poses substantial challenges, as it can lead to considerable downtime, safety risks, and environmental concerns. As a result, current strategies predominantly focus on replacement and remanufacturing, each with its pros and cons.

3.1. Replacement of Failed EEE Products

The most common approach to addressing failed equipment in the O&G industry is replacement. This strategy allows companies to regain operational capacity quickly, minimizing downtime and mitigating potential revenue loss. However, this approach has several drawbacks, which are detailed as follows.

3.1.1. E-Waste

The rapid replacement of EEE devices leads to a substantial increase in electronic waste, often ending up in landfills [19]. E-waste disposal poses serious environmental concerns as it contains hazardous materials such as lead, mercury, and cadmium, which can pollute the air, soil, and water resources [20]. Furthermore, improper e-waste management contributes to the depletion of precious resources such as gold, silver, and rare earth elements utilized in electronic components [21]. While recycling is a potential management strategy, its effectiveness in addressing these issues is often limited due to inefficient recycling processes, inadequate recycling rates, and the intricate compositions of EEE devices.

3.1.2. Cost

Constantly replacing equipment can be costly, particularly when factoring in expenses related to purchasing, shipping, and installing new components [22]. Occasionally, stakeholders may even need to substitute an entire plant due to the obsolescence of specific devices within the system. This financial burden can strain the budgets of oil and gas facilities, making it challenging to invest and allocate funds to other essential areas such as safety, research, and development.

3.2. Remanufacturing of Failed EEE Products

On the other hand, some end-users have adopted remanufacturing as an alternative strategy to mitigate the negative environmental impact and cost associated with equipment replacement. Remanufacturing involves repairing or rebuilding failed EEE products to prolong their lifespan, reduce e-waste, and reduce expenses [23]. Therefore, this strategy helps to reduce lead times and offers enhanced reliability by introducing improvements to failed EEE devices when addressing the root causes of equipment failure.

In addition, it deviates from conventional recycling methods by concentrating on reusing EoL products at the component level instead of the raw material level, as illustrated in Figure 4. Therefore, industrial remanufacturing is commonly mistaken for reconditioning, wherein a used product is restored to functionality without a warranty equivalent to a new item, and for repairing, which merely fixes specific simple issues [24]. Remanufacturing, although more energy- and resource-intensive than reconditioning or repairing, produces a higher quality product with an extended use life. This thorough process entails disassembling, cleaning, repairing, and replacing worn parts to produce a product that matches or exceeds the original equipment's performance [25].

Generally, the expense of remanufacturing ranges between 30% and 50% of the cost of new EEE products [23]. Despite this, remanufacturing offers a variety of advantages, including environmental benefits, reduced costs, and improved reliability, as well as certain limitations, which are detailed as follows.

3.2.1. Feasibility

Not all failed EEE devices can be feasibly repaired or remanufactured. Factors such as the severity of the failure, the obsolescence of spare parts, or the presence of proprietary technology may hinder the remanufacturing process. Additionally, costs incurred in accessing the schematics, software, or tools necessary for remanufacturing and repairing techniques can further exacerbate the financial strain. For example, Figure 5 illustrates an attempt to repair a drilling rig unit.

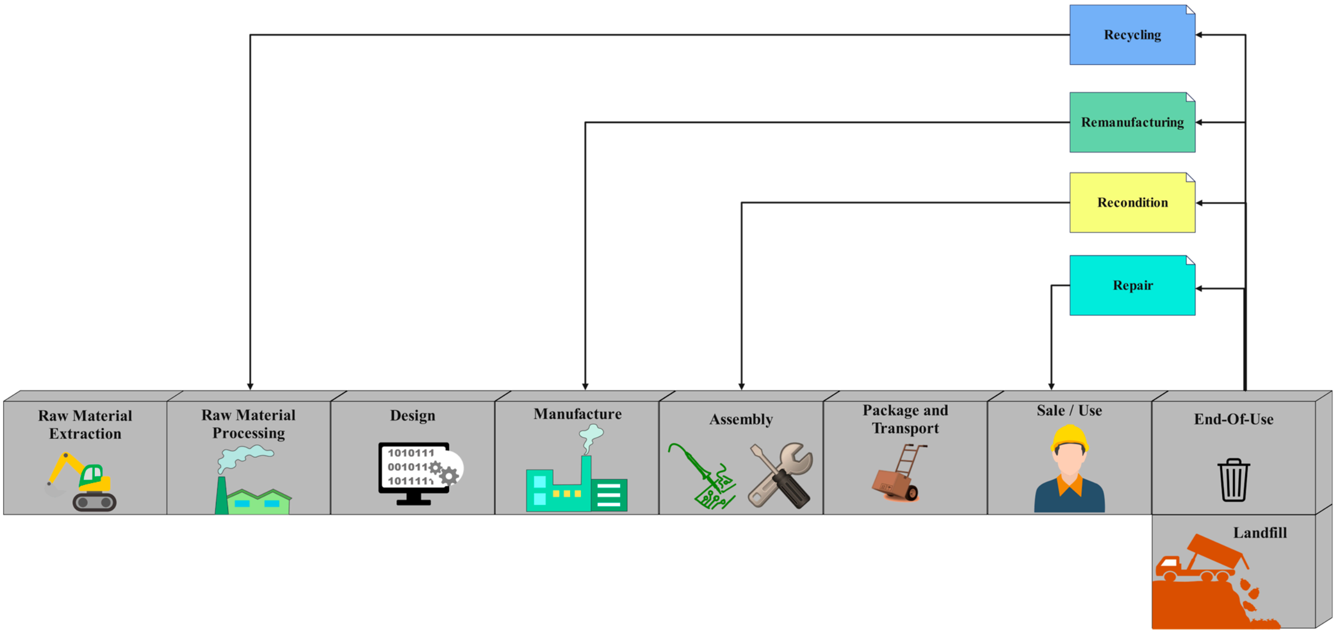

Figure 4. EEE treatment cycles at the end of life.

Figure 5. Attempt at repairing a drilling rig unit.

3.2.2. Time

Remanufacturing can be a time-consuming process, especially for complex or specialized equipment. Consequently, it may result in prolonged downtimes, negatively impacting O&G operations. Therefore, repairing may become more time-consuming and challenging due to limited availability of replacement parts, inadequate documentation, challenges accessing online resources, language barriers stemming from single-language documentation, and concerns regarding software accessibility.

3.2.3. Quality and Reliability

Remanufactured equipment may not perform as reliably as new equipment, potentially leading to additional downtime, safety risks, or decreased efficiency.

3.2.4. Skilled Labor

Remanufacturing typically requires skilled labor to diagnose, troubleshoot, repair, and test equipment. Consequently, a shortage of skilled labor can constrain the industry's capacity to adopt remanufacturing on a large scale [23].

To sum up, remanufacturing offers a sustainable method for restoring defective EEE products by skillfully replacing failed components and electronic parts. This approach proves especially valuable in the O&G sector, wherein EEE products are in high demand. However, remanufacturing requires meeting specific requirements to be successful. For instance, providing spare parts and eliminating planned obsolescence are essential for fostering industrial repairability. By addressing these factors, the benefits of this strategy can be maximized, and the lifespans of EEE devices can be extended.

4. Index of Repairability (IOR) for EEE in Oil and Gas Industry: A Novel Solution

Previous research has introduced various repairability assessment systems in the existing literature to promote remanufacturing and EoL product solutions [26]. These systems aid in determining a product's ease of repair, impact product design and decision-making among stakeholders, and foster a circular economy.

4.1. Scoring Systems for Repairability

Each system presents its unique approach to assessing product repairability. This paper discusses six notable scoring systems and standards, as summarized in Table 1, highlighting their methodologies and criteria.

As a result, existing repairability assessment systems offer a comprehensive framework for evaluating the repairability of electronic devices. These systems primarily focus on household equipment and personal devices such as smartphones and laptops. Moreover, they consider numerous parameters, such as the simplicity of disassembly and reassembly, the accessibility of replacement components, software, information accessibility, and the required tools.

However, the repairability of industrial electronics, particularly within the O&G sector, has not been as extensively investigated as that of consumer electronics. Consequently, developing and implementing a suitable scoring system that addresses the unique challenges surrounding EEE in the O&G sector is crucial. This system should consider various factors, from the initial equipment development by OEMs to assisting technicians in recovering and repairing malfunctioning products.

4.2. Mathematical Modeling

We aimed to draw attention to the underexplored realm of repairability in industrial electronics, specifically within the O&G domain. By emphasizing the necessity for further research and development in this field, we introduced a novel approach to enhance the repairability of EEE devices in the O&G sector. This involves developing a new scoring system to effectively assess the repairability of industrial electronic equipment, from the design stage by OEMs to the hands of expert technicians. Our scoring system, the Index of Repairability (IOR), is grounded in mathematical modeling and considers factors carefully selected and rated by experts and professionals. This is so it can be adopted as an initiative led by the government.

Table 1. A synopsis of the six selected scoring systems.

Repairability Assessment Systems	Products Eligible for Testing	Criteria
Assessment Matrix for Ease of Repair (AsMeR) [27]	All EEE	The repair process comprises five key stages: identifying the product, determining the cause of failure, disassembling and reassembling, replacing any necessary parts, and restoring the product to a functional state. In addition, it considers three crucial repairability factors: providing information, designing the product for ease of repair, and offering adequate service support, catering to both professional repair technicians and DIY repair enthusiasts.
Joint Research Centre Repair Scoring System (RSS) [28]	Vacuum cleaners, laptops, TVs, mobile phones, washing machines, and dishwashers	This model is designed for professional repair specialists to evaluate repairability, reusability, and upgradability.
iFixit 2019 Smartphone Repairability Scoring System [29]	Mobile phones	This model emphasizes eight criteria aimed at evaluating the simplicity of self-repair.
General Methods for the Assessment of the Ability to Repair, Reuse, and Upgrade Energy-Related Products (EN 45554) [30]	All EEE	A universal assessment method for repair, reuse, and upgrade, this approach offers a generic set of tools without focusing on specific products. It is designed for use by both professional repairers and self-repair enthusiasts.
Label of Excellence for Durable, Repair-Friendly Designed Electrical and Electronic Appliances (ONR:192012) [31]	Brown goods and white goods	This evaluation encompasses durability and repairability, with criteria focusing on product design, information provision, and services. This approach is intended for professional repairers.
French Reparability Index (FRI) [32]	Washing machines, TVs, laptops, smartphones, and lawnmowers	This model is centered around five criteria: documentation, disassembly, replacement part availability, replacement part cost, and other device-specific factors. It caters to both professional repairers and self-repair enthusiasts.

Therefore, utilizing set theory, the Index of Repairability model serves as a comprehensive framework for evaluating the repairability of EEE in the O&G industry, incorporating a set of four factors: design, documentation, software, and spare parts, denoted as F.

$$\text{F} = \{\text{Design, Documentation, Software, Spare parts}\} \quad (1)$$

We define f as an element of F, representing a factor. The IOR model can be expressed by adding up the products of each factor and its weight as follows:

$$\forall f \in F : \text{IOR} = \sum_{i=1}^{4} f_W(f_i) \times f_S(f_i) \quad (2)$$

where f represents a factor from F that constitutes the IOR, and f_W represents the weight assigned to each factor f by the technicians, subject to the constraint that each weight is between 0 and 1, and the sum of all weights is equal to 1, as expressed in Equations (3) and (4), respectively.

$$\forall f \in F : 0 < f_W(f) < 1 \quad (3)$$

$$\forall f \in F : \sum_{i=1}^{4} f_W(f_i) = 1 \quad (4)$$

Subsequently, the weight factors were established by carrying out an in-depth and comprehensive technical survey that utilized a five-point Likert scale to collect and assess the scores for each of the four factors in set F, ranging from one to five. The participating experts had an average experience of 14 years, spanning 1 to 32 years in industrial electronics servicing. Consequently, the weights assigned to each proposed factor were derived by analyzing the gathered data using the analytic hierarchy process (AHP) and the geometric mean method. The AHP offers a way to compute weights for hierarchical sequential criteria using pairwise matrix comparisons, denoted as M, as illustrated in Equation (5). In an AHP pairwise comparison matrix, the diagonal represents the self-comparison of the factors. Consequently, the matrix has ones on its diagonal, reflecting the elements' self-comparison property. Apart from the diagonal elements, the other elements in the matrix signify the proportion and comparative significance of the evaluated factors, as determined by the average values gathered from the survey data. These pairwise comparisons enable the AHP method to assess the overall priority of each factor in the decision-making process or analysis [33].

$$M: \begin{bmatrix} Factor/Factor & Design & Documentation & Spare\ parts & Software \\ Design & 1 & 1.1 & 1.086419753 & 0.854368932 \\ Documentation & 0.909090909 & 1 & 0.987654321 & 0.776699029 \\ Spare\ parts & 0.920454545 & 1.0125 & 1 & 0.786407767 \\ Software & 1.170454545 & 1.2875 & 1.271604938 & 1 \end{bmatrix} \quad (5)$$

Nonetheless, alternative methods for weight estimation could also be considered for this purpose [34]. Therefore, the weight factors were calculated using the geometric mean method, with values rounded to 2 decimal places (0.01) for increased precision and clarity, as per Equations (2) and (3). Both the ultimate factor weights and normalized values derived from pairwise matrix comparisons are detailed in Table 2. Furthermore, the geometric mean calculation approach was preferred due to its superior accuracy and lower sensitivity to inconsistencies found in the pairwise comparison matrix, even though it demands slightly more complex calculations.

Table 2. Normalized weight of each factor.

Factor	Normalized Weight	Weight Factor Using Geometric Mean
Design	0.251303742	0.25
Documentation	0.228457947	0.23
Spare parts	0.231313671	0.23
Software	0.294139607	0.29

On the other hand, f_S represents the cumulative score assigned to each factor by OEMs according to the EEE product characteristics. Each cumulative score factor in the model has five criteria, all of which are weighted equally, defined in Table 3, discussed in detail in the next section, and determined via the sum of each criterion's Boolean values (zero or one). In mathematical terms, the cumulative score of each factor f can be represented by defining a set of criteria for each score factor denoted as C_f, as per Equation (3), wherein the cardinality of C_f is five, and each criterion is a Boolean value of either zero or one. Therefore, the cumulative score factor is calculated by adding up the Boolean values of each criterion using Equation (5). Consequently, the resulting sum of criteria can only yield one of the six possible values, namely, zero, one, two, three, four, or five, which is expressed mathematically using Equation (6).

$$\forall f \in F : \exists c \in C_{f_s} : \mathrm{c} \in \{0,1\} \cap C_{f_s} \subseteq \{c_1, c_2, c_3, c_4, c_5\} \quad (6)$$

$$\forall f \in F : \exists c \in C_{f_s} : f_S = \sum_{i=1}^{5} c_i \quad (7)$$

$$\forall f \in F : f_S \in \{0,1,2,3,4,5\} \quad (8)$$

Table 3. Criteria for cumulative score factors.

Cumulative Score Factor	Criterion
Design	Modularity Clear labeling Ease of disassembly Safety considerations
Documentation	Testing points and waveforms Availability of service/user manuals Online documentation Documentation in multiple languages Troubleshooting and maintenance guidelines User/technician feedback
Spare parts	Replacement parts availability Spare parts cost Spare parts reliability and quality Spare parts datasheets Spare parts warranty
Software	Software updates availability Original firmware availability Remote/online technical support Reset/data recovery Access to the software tools

Finally, the IOR can be calculated by substituting the numerical weight and cumulative score factors, as demonstrated in Equation (9), which were derived via Equation (2).

$$\begin{aligned} IOR = 0.25 \times f_S(Design) + 0.23 \times f_S(Documentation) \\ + 0.23 \times f_S(Spare\ parts) + 0.29 \times f_S(Software) \end{aligned} \tag{9}$$

Therefore, the resulting IOR value falls within the range of 0.0 to 5.0, rounding to 1 decimal place (0.1) for increased precision and ease of interpretation, as shown in Equation (10). As a result, EEE with a higher IOR indicates that the product can be easily repaired or remanufactured. In contrast, a lower IOR suggests that the EEE is more challenging to repair, requiring additional resources, expertise, and knowledge.

$$0.0 \leq IOR \leq 5.0 \tag{10}$$

Additionally, the assessment system can be divided into five distinct categories determined during equipment manufacturing based on the four factors, as illustrated in Table 4. As a result, these categories provide a comprehensive and clear understanding for professionals and technicians regarding the difficulty they may encounter during repairs. Furthermore, this information can assist stakeholders in making informed decisions and careful selections before purchasing EEE by encouraging them to opt for more easily repairable devices, promoting sustainable practices and responsible consumption.

4.3. Pictogram Logo and Graphical Charter for the IOR

The IOR, an innovative scoring system, features a pictogram logo and graphical charter specifically designed to offer clear, visually appealing, and meaningful communication for professionals in the industrial electronics field within the O&G sector.

Consequently, OEMs can adopt this system as it combines the crucial repairability factors from Equation (9), delivering a comprehensive representation for ease of repair. In addition, the logo can be easily applied as an adhesive label on EEE intended for various stages of O&G operations, ensuring its visibility and usefulness throughout the repair, remanufacturing, and maintenance processes.

Table 4. IOR categories and score ranges with corresponding factors.

IOR Category	Score Range	Design	Documentation	Spare Parts	Software
Very low repairability	$0.0 \leq IOR \leq 0.9$	Non-modular and inaccessible	Inadequate	Poor quality and not available	No access
Low repairability	$1.0 \leq IOR \leq 1.9$	Minimal modularity and accessibility	Lacking	Low quality and rarely available	Restricted access
Moderate repairability	$2.0 \leq IOR \leq 2.9$	Some modularity and accessibility	Sufficient	Average quality and limited availability	Some restrictions
High repairability	$3.0 \leq IOR \leq 3.9$	Modular and accessible	Detailed	Good quality and widely available	Limited restrictions
Very high repairability	$4.0 \leq IOR \leq 5.0$	Highly modular and accessible	Comprehensive	High-quality and easily available	Open and easy access

As a result, the IOR pictogram, as depicted in Figure 6, integrates the visual elements of a digital multimeter (DMM) and soldering iron, signifying the most commonly used tools in electronic repairs. The DMM's knob is portrayed as a soldering iron pointing to the maximum rating and caliber of the IOR. The circles within the knob's circumference represent the four key factors: design, documentation, software, and spare parts, which constitute the IOR. The DMM's display screen displays the summarized IOR score for the equipment, offering a clear and concise representation upon the completion of the design.

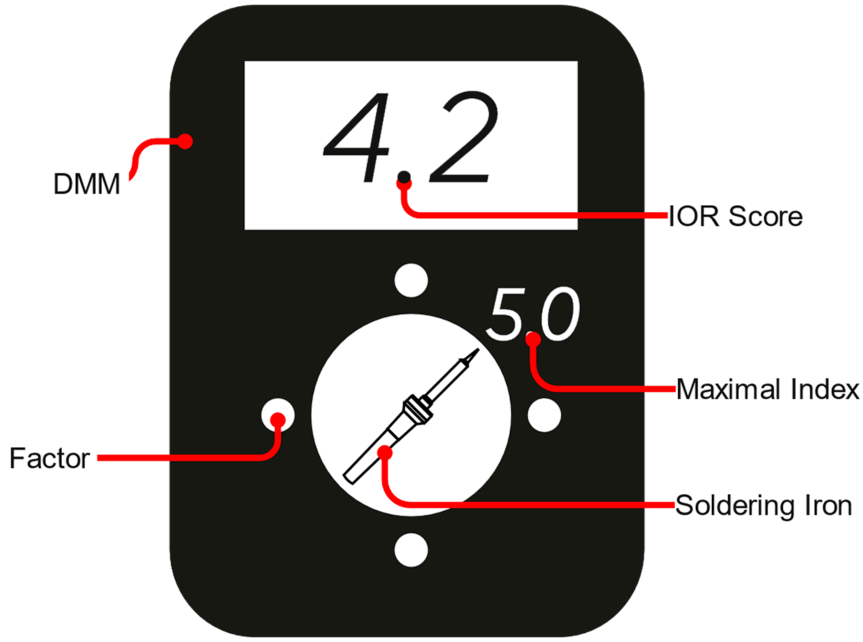

Figure 6. Pictogram logo of IOR.

Moreover, the chosen font for the logo is the elegant Raleway font [35], which is an open-source font that helps avoid copyright infringement and is widely utilized in various logo designs. Hence, Table 5 displays five potential IOR logos, each associated with a distinct range of scores and a color spectrum from red to green, including gradients in between using both the CMYK and RGB color models. For instance, a higher IOR score indicates that the EEE can be easily repaired and is symbolized with green. Conversely, a lower IOR score suggests that the equipment is more challenging to repair and is represented with red.

Table 5. The five principal categories of IOR for EEE.

IOR Pictogram Logo	Range	Color RGB (CMYB%)
5.0 Index Of Repairability	$0.0 \leq IOR < 1.0$	217-22-39 (7-98-86-1)
5.0 Index Of Repairability	$1.0 \leq IOR < 2.0$	254-116-27 (0-64-89-0)
5.0 Index Of Repairability	$2.0 \leq IOR < 3.0$	255-201-1 (0-22-93-0)
5.0 Index Of Repairability	$3.0 \leq IOR < 4.0$	158-204-0 (84-13-94-2)
5.0 Index Of Repairability	$4.0 \leq IOR \leq 5.0$	0-148-67 (84-13-94-2)

4.4. Procedure for Calculating the IOR

Within the scope of this government initiative, OEMs can utilize Equation (9) to determine the Index of Repairability during manufacturing. As a result, the IOR is computed using a weighted sum of the four cumulative score factors: design, documentation, spare parts, and software. A detailed framework demonstrating the step-by-step process for calculating the IOR is depicted in the comprehensive flowchart in Figure 7, which serves as a guide for OEMs during the design process of any EEE product and as a verification resource for technicians assessing products designed with this evaluation system. In addition, this visual guide facilitates understanding and applying the IOR calculation in various contexts, aiding technicians and manufacturers in making informed decisions about repairability and design improvements.

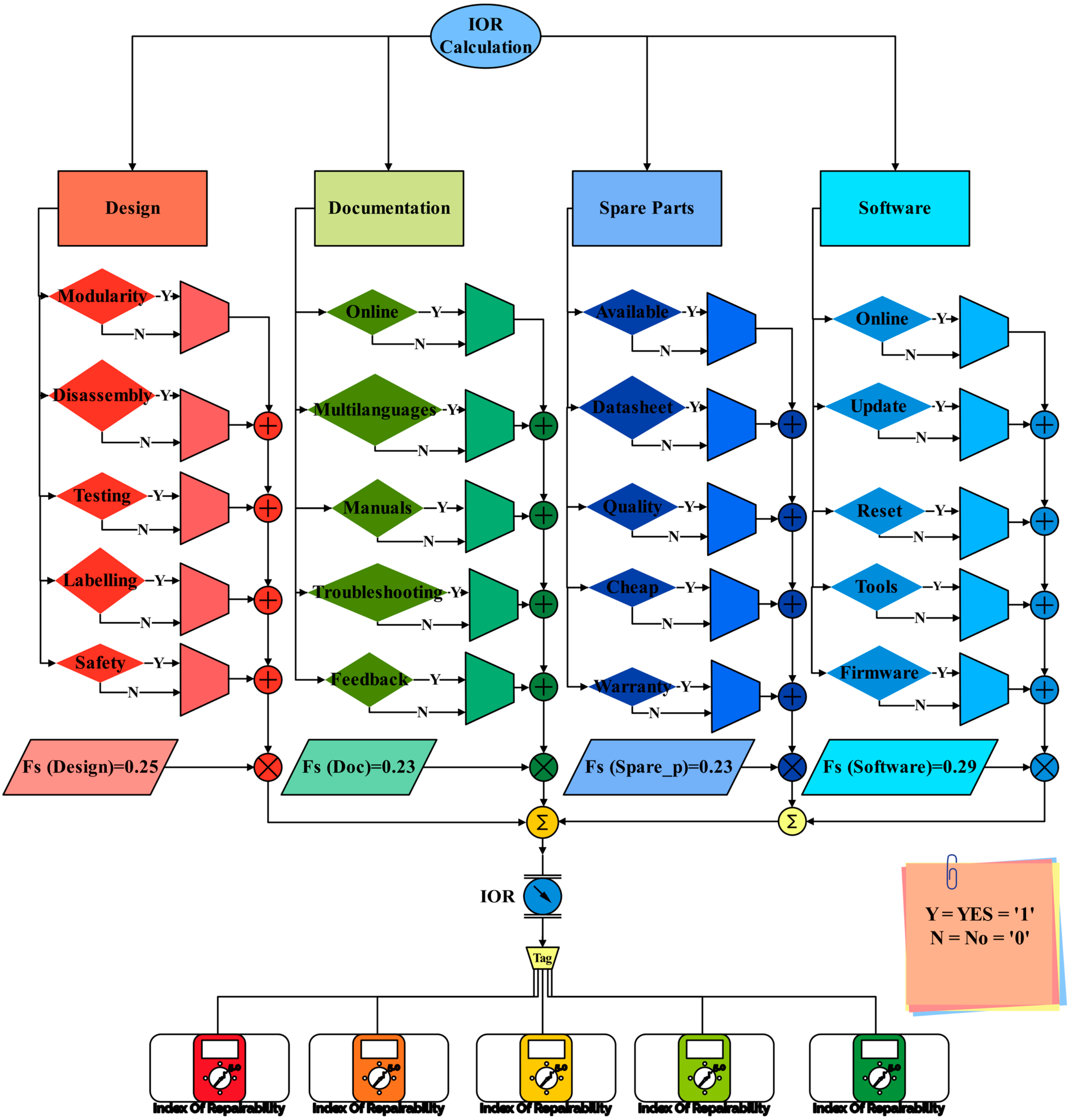

Figure 7. Workflow for computing the IOR score.

Additionally, to calculate the IOR, the criteria for each cumulative score factor, as described in Table 3, are checked in the following manner.

Firstly, the design cumulative score factor evaluates a product's ease of disassembly, explicitly focusing on the printed circuit board (PCB) to enable hassle-free access to components such as isolate-gate bipolar transistor (IGBT) modules. Additionally, it considers using fasteners, screws, and nuts to facilitate straightforward assembly and disassembly, ultimately promoting more efficient repair and maintenance processes. Consequently, it considers the modularity of components, such as separating the power stage from the control motherboard and power electronics. Safety considerations for specialized operations, such as in O&G, are also assessed, wherein using solid-state relays (SSRs) instead of electromagnetic relays minimizes spark risks. Furthermore, this factor reviews the presence of clearly labeled testing points, motherboard voltages, and integrated circuits (ICs) for repair purposes. Consequently, assigning a binary score of zero or one for each criterion, with zero indicating the criterion is unmet and one signifying it is met. After the evaluation, the cumulative design score factor is calculated by summing all criteria scores and multiplying the total by a weight of 0.25.

Secondly, the documentation cumulative score factor assesses the availability and quality of resources such as repair manuals, troubleshooting guides, PCB schematics, service and operation manuals in multiple languages, and other materials available on the internet that assist experts in repairing the product. Additionally, it evaluates the presence of user and technician feedback channels with OEMs. For each criterion, a binary score of zero or one is assigned, where zero indicates the criterion is not met, and one signifies it is met. After evaluating all criteria, the cumulative documentation score factor is calculated by summing the scores and multiplying the total by a weight of 0.23 based on the product's documentation assessment.

Next, the spare parts cumulative score factor evaluates the availability, affordability, compatibility, warranty, and quality of spare parts required for repairs that distributors provide. Additionally, it also considers the accessibility of datasheets for replacement parts to address the shortage of specific customized ICs and evaluates whether programmed obsolescence is present or absent. For each criterion, a binary score of zero or one is assigned, with one indicating the criterion is not met and one signifying it is met. After evaluating all criteria, the cumulative spare parts score factor is calculated by summing the scores and multiplying the total by a weight of 0.23.

Last but not least, the software cumulative score factor evaluates the ease of diagnosing software issues remotely and online, the availability of software updates and original firmware on the internet without restrictions, and the ability to perform data recovery and reset without losing data. Additionally, it assesses the accessibility of specific tools and programming methods for EEE and motherboards, such as JTAG (Joint Test Action Group) and ISP (in-system programming). For each criterion, a binary score of zero or one is assigned, with zero indicating the criterion is not met and one signifying it is met. After evaluating all criteria, the cumulative software score factor is calculated by summing the scores and multiplying the total by a weight of 0.29.

Moreover, the IOR is calculated by summing all four cumulative score factors according to Equation (9) and rounding the value to 1 decimal place (0.1). The resulting IOR score will range from 0.0 to 5.0, and an adhesive tag will be assigned to the EEE according to the classification in Table 3. A higher score signifies a more repairable product, while a lower score indicates a less repairable product that requires more resources and expertise.

On the other hand, the range of zero to five for each cumulative score factor (design, documentation, spare parts, and software) offers many possibilities, with 1296 unique combinations. Consequently, it would be impractical to list them all. Instead, visualizations such as 3D scatter plots can effectively represent these combinations and their corresponding IOR scores.

Figure 8 showcases a series of 3D scatter plots that effectively visualize the multidimensional data associated with the IOR score in a single graphic. Each plot represents four dimensions of the data: design (x-axis), documentation (y-axis), spare parts (z-axis), and IOR (color). The size of the marker points in these plots represents the software factor, which can be considered a fifth dimension and holds the most significant weight. With six different three-dimensional scatter plots labeled with letters from (a) to (f), illustrating the varying levels of software, this comprehensive visualization helps understand the relationships between the factors and their impact on the IOR score. Moreover, the color scale, ranging from red (lowest) to green (highest), signifies the IOR value. Upon visually inspecting these scatter plots, it is evident that as the values of design, documentation, and spare parts increase, the IOR value also generally rises. Additionally, the software factor plays a significant role in determining the IOR value, as demonstrated by the variation in marker sizes across the plots.

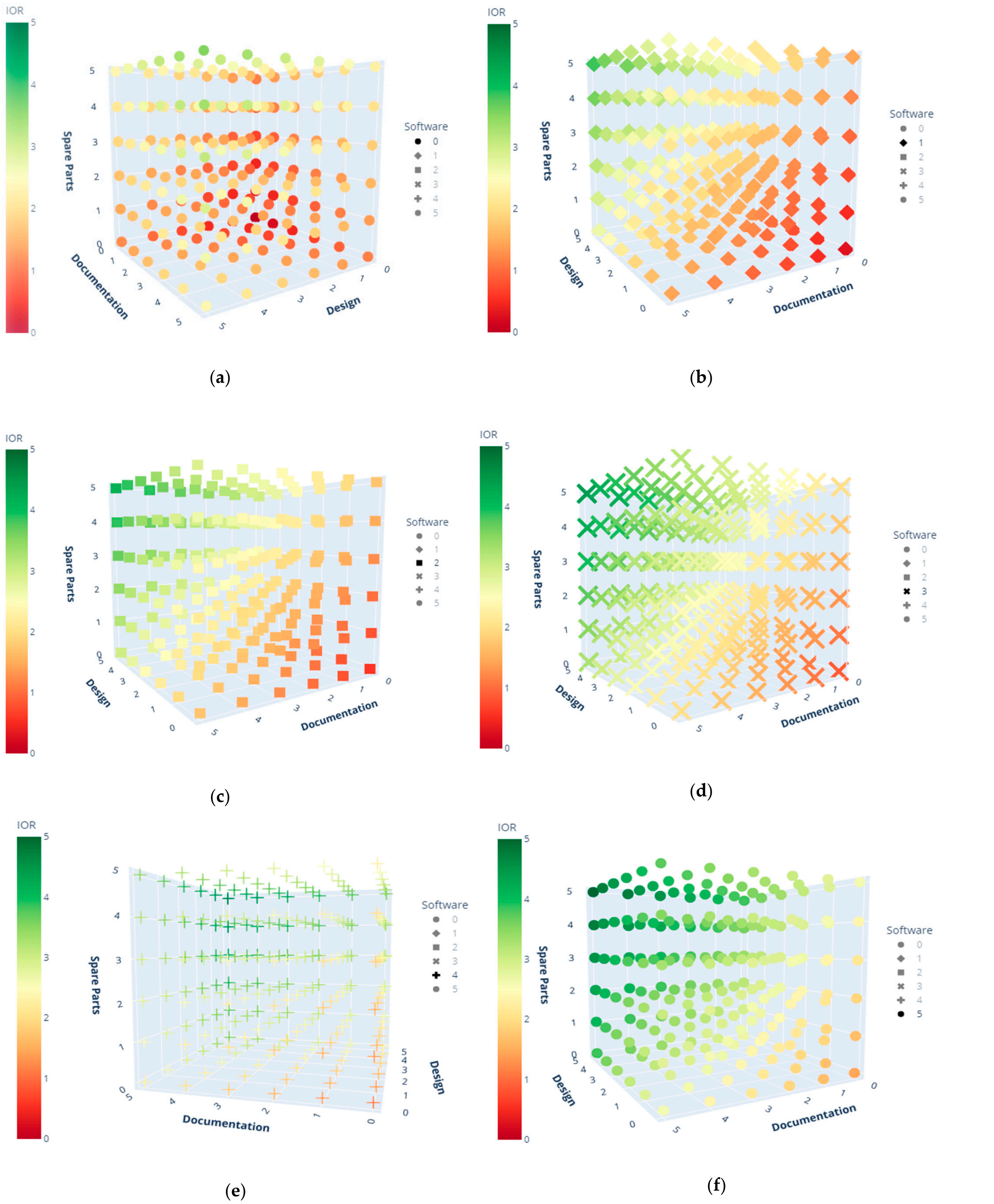

Figure 8. Multidimensional factors analysis influencing IOR score: (**a**) software = 0, (**b**) software = 1, (**c**) software = 2, (**d**) software = 3, (**e**) software = 4, and (**f**) software = 5.

Thus, employing 3D scatter plots is a valuable instrument for decision making and optimization, allowing stakeholders to identify trends and patterns in the multidimensional data. However, the evident positive correlation between the factors and the IOR score equips stakeholders with a valuable understanding of the interwoven dynamics of factors affecting and improving the repairability of EEE products.

On the other hand, specific points, such as maximum or minimum values in the data, can be studied separately and may require further investigation. For instance, the green point with a high IOR score of 3.5 when the software factor is unavailable and all the other factors equal 5. This can be attributed to equipment that does not rely on software, such as switched-mode power supplies (SMPSs) and other power supplies that only depend on non-programmable integrated circuits and electronic components.

In summary, this repairability assessment scoring system can be used to compare the repairability of various EEE products and establish benchmarks for improvements in product design by OEMs. Furthermore, it can be a part of a government-led initiative. Consequently, technicians can utilize the IOR for evaluation during or before repairs to determine whether to perform a repair or replacement in critical situations, helping to prevent extended downtime and production interruptions. However, as a result, if the IOR is implemented, it will only apply to newly developed and manufactured EEE equipment, leaving previous models to be managed with conventional repair strategies unless OEMs provide updates or resources.

In this context, OEMs can devote more resources to the factors discussed, leading to higher repairability scores by designing and adapting EEE products for remanufacturing. A previous study [36] introduced the Remanufacturing Information Feedback Framework (RIFF), a method for strategically planning and practically implementing feedback from remanufacturing to design departments. This resulted in a more efficient, faster, and cost-effective remanufacturing process. The previous literature has established several frameworks [37–42] and design guidelines to foster remanufacturing [43,44].

5. Impact of IOR on O&G Sector

Artificial lift systems play a vital role in the upstream petroleum sector, especially given the sector's significant dependence on EEE. In addition, these systems influence oil production, as any interruption can disrupt oil flow. Consequently, adopting effective maintenance strategies in the O&G industry is essential for ensuring ALSs' efficiency, longevity, and overall operational costs. By incorporating the IOR alongside five main types of maintenance strategies and methodologies, stakeholders can enhance ALS performance and better understand how to maintain and repair their equipment:

5.1. Reactive or Run-to-Failure (RtF) Maintenance

Incorporating the IoR into the reactive or run-to-failure (RtF) maintenance strategy, which is a low-cost method that involves operating equipment until it fails before performing maintenance [15], yields several benefits.

One of the primary advantages is improved safety by identifying high-risk equipment, which facilitates more targeted maintenance efforts and reduces potential accidents or incidents, potentially contributing to overall operational safety.

The second key benefit revolves around the strategic organization of maintenance tasks. By leveraging the insights provided by the IoR, maintenance teams can channel their efforts toward equipment demonstrating higher reparability. Such an approach could substantially decrease downtime, contributing to more efficient and effective maintenance management.

5.2. Preventive or Time-Based Maintenance (PM or TbM)

This strategy involves scheduled maintenance tasks based on historical data or fixed intervals to prevent unexpected breakdowns and extend the asset's lifespan [15]. Incorporating the IoR into this maintenance strategy yields several benefits.

A key advantage of incorporating the IoR is the enhancement of maintenance planning. Consequently, maintenance teams can allocate their resources more efficiently, thereby facilitating a more effective prioritization of maintenance tasks.

Furthermore, optimizing maintenance budgets and reducing overall costs is possible by directing maintenance and repair efforts primarily towards more effortless and efficient equipment.

5.3. Condition-Based Maintenance (CbM)

This approach uses sensors to monitor equipment conditions in real time, and maintenance is performed when specific parameters indicate potential failure [45]. This optimizes maintenance intervals and minimizes unscheduled downtime. Incorporating the IoR into this maintenance strategy yields several benefits.

This integration fosters superior decision making concerning maintenance activities, ultimately leading to an improvement in equipment reliability. As a direct consequence, downtime can be substantially reduced, improving operational efficiency and productivity.

In addition to enhancing reliability, the use of the IoR facilitates more efficient resource allocation within maintenance teams. By focusing on EEE with higher IoR scores, these teams can ensure that critical equipment is duly maintained and repaired on time. As a result, this strategic approach to resource allocation and maintenance prioritization can significantly improve crucial equipment's overall performance and lifespan.

5.4. Predictive Maintenance (PdM)

This strategy collects data on critical conditions and compares them with historical records to identify abnormal operations [46]. The goal is to predict equipment failure and schedule maintenance accordingly, improving efficiency and minimizing operating expenses. Incorporating the IoR into this maintenance strategy yields several benefits.

Therefore, this integration can greatly contribute to more informed decision making in maintenance activities. In addition, this synergistic approach empowers maintenance teams to discern more accurately when maintenance is required, thereby minimizing unnecessary interventions and reducing the risk of equipment failure.

Moreover, by enabling the timely replacement of worn or damaged parts, the overall durability of equipment can be considerably enhanced. This incorporation contributes to maintaining operational efficiency and leads to significant cost savings in the long run due to reduced equipment replacement needs.

5.5. Risk-Based Maintenance (RbM)

RbM prioritizes maintenance frequency and type based on the risk of equipment failure [15]. Higher-risk equipment is monitored and maintained more frequently, while lower-risk equipment is subject to less stringent maintenance programs. Incorporating the IoR into this maintenance strategy yields several benefits.

A significant benefit is a more comprehensive risk assessment. Consequently, maintenance teams will be equipped with a more profound understanding of potential risks related to equipment failure. In addition, this understanding considers the criticality and reparability of the equipment, thereby enabling a more nuanced approach to maintenance planning.

Moreover, the combined use of the IoR for EEE with RbM strategies reduces the overall risk of failure throughout the facility. This combination minimizes risk in the most cost-effective manner and leads to improved equipment reliability and decreased downtime. Consequently, the overall efficiency of the facility can be significantly enhanced.

Thus, incorporating the IoR into ALS maintenance strategies can significantly enhance the effectiveness and efficiency of maintenance operations in the O&G industry while enabling informed decision making and prioritization. Integrating the IoR leads to numerous benefits, such as improved safety, cost-effective maintenance, increased reliability, extended equipment lifespans, reduced risk, and support for sustainable product eco-designs by

OEMs. This alignment with the industry's growing focus on sustainability and environmental responsibility allows stakeholders to optimize resources, minimize downtime, and boost operational efficiency, paving the way for a more competitive and sustainable future in the oil and gas sector.

6. Conclusions

In conclusion, the innovative mathematical approach developed using set theory and the AHP scheme to evaluate the repairability of industrial EEE products presents a crucial and practical framework that OEMs can adopt through government-led initiatives. By applying eco-design principles, the efficiency and effectiveness of maintenance operations in the O&G industry, particularly in artificial lift systems, can be enhanced. Furthermore, stakeholders can optimize resources, minimize downtime, and improve operational efficiency, fostering a more competitive and circular economy.

This initiative requires collaboration between stakeholders, the development of standardized criteria, regulatory enforcement, public procurement policy changes, incentives for OEMs, technician training programs, and public awareness campaigns. These measures collectively ensure improved product design, sustainability, and e-waste reduction.

Thus, the Index of Repairability (IOR) based on four criteria can help extend EEE products' lifespans and reduce the need for replacements by encouraging remanufacturing. In addition, the IOR score ranges, and the graphical design developed alongside the mathematical framework, can be adopted as a visual aid for technicians and to prioritize products with higher IOR scores in maintenance contracts, increasing the likelihood of successful remanufacturing.

Finally, this study opens up several exciting avenues for potential future research. A promising direction might be the development of more detailed and sophisticated guidelines aimed at OEMs. Such advice would focus on the design and adaptation of EEE products to promote remanufacturing. While this study focused on industrial electronics in the O&G sector, these guidelines could be applied to a broader range of industrial electronic equipment across different industries.

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