AI-Enhanced Assessment of Component Degradation Impact on Industrial Electronic Product Reliability

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***Abstract*— The electronics industry has a significant environmental impact due to high levels of carbon dioxide emissions and electronic waste generated during the production of electronic devices. This paper examines the impact of degraded components on the reliability and environmental sustainability of electronic products, with a focus on the difference between ground benign (GB) and ground mobile (GM) conditions. A board containing 215 components is used as a baseline for calculating the mean time between failures (MTBF) of electronic products under standard GB and GM conditions, which is then compared with the MTBF under conditions where individual components are degraded. The paper shows that the effect of degraded components has a significant impact on the MTBF of the product, leading to higher failure rates and increased environmental pollution. The results highlight the need to control the quality of materials used in the production process to improve the overall MTBF and environmental sustainability of the product. The paper also evaluates the economic and environmental impact of using unchecked components, showing that it affects the reliability and lifespan of products and is the main cause of higher-than-predicted failure rates and increased electronic waste. By performing a 100% inspection of all components, using advanced technology, and controlling the quality of materials used in the production process, it can be ensured that only high-quality components are used in electronic products, thereby increasing their reliability, reducing the failure rate in the field, and minimizing the environmental impact of electronic waste.**

***Index Terms*— electronics industry, reliability, MTBF, degraded components, CO_2 emissions, e-waste, environmental impact, quality, inspection, sustainability, advanced inspection technology.**

I. INTRODUCTION

THE electronics industry has a significant impact on the environment with high levels of CO_2 emissions and electronic waste (e-waste) generated from the production of electronic devices [1]. According to the United Nations [2], e-waste is the fastest-growing waste stream in the world. An estimated 50 million tons are generated annually, containing hazardous materials that pose a threat to human health and the environment if not properly disposed of [2], [3]. The manufacturing of electronic devices contributes to 2% of global greenhouse gas emissions, and the energy consumption of electronic devices in use also adds to the carbon footprint [3], [4]. A study estimates that the average CO2 emissions per laptop production is 283.4 kg, and 50.5 kg for a cell phone [5], [6].

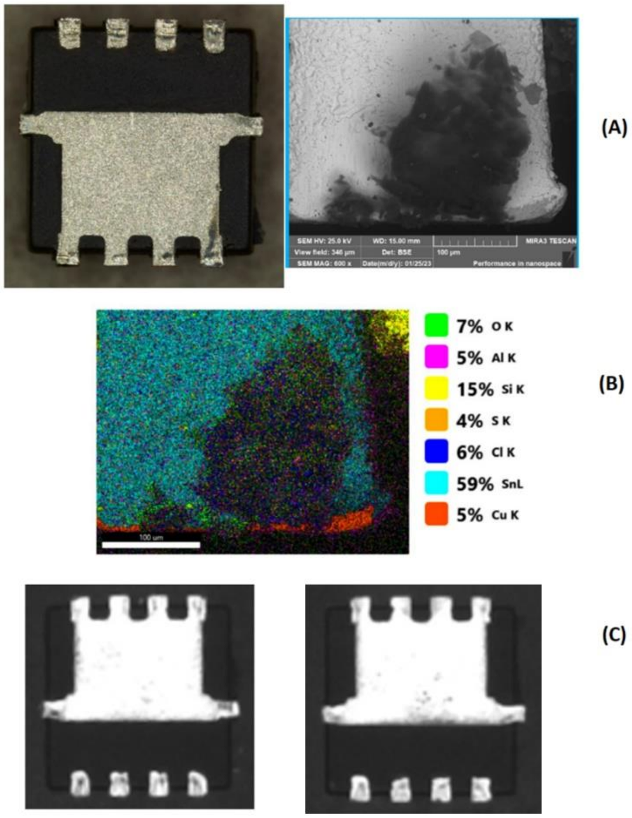

Fig. 1. An IC component with evidence of corrosion and Sn plating deficiency negatively impacting solderability and bond reliability. (A) As seen in microscopy, (B) As verified by SEM-EDX lab analysis, (C) as detected during assembly by the presented method.

The improvement of the reliability of electronic products is a crucial aspect of enhancing the profitability of electronic manufacturing while reducing the negative impact on the environment. The electronic industry has made significant progress in optimizing its manufacturing process through the adoption of I4.0 advanced tools for monitoring and optimizing the assembly process [7]–[11]. The IPC-A-610 standard is widely adopted by most manufacturers, mandating the assurance of component quality and freedom from corrosion. However, there is currently no available method for in-line verification of compliance with these requirements [12]. Various Industry 4.0 tools and research methodologies are being employed for failure analysis and optimization [13]–[16]. However, the present approach to managing electronic

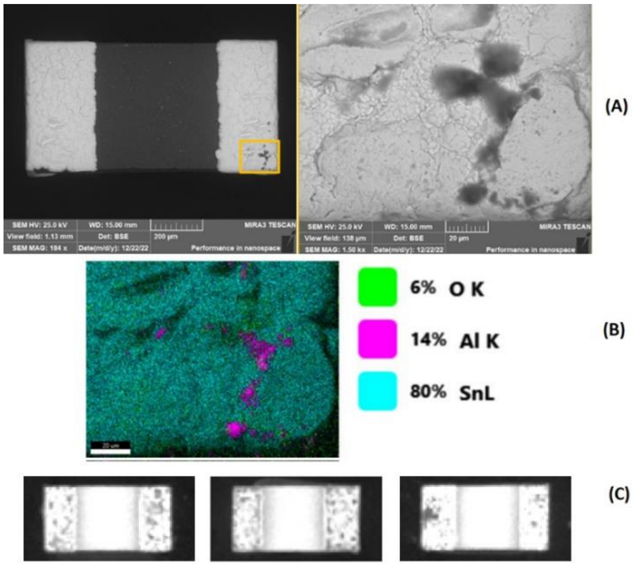

Fig. 2. A chip resistor with evidence of Aluminum oxide contamination negatively impacting solderability and bond reliability. (A) As seen in microscopy, (B) As verified by SEM-EDX lab analysis, (C) as detected during assembly by the presented method.

components rely on the conventional method of procurement from reputable sources without sufficient quality verification. However, this prevailing conventional approach of sourcing electronic components from trusted suppliers, without conducting thorough quality verification, falls short in effectively mitigating failures. It is estimated that approximately 80%, of failures within the electronic industry derive from faulty components [17].

The malfunction of an electronic component can trigger heightened waste generation, thereby escalating emissions and electronic waste. Additionally, it curtails the product's longevity, further exacerbating the waste stream. This research aims to assign measurable metrics to this phenomenon. The quantification of a product's lifespan is achieved through its MTBF.

Reliability prediction methodologies, such as the Telcordia Method and MIL-HBK-217f, employ statistical models and failure rate data to estimate component lifespans and predict circuit board MTBF [18]. By estimating MTBF, it becomes possible to calculate the cost associated with a single component's failure concerning the anticipated product lifespan.

This paper presents a practical case illustrating how defective components (see examples in Fig. 1) influence product lifespan and the related environmental consequences. We contend that the industry's elevated failure rate, surpassing calculated expectations, stems from the utilization of suboptimal electronic parts. We propose that transitioning to exclusively approved components could lead to attaining the projected lower failure rate.

Given the essentially stochastic occurrence of faulty components, conventional sampling methods are unsuitable for addressing this issue [17], [19]–[21]. Instead, a comprehensive approach necessitates the inspection of all components. Regrettably, current inspection methods lack this capability.

Furthermore, the paper introduces an innovative approach in the form of a reliable quality verification system, designed to curtail the failure rate and enhance the longevity of electronic products [17], [21], [22]. The proposed solution involves an in-line visual authentication and qualification system during the assembly process. This system detects visual defects, corrosion, and counterfeits in real-time, thereby preempting the underlying causes of failure and alleviating the environmental footprint of the electronics industry. The resolution to this challenge entails the potential elimination of entire reels upon the identification of a substantial quantity of flawed components, or the targeted addressing of individual instances on the board after their processing.

II. ENVIRONMENTAL IMPACT OF ELECTRONIC DEVICES

The production and disposal of electronic devices generate a significant amount of pollution, mainly in the form of electronic waste (e-waste) and CO_2 emissions [6], [23]. E-waste contains hazardous materials that pose a threat to human health and the environment if not properly disposed of, such as lead, mercury, and flame retardants [24]. The manufacturing of electronic devices contributes to 2% of global greenhouse gas emissions, and the energy consumption of electronic devices in use also adds to the carbon footprint [6], [23]–[28].

Throughout the product lifecycle of an electronic device, there are several stages where pollution is generated, including raw material extraction, production, transportation, use, and disposal. In the production stage, the sourcing of materials, manufacturing processes, and waste management practices are the primary sources of pollution. For example, the production of printed circuit boards (PCBs) generates waste chemicals, such as copper sulfate, ferric chloride, and ammonium persulfate, that are hazardous to human health and the environment [24], [27]. During the use phase, the energy consumption of electronic devices contributes to the carbon footprint, with electricity generation accounting for up to 60% of the total CO_2 emissions from electronic devices.

Conventional methods for reducing the environmental impact of electronic devices have focused on improving waste management practices and increasing the use of renewable energy sources for electricity generation [6], [27], [29]–[31]. While these approaches have been effective to a certain extent, they address only part of the problem, and the root causes of pollution are not fully addressed. For instance, products that fail prematurely and require replacement contributes significantly to e-waste[6]. Moreover, their production results in the unnecessary consumption of raw materials, energy, and water, as well as the generation of pollutants.

We will now proceed to examine how to accurately estimate the lifespan of a product and thoroughly explore the considerable influence of defective components on this vital factor.

III. INFLUENCING FACTORS ON MTBF: REAL-WORLD CONSIDERATIONS

A. Overview of MTBF Calculation in Electronics

The MTBF calculation assumes that all components are in perfect condition and operating under optimal conditions, which may not reflect real-world scenarios. In reality, electronic components can degrade over time due to various factors, such as environmental conditions, aging, or manufacturing defects. These factors can impact the reliability and longevity of the product and can significantly reduce the expected MTBF. Furthermore, the failure rate of electronic components can vary significantly depending on the environmental conditions in which they are used. For example, components used in harsh or extreme conditions, such as high temperature, high humidity, or high vibration environments, may have a shorter lifespan than components used in more moderate conditions. This can result in a significant reduction in the overall MTBF of the product. Therefore, while MTBF calculation is a useful tool for evaluating the reliability of electronic products, it is important to keep in mind that the calculation is based on assumptions that may not reflect real-world conditions. To improve the accuracy of the MTBF calculation, it is necessary to consider the impact of realistic conditions and the potential degradation of components over time. By doing so, manufacturers can better predict the reliability of their products and make more informed decisions about design improvements or replacement schedules.

B. The Reality of Component Quality

Electronic components are not perfect, and their quality at the time of assembly has a significant impact on their individual lifespan. Various factors can contribute to the degradation of components, including the manufacturing process, handling, storage, and environmental factors. The estimated defect rate in electronic components is approximately 150 parts per million (ppm) [17], [19], [20]. Additionally, components can be subject to corrosion and mold (see examples in Fig.1, and Fig. 2), which can also occur at a rate of approximately 200 ppm [17]. Furthermore, the quality of the component at the time of assembly determines its individual lifespan. Even if a component is not initially defective, the stress of the assembly process and subsequent operation can cause it to degrade over time. In reality, the initial conditions of all components need to be integrated to assess the effective lifespan of the assembled product.

Neglecting this integration can cause inaccuracies in MTBF predictions, leading to overestimating the real lifespan of the product. This can result in premature failures and increased costs associated with product recalls and returns. Therefore, it is essential to take into account the quality of components at the time of assembly and their individual lifespans to accurately predict the MTBF of the product.

C. Calculating the Real Lifespan of a Product

In order to accurately estimate the real lifespan of a product, it is important to consider the initial conditions of each component on the board and how they may degrade over time. This includes factors such as corrosion, mold, cracks, defects, counterfeit materials, age, and other factors. Each of these individual factors can contribute to the degradation of the component and ultimately affect the overall MTBF of the product. To estimate the effective lifespan of the assembled product, these individual factors need to be estimated and multiplied by the degradation factor of each component. Integrating these individual factors across all components can provide a more accurate assessment of the effective lifespan of a specific assembled product. In practice, the real MTBF is often measured experimentally to provide a more accurate estimation of product reliability. By conducting experiments and testing the product under various conditions, it is possible to obtain a more accurate estimate of the product's actual MTBF and how it may be affected by various factors. This can help manufacturers to improve the quality and reliability of their products and ensure that they meet the expectations of their customers. This study's scope does not encompass quantitative estimation of the degradation factor. Instead, it focuses on presenting the mechanism through which these factors exert their impact, illustrated through a test case example.

TABLE I. BASELINE EXAMPLE BOM AND MTBF VALUES FOR AN EXAMPLE BOARD.

Type	Amount	Office	Automotive	Degradation factor
Capacitor	97	0.000051	0.1499814	1
Resistor	97	0.00037	0.550378	1
IC	5	0.017	0.277	1
IC	5	0.01	0.152	1
IC	5	0.00196	0.047648	1

.IV. THE IMPACT OF DEGRADED COMPONENTS ON THE MTBF

In this section, we examine how the MTBF of electronic products is impacted by the presence of degraded components. Our primary focus centers on delineating the distinctions between ground benign (GB) and ground mobile (GM) conditions [18]. For the sake of clarity, we operate under the assumption that server rooms emulate GB conditions, while the automotive environment embodies a blend of 80% GM and 20% GB scenarios. See Fig. 3. For a projected failure rate of an assembled PCB's in GB conditions (server room) of the BOM presented in Table I-III, and Fig. 4. With the projected failure rate of an assembled PCB's in automotive conditions.

In the subsequent analysis, we dissect a specific case featuring a board housing 5 components outlined within the Bill of Materials (BOM): 100 Multi-Layer Ceramic Capacitors (MLCC), 100 chip resistors, 5 Analog to Digital Converters (ADC), 5 regulators, and 5 EEPROMs. Through a conventional MTBF calculation applied in server room conditions, the projections indicate an anticipated failure rate of 0.164% after one year; meanwhile, under automotive conditions, this rate escalates to 1.094% (refer to Table I). The heightened failure incidence in the automotive context is ascribed

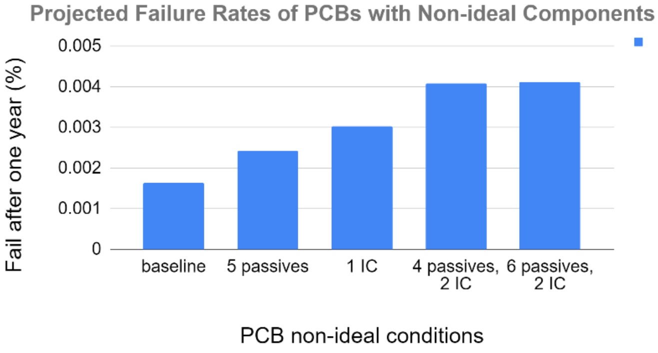

Fig. 3. Projected failure rate of an assembled PCB's in GB conditions (server room) of the BOM presented in Table I-III. The predicted MTBF is shown for the baseline PCB with no faulty components with examples od various levels of defects in the board.

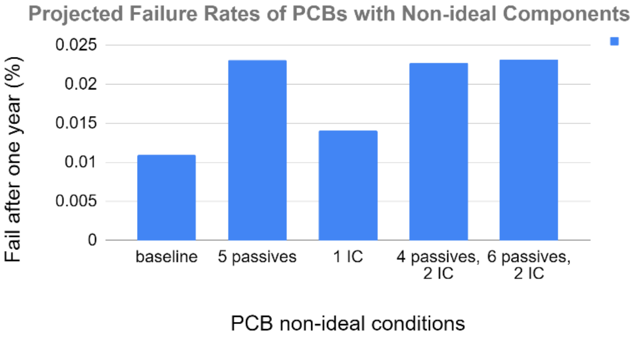

Fig. 4. Projected failure rate of an assembled PCB's in automotive conditions of the BOM presented in Table I-III. The predicted MTBF is shown for the baseline PCB with no faulty components with examples od various levels of defects in the board.

to intensified environmental stress compared to office environments.

However, the integration of a more realistic partially degraded components into our analysis, characterized by a lifespan reduction of that component by a factor of 10 for a minor degradation, or 50 for a more severe case, significantly magnifies the failure rate (refer to Table II for MTBF calculations of the degraded board and Table III for MTBF estimation across both office and automotive contexts). As illustrated in Table III, the fail rate of the more realistic degraded materials exhibits a failure rate of 0.41% after one year of operation, contrasting the 0.164% assumption based on the premise of all components being ideal. In the context of the automotive environment, the forecast increases to 1.094% and 2.32%, respectively.

As a practical exercise in examining various use cases, consider the following scenarios: If a single Analog to Digital Converter (ADC) undergoes degradation, the projected fail rate under server room conditions becomes 0.304%, escalating to 1.406% under automotive conditions (as depicted in Fig. 1). In the instance of a Multi-Layer Ceramic Capacitor (MLCC) experiencing degradation, the fail rate after a year will rise to 0.166% within GB conditions and 1.160% in the automotive context. Likewise, the degradation of a sole chip resistor (illustrated in Fig. 2) would yield a fail rate of 0.180% within server room conditions and 1.337% within automotive settings. Similarly, a scenario where a single ADC encounters degradation would result in a fail rate of 0.304% within server room conditions, and a corresponding 1.406% under automotive conditions.

TABLE II. BOM AND MTBF VALUES FOR A DEGRADED BOARD. THE DEGRADATION FACTOR REDUCES THE LIFE OF THE COMPONENT BY A FACTOR OF 10 OR 50 AS AN EXAMPLE.

Type	Amount	Office	Automotive	Degradation factor
Capacitor	97	0.000051	0.1499814	1
Resistor	97	0.00037	0.550378	1
IC	5	0.017	0.277	1
IC	4	0.01	0.152	1
IC	4	0.00196	0.047648	1
Capacitor	2	0.00051	0.010444	10
Capacitor	1	0.00255	0.07731	50
Resistor	2	0.0037	0.11348	10
Resistor	1	0.0185	0.2837	50
IC	1	0.17	0.394	10
IC	1	0.098	0.5956	50

TABLE III. MTBF ESTIMATION FOR DEGRADED BOARDS IN OFFICE AND AUTOMOTIVE ENVIRONMENTS.

	Office	Automotive
MTBF (million hours)	2.122	0.377
MTBF (years)	242.292	43.052
Fail after year (%)	0.41%	2.32%

It's crucial to highlight that these degraded components typically remain undetectable during the production stage testing due to the fact that their failure rate becomes apparent only after an extended period of time. These degraded components significantly contribute to the statistical calculation of the product's MTBF and its corresponding failure rate in real-world conditions, which are heavily influenced by the level of environmental stress they experience.

In office environments, the established industry-standard failure rate of approximately 1.5% within a year predominantly results from the presence of degraded components within the products. Remarkably, the theoretical failure rate of 0.164% indicates that the observed 1.5% failure rate already accounts for the existence of degraded components. Through the implementation of stringent material quality control measures during the production process, the incidence of degraded components can be curtailed, leading to an enhancement in the overall MTBF of the product.

V. ECONOMIC AND ENVIRONMENTAL IMPACTS

The reliability of electronic products is directly related to the quality of the components used in their production. As we have shown in the previous section, using unchecked components can significantly reduce the overall MTBF of the product. This reduction in MTBF can have a significant impact on both the economic and environmental aspects of the product.

A. Economic Impact

The higher than predicted failure rates due to degraded components have a major impact on the economy. Approximately 1.5% of products fail within the first year of operation, with the majority of the failures attributed to degraded components. This failure rate results in significant costs associated with product returns and recalls. By controlling the quality of the components used in production, it is possible to reduce the occurrence of degraded components and improve the overall reliability of the product. This can result in a reduction of over 50% in the number of returns and recalls.

B. Environmental Impact

To highlight the environmental impact of product failures, a test case is presented to demonstrate the environmental pollution resulting from faulty components. Two scenarios are considered. In the first scenario, the product is entirely scrapped, leading to e-waste and the need for a replacement product. In [23], [25], [27], [29], [32], [33], an estimation of CO2 emissions and e-waste generated during the manufacturing of an electronic product was conducted. These findings are presented in Table IV, featuring columns displaying the total embodied CO2 and e-waste. In the second scenario, where poor-quality components curtail the product's lifespan, these effects are depicted in columns 3 and 4 of the table.

During the production process, electronic components are typically supplied on reels that contain thousands of units of a single component type. It's worth noting that statistically, around 150 ppm of these components may exhibit some form of defect, while approximately 200 ppm could be affected by corrosion or mold. Consequently, it's plausible for a reel to contain a certain proportion of degraded components. This situation can potentially lead to a decrease in the overall MTBF of the product. In the course of production, a reel contaminated with corrosion was promptly identified (as illustrated in the accompanying Fig. 1 and 2). Subsequent analysis revealed that while the corrosion might not severely impact solderability, it was likely to contribute to an increased failure rate in real-world conditions [34]. As evidenced in the example provided in section IV, this phenomenon could lead to a reduction in the average lifespan of assembled laptops from 4 years to approximately 3 years.

To quantify the environmental impact of using this corroded reel, we estimate the following: considering the reel held 10,000 components and was used in 2,000 circuit boards of laptops, early detection and removal of the reel from production saved the environmental emission of 91.2 kg of CO2 and 0.32 kg of e-waste per laptop (see Table IV), for a theoretical total of 188.8 tons from a single faulty reel. For a single component, the CO2 emission is 18.9 kg and the e-waste of 32 mgr. In this particular case, the failure mechanism is corrosion propagation resulting from thermal cycling and humidity exposure, which leads to a 33% reduction in the life expectancy of the products assembled with the contaminated reel.

TABLE IV. E-WASTE AND CO2 EMISSIONS DUE TO DECREASE BY 33% OF LIFESPAN [6]

Electronic devices	Total embodied CO2 (kg/device)	E-waste (kg/device)	CO2 emissions due to decrease of 33% in lifespan	E-waste increase due to decrease of 33% in lifespan
Laptop	283.4	6.08	91.2	1.216
Mobile phone	50.5	0.02	22.02	0.01
Tablet	116.1	0.21	39.55	0.15

It's important to note that this estimation represents a maximum-case scenario and might not reflect real-world situations accurately. In practical terms, not all failures would necessitate complete scrapping or replacement. However, this calculation serves as a useful benchmark for understanding the potential environmental impact of such occurrences.

VII. SOLUTION

In the field of electronic component assembly, the detection of defects, including corrosion and cracks, presents significant challenges due to their often-inconspicuous nature. However, recent advancements in technology, particularly in big data and artificial intelligence (AI), provide a promising avenue for addressing these issues effectively.

The solution proposed in [17] addresses the critical concern of detecting defects, thereby enhancing their overall performance and reliability. This approach leverages advanced AI algorithms in conjunction with cameras integrated into pick-and-place machines, capturing images of electronic components during the assembly process (Fig. 5). These captured images undergo meticulous scrutiny through AI algorithms, which reveal subtle visual cues indicative of defects. These cues encompass a range of characteristics, such as discoloration, oxidation, surface degradation, and even the presence of cracks. An intrinsic capability of this methodology is its ability to differentiate between routine surface irregularities and genuine instances of defects, enabling a comprehensive evaluation of component quality. By facilitating the early identification of potentially compromised units, the solution not only enhances the immediate inspection process but also prevents the escalation of defects that might lead to more severe issues later on.

The impact of this defect detection methodology extends beyond the immediate inspection phase. It plays a crucial role in precluding the progression of defects, such as cracks and corrosion, which may arise from environmental influences over time [35]. The optical method has the capacity to identify surface-level anomalies on the external packaging of components. However, it is not designed to detect internal faults like broken wire-bonds or damaged chips within the package. Nonetheless, it can effectively detect indicators that precede these internal issues. For instance, it can identify early signs of corrosion and mold, which are indicative of potential crack propagation in components like MLCCs. Detecting corrosion not only helps prevent the corrosion itself but also averts the development of cracks. Additionally, if there are visible external signs of exposure to humidity, it could serve as a hint that the component might be compromised.

By identifying and rectifying defective components during the initial production stages, this method safeguards the integrity, longevity, and reliability of electronic products. Fig. 5 illustrates instances of contamination detected on MLCC soldering terminations by the system, showcasing the practicality and efficiency of the proposed approach. The removal can be achieved through the disqualification of entire reels upon detection of a significant proportion of defective components, or by selectively addressing individual instances on the board following their processing.

The inspection process can be performed at different stages of the production process, such as when the components are loaded onto the production line, or after the components have been mounted onto the printed circuit board.

Once the components have been inspected, they can be sorted into different categories based on their quality and reliability. This can be done using a ranking system that assigns each component a reliability score based on its appearance attributes (e.g., authenticity, corrosion, mold, cracks, etc.). The scores can be used to estimate the life of the product in different environmental conditions, based on the known degradation mechanisms of each component.

For example, suppose that a production line is using 1,000 capacitors that are supplied on a reel. After inspection, it is found that 10% of the capacitors have some form of degradation, which would result in a lower MTBF for the product. Using the inspection system, the degraded capacitors can be identified and sorted out of the production process, ensuring that only high-quality components are used in the final product.

In this way, the inspection and sorting system can help to ensure the reliability and sustainability of electronic products, by preventing the use of substandard or degraded components in the production process.

VI. CONCLUSION

The reliability and MTBF of electronic products are critical factors that determine their quality and longevity. Our study has shown that degraded components have a significant impact on the MTBF of the product, and that conventional MTBF calculations that assume all components are perfect do not reflect the true failure rate of electronic products in the field. Our simulated analysis of a board with 215 components has shown that the effect of realistic materials has a dramatic effect on the MTBF of the product. For example, 5 degraded passive components decreases the lifespan of the product by 149% in server room and by 211% in automotive environment. It is important to note that these degraded components will not be detected during the production stage testing, and therefore it is necessary to perform a 100% inspection of all components in order to ensure the reliability of the product.

From an economic standpoint, unchecked components have a significant impact on the cost of the product. Returns due to degraded components can be reduced by over 50%, and recalls can be almost entirely avoided by controlling the quality of materials used in the production process. Furthermore, the cost of scrapping, remanufacturing, and shortening the lifespan of the product has a negative impact on the environment, as more products will need to be made. A single contaminated components reel can theoretically incur a staggering environmental cost of 188.8 tons of CO_2 emissions by the reduced lifespan.

In order to ensure the reliability of electronic products and reduce their failure rate in the field, it is necessary to perform a 100% inspection of all components using advanced technology such as AI and big data. By doing so, only high-quality components will be used in the production process, thereby increasing the reliability and MTBF of the product. The cost savings and environmental benefits of this approach are significant, and it is crucial for the electronic industry to adopt it as a standard practice.

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