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A Novel ILP Formulation for PCB Maintenance Considering Electrical Measurements and Aging Factors: A "Right to Repair" Approach

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Abstract: The design of longer-lasting products, such as domestic electric appliances, is a key-stone approach of the circular economy to reduce the use of non-reusable materials and the number of wastes to be managed at the end of the product's life as well as to extend it. The manufacturing of modern electric appliances includes the incorporation of printed circuit boards (PCBs). PCBs provide mechanical support and electrically connect electrical or electronic components using conductive trackpads and other features etched from one or more sheet layers of copper laminated onto and/or between sheet layers of a non-conductive substrate. This paper proposes a PCB maintenance framework, fully compliant with the "Right to Repair" concept, considering the impact of their aging failures based on measurements made on them, as well as the repair and replacement costs of their components. Herein, we present an algorithm that assesses the problem of handling the repair and replacement cost corresponding to specific failures while ensuring that the total cost of repair does not exceed a predefined value. This is achieved through an integer linear programming (ILP) formulation which maximizes the benefit to the life expectancy, *Li*, of an appliance, constrained by a customer's limited budget. The proposed methodology is tested with different PCBs and considers different types of appliances. More specifically, two cases concerning PCBs of washing and dishwasher machines are studied to examine the dependency of the solutions on the aging rate of their various components. The simulation results show that considering a medium budget, after 3 years, we can achieve a health benefit of 92.4% for a washing machine's PCB, while for a dishwasher's PCB, the health benefit drops to 86.3%.

Keywords: aging; domestic appliances; failure rate; integer linear programming; printed circuit boards; service budget

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1. Introduction

It is commonly recognized and accepted that population and quality of life increases, particularly in industrialized countries, are projected to accelerate significantly over the next two to three decades. According to Frans Timmermans, the European Commission's First Vice-President announced, "if we do not reform the way we manufacture and use plastics, there would be more waste in our oceans than seafood by 2050".

A significant portion of waste is generated when electrical and electronic equipment is disposed of. Waste from electrical and electronic equipment (WEEE), often known as "e-waste" refers to a wide variety of items that have reached the end of their useful life, such as washing machines, refrigerators, laptops, and mobile phones. These wastes include a combination of dangerous elements that may cause environmental and health issues if not properly disposed of, as well as rare earths and precious metals that can be recovered and reused via the employment of appropriate recycling procedures.

Accurate forecasting of e-waste increase is essential for recycling system installation, facility design and optimization of resource allocation [1]. Considering that 30.2%, 67.7%, and 2.1% of the appliances studied, respectively, fall into the recycling, prospective reuse and direct reuse categories, 70% of household WEEE may possibly be recycled [2].

The European Union legislation supports waste reduction and re-use, as well as significant material recovery. Such an approach is particularly appealing for the management of Waste Electrical and Electronic Equipment (WEEE), which is viewed as an urban stockpile of various metals, including precious metals and rare earth elements. The circular economy is a concept for increasing the sustainability of consumption patterns by optimizing product lifecycles. Metal recovery is a major emphasis of WEEE management techniques, and it has attracted a lot of attention, owing to the waste stream's ever-increasing output [3]. Considering the fast expansion of household appliances in the previous two decades, the waste of printed circuit boards is one of the most dangerous and hazardous waste materials [4]. The overall environmental accounting of the value chains relies on trace metals. High-quality recycling guarantees that the materials and energy included in WEEE are efficiently recovered. This rebirth entails that proper waste management has a net positive impact on the environment in terms of global warming potential (GWP) for all WEEE kinds [5]. Due to the roughly 30% metal concentration, several publications were published illustrating the process pathways for recycling this poisonous but otherwise beneficial waste [4]. Recent works based on economic models highlighted the profitability in the recovery of waste printed circuit boards in terms of different aspects such as plant saturation level, gold (Au) content, Au market price, Au final purity level, waste PCBs (WPCBs) purchase cost, and opportunity cost [6].

Nowadays, many countries encourage environmentally-friendly consumer choices and a reuse culture targeting to enhance product reparability, extend product life and reduce e-waste. Under these conditions, the "Right to Repair" movement becomes more populated. The grassroots of this movement advocates for the ability of consumers to repair their own appliances [7].

The Australian Treasury Department published a consultation document that referred to a required vehicle repair system [8]. The history of repair markets in the United States as well as the techniques used by manufacturers to restrict repair, the implications of restricted repair markets, and the antitrust and other legal tools available to break free closed repair markets are examined in [9].

The European Union (EU) has already established a legal framework in this direction [10–14]. According to [15], 77% of citizens are prepared to repair malfunctioning equipment rather than buy new ones to reduce household waste. Those who disagree with the assertion are more likely to discard things because they believe getting them fixed is too difficult or expensive, while a more recent survey shows that 64% of consumers have fixed products [15].

Reusability and extending the life of appliances are two of the most cost-effective methods of conserving resources [16]. When time is considered, reusability may be defined as the probability that a product utilized for a time period will reach the end of its useful life in the following unit time (i.e., in the interval between t and t + 1), but the product is reusable [17]. When household appliances are considered, and solid statistical arguments in favor of reuse are made, almost 33% fewer raw materials might be used [18]. Reusing home equipment results in a 12% decrease in energy use. Domestic appliances account for about 1.8% of total energy use at the national level (Austria: 670 kWh/cap. year vs. 38,000 kWh/cap. year; [19]). On the other hand, reducing the life of appliances for functional and social reasons results in significant resource depletion and increased waste generation [20].

Additionally, to ensure the longest potential life for these household appliances, we must create methods to extend their life cycle over an extended length of time. Focusing on washing machines, recent work shows that 69% of German households chose to replace their washing machine due to a malfunction [21].

Manufacturers of electrical household appliances are developing plans for repairing and replacing electronic equipment, balancing the requirement for high dependability against the budgetary constraints imposed by a highly competitive business environment. The majority of manufacturers are in the process of upgrading their appliances, emphasizing the importance of having a long-term strategy for managing electrical component obsolescence. Cost-benefit analysis of improvement projects on a component-by-component or system-by-system basis continues to be difficult in today's corporate environment [22].

Depending on the product type and its operating environment, PCB aging is influenced by temperature and humidity, while the manufacturing process needs to be efficient to improve the board's cleanliness [23].

The reliability of electronic assemblies has become critical for any type of application and is an important feature that must be carefully examined during the equipment's design, implementation and operation phases. Accelerated aging testing has established itself as an efficient way for estimating the lifetime and reliability of various products. In the electronics industry, the advantage of this method is the ability to accelerate the normal aging process, allowing for the evaluation of electronic modules' resistance to the adverse effects of specific climatic conditions such as heat, vibrations, radiations and humidity over a reasonable period of time. This strategy is particularly advantageous during the prototype phase when the newly developed equipment has not yet been utilized for a sufficient period of time to experience spontaneous failure at the end of its useful life. Among the several external influences affecting an electronic PCB, the temperature is the most essential, causing correlating, subsequent stresses that can be observed also at the mechanical level [24].

The purpose of [25] is to shed light on the aging effects on electronic instrument and control (I&C) circuit boards. The concern is that circuit boards used in I&C systems may have aging failures, which might result in a plant trip or system unavailability. The overarching goal is to find how to quantify failure precursors in I&C circuit boards and how to use these measurements to estimate the chance of failure during the next operational period with a statistical confidence level.

Numerous approaches were described for determining the statistical confidence level of a circuit. The MIL-HDBK-217 describes prediction approaches for predicting system reliability [26]. These techniques are based on the Arrhenius equation, an exponentially temperature-dependent expression that is an excellent predictor of component aging. It does not address failure modes caused by specific shocks or environmental difficulties that are not consistent with the assumptions of the aging model. Mechanical vibration and shock, humidity and power on/off cycling, for example, are all temperature-independent and are observed as failure modes. Even some temperature-related loads, such as temperature cycling and thermal shock, would result in non-Arrhenius failures. More importantly, the dependability of numerous electrical components is increasing. As a result, component failure is no longer a significant cause of system failure. However, the [26] model continues to provide guidance on how to anticipate system dependability using part failure data.

It is essential to perform maintenance on the PCBs of a household appliance to extend their life, considering aging factors. In this work, we employ an integer linear programming (ILP) method in a MATLAB environment, to simulate various scenarios, taking into consideration a customer's budget, i.e., the maximum amount of money ready to spend and the failure rate of the PCB's components. The ILP solves a system with the purpose of maximizing the "replacement ratio", i.e., the gain of replacing several PCB parts, given their number and cost, the service expenses and the aging factor. These tests were carried out on different appliances PCBs, washing and dishwasher machine PCBs, and the findings were used to perform repairs on these boards.

The main contributions of the proposed formulation are summarized below:

1. It develops a systematic and efficient procedure, which is fully compliant with the "Right to Repair" in terms of more durable products.
2. To the best of the authors' knowledge, this is the first time that a systematic method for PCBs maintenance combined with aging factors of components and the client's budget to solve the maintenance problem.

3. The problem is solved using a simple, flexible, and easy-to-implement ILP method considering any number and type of components and can be employed in any type of domestic appliance.

Note that the proposed methodology can be easily implemented for any type of appliances' PCB, without considering the low, medium or high grade of the PCB.

This paper is organized as follows: Section 2 presents the PCB aging factors background, while Section 3 presents the analytical calculations of these factors considering specific PCB components. Section 4 formulates and presents the proposed ILP algorithm for PCB maintenance. Section 5 presents and discusses the simulation results of the proposed methods. Conclusions are drawn in Section 6.

2. PCB Aging

In the subsections that follow, a description of the failure mechanisms and rate factors is presented addressing specifically the components on this board, which again is based upon the approach used in [26]. The equation for the part failure rate of its component is shown in Table 1.

Table 1. Part failure rate for PCB components.

PCB Components	Part Failure Rate (Failures/10^6 h)	
Diode Rectifier	$\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_C \cdot \pi_Q \cdot \pi_E$	(1)
Push-Button Microswitch	$\lambda_p = \lambda_b \cdot \pi_{CYC} \cdot \pi_L \cdot \pi_C \cdot \pi_E$	(2)
Thyristor	$\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_R \cdot \pi_S \cdot \pi_Q \cdot \pi_E$	(3)
Resistor	$\lambda_p = \lambda_b \cdot \pi_R \cdot \pi_Q \cdot \pi_E$	(4)
Capacitor	$\lambda_p = \lambda_b \cdot \pi_{CV} \cdot \pi_Q \cdot \pi_E$	(5)
Relay	$\lambda_p = \lambda_b \cdot \pi_L \cdot \pi_C \cdot \pi_{CYC} \cdot \pi_F \cdot \pi_Q \cdot \pi_E$	(6)
Choke	$\lambda_p = \lambda_b \cdot \pi_C \cdot \pi_Q \cdot \pi_E$	(7)
Triac	$\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_R \cdot \pi_S \cdot \pi_Q \cdot \pi_E$	(8)
Varistor	$\lambda_p = \lambda_b \cdot \pi_{TAPS} \cdot \pi_R \cdot \pi_V \cdot \pi_Q \cdot \pi_E$	(9)
Autotransformer	$\lambda_p = \lambda_b \cdot \pi_Q \cdot \pi_E$	(10)
Rotary switch (selector)	$\lambda_p = \lambda_b \cdot \pi_{CYC} \cdot \pi_L \cdot \pi_E$	(11)

2.1. Diode Rectifier

Considering the part failure rate λp for diodes (rectifier) described by Equation (1), λ_b is the base failure rate, π_T is the temperature factor, π_S is the electrical stress factor, π_C is the contact construction factor, π_Q is the quality factor and π_E is the environmental factor.

The handbook lists several different types of low-frequency diodes, such as general-purpose analog, switching, fast recovery, power rectifier, transient suppressor, current regulator, voltage regulator and voltage reference. Each type tends to have the acceleration factors shown above, although the values may differ from diode type to diode type. For this board, the diodes used are all power rectifiers with fast recovery. The aging of diodes is accelerated with increasing temperature, compared to operation at a reference temperature. The temperature factor π_T, modifies the base rate as shown in equation:

$$\pi_T = \exp\left(^{-3091}\left(\frac{1}{junction\ temperature + 273} - \frac{1}{298}\right)\right) \tag{12}$$

The electrical stress factor π_S is given from the equation below:

$$\pi_S = \left(\frac{V_1}{V_2}\right)^{2.43} \tag{13}$$

2.2. Push-Button Micro Switch

Considering the part failure rate λp for microswitches described by Equation (2), λ_b is the base failure rate, π_{CYC} is the cycling factor, π_L is the load stress factor, $\pi_{\mathbf{C}}$ is the contact form and quantity factor and π_E is the environmental factor.

The π_L, modifies the base failure rate as shown in equation:

$$\pi_L = \exp\left(\frac{\frac{I_1}{I_2}}{0.8}\right)^2 \; for\ resistive\ load \tag{14}$$

2.3. Thyristor

Considering the part failure rate λp for thyristors described by Equation (3), λ_b is the base failure rate, π_T is the temperature factor, π_R is the current rating factor, π_S is the voltage stress factor, π_Q is the quality factor and π_E is the environmental factor.

The π_T, modifies the base rate as shown in equation:

$$\pi_T = \exp\left({}^{-3082}\left(\frac{1}{junction\ temperature + 273} - \frac{1}{298}\right)\right) \tag{15}$$

The π_R, modifies the base rate as shown in equation:

$$\pi_R = (\text{rms rated forwarded current})^{0.40} \tag{16}$$

The π_S, modifies the base rate as shown in equation:

$$\pi_S = \left(\frac{V_3}{V_4}\right)^{1.9} \tag{17}$$

2.4. Resistor

Considering the part failure rate λp for resistors described by Equation (4), λ_b is the base failure rate, π_R is the resistance range factor, π_Q is the quality factor and π_E is the environmental factor.

Assuming that T is the ambient temperature in (°C), the λ_b, is modified as shown in the following equation:

$$\lambda_b = 3.25 \times 10^{-4} \exp\left(\frac{T+273}{343}\right)^3 \exp\left(\frac{P_1}{P_2}\left(\frac{T+273}{273}\right)\right) \tag{18}$$

2.5. Capacitor

Considering the part failure rate λp for capacitors described by Equation (5), λ_b is the base failure rate, π_{CV} is the capacitance factor, π_Q is the quality factor and π_E is the environmental factor.

The λ_b, is modified as shown in equation:

$$\lambda_b = 0.00254\left[\left(\frac{\frac{(V_5+V_6)}{V_2}}{0.5}\right)^3 + 1\right] \times \exp\left(5.09\left(\frac{T+273}{358}\right)^5\right) \tag{19}$$

where T = ambient temperature (°C)(with max price 105 °C).

The π_{CV}, is modified as shown in equation:

$$\pi_{CV} = 0.34 \times C^{0.18} \quad (20)$$

2.6. Relay

Considering the part failure rate λp for relays described by Equation (6), λ_b is the base failure rate, π_L is the load stress factor, π_C is the contact form factor, π_{CYC} is the cycling factor, π_F is the application and construction factor, π_Q is the quality factor and π_E is the environmental factor.

The base failure rate λ_b, is modified as shown in equation:

$$\lambda_b = 0.00555 \exp\left(\frac{ambient\ temperature + 273}{352}\right)^{15.7} \quad (21)$$

The load stress factor π_L, is modified as shown in equation:

$$\pi_L = \exp\left(\frac{S}{0.8}\right)^2 (resistive\ load) = \exp\left(\frac{\frac{I_1}{I_2}}{0.8}\right)^2 \quad (22)$$

2.7. Choke

Considering the part failure rate λp for chokes described by Equation (7), λ_b is the base failure rate, π_C is the construction factor, π_Q is the quality factor and π_E is the environmental factor.

The λ_b, is modified as shown in equation:

$$\begin{aligned} \lambda_b &= 0.000335\ \exp\left(\frac{T_{HS} + 273}{329}\right)^{15.6} \\ T_{HS} &= T_A + 1.1\ (\Delta T) \end{aligned} \quad (23)$$

2.8. Triac

Considering the part failure rate λp for triacs described by Equation (8), λ_b is the base failure rate, π_T is the temperature factor, πR is the current rating factor, π_S is the voltage stress factor, π_Q is the quality factor and π_E is the environmental factor.

The π_T, modifies the base rate as shown in equation:

$$\pi_T = \exp\left(-3082\left(\frac{1}{junction\ temperature + 273} - \frac{1}{298}\right)\right) \quad (24)$$

The π_R, modifies the base rate as shown in equation:

$$\pi_R = (rms\ rated\ forward\ current)^{0.40} \quad (25)$$

The π_S, modifies the base rate as shown in equation:

$$\pi_S = \left(\frac{V_3}{V_4}\right)^{1.9} \quad (26)$$

2.9. Varistor

Considering the part failure rate λp for varistors described by Equation (9), λ_b is the base failure rate, π_{TAPS} is the potentiometer taps factor, π_R is the resistance factor, π_V is the voltage factor, π_Q is the quality factor and π_E is the environmental factor.

The λ_b, is modified as shown in equation:

$$\lambda_b = 62 \times 10^{-4} \exp\left(\frac{T+273}{358}\right)^5 \exp\left(\frac{P_1}{P_2}\left(\frac{T+273}{273}\right)\right) \tag{27}$$

The π_{TAPS}, modifies the base rate as shown in equation:

$$\pi_{TAPS} = \frac{(Number\ of\ potentiometer\ taps)^{\frac{3}{2}}}{25} + 0.792 \tag{28}$$

2.10. Autotransformer

Considering the part failure rate λp for autotransformers described by Equation (10), λ_b is the base failure rate, π_Q is the quality factor and π_E is the environmental factor.

The λ_b, is modified as shown in equation:

$$\begin{aligned} &\lambda_b = 0.0018 \exp\left(\tfrac{T_{HS}+273}{329}\right)^{15.6} \\ &T_{HS} = T_A + 1.1\ (\Delta T) \end{aligned} \tag{29}$$

2.11. Rotary Switch (Selector)

Considering the part failure rate λp for rotary switches described by Equation (11), (λ_b) is the base failure rate, (π_{CYC}) is the cycling factor, (π_L) is the load stress factor and π_E is the environmental factor.

The λ_b, is modified as shown in equation:

$$\begin{aligned} \lambda_b = \quad & \lambda_{b1} + number\ of\ active\ contacts\ (\Pi_N) \times \lambda_{b2} = \\ & 0.086 + 15.00 \times 0.089 = 1.42 \end{aligned} \tag{30}$$

The (π_L), is modified as shown in equation:

$$\pi_L = \exp\left(\frac{\frac{I_1}{I_2}}{0.8}\right)^2 \tag{31}$$

Note that V_1 is the applied voltage, V_2 is the rated voltage, V_3 is the blocking applied voltage, V_4 is the blocking rated voltage, V_5 is the applied D.C voltage, V_6 is the peak A.C voltage, I_1 is the operating load current, I_2 is the rated resistive load current, P_1 is the operating power and P_2 is the rated power.

3. Aging Factors Calculation

To perform the analysis of the proposed formulation we examined the PCBs of a washing machine and a dishwasher. For example, Figure 1 shows the printed circuit board of the washing machine and its components. The components of the particular printed circuit boards and their corresponding cost are listed in Table 2. The suggested methodology's goal is to determine which of the components listed in Table 2 should be replaced in order to prolong the life of each PCB within the constraints of the customer's budget. The information for the cost of each component is derived from different manufacturers' catalogs considering their corresponding retail prices and averaging them.

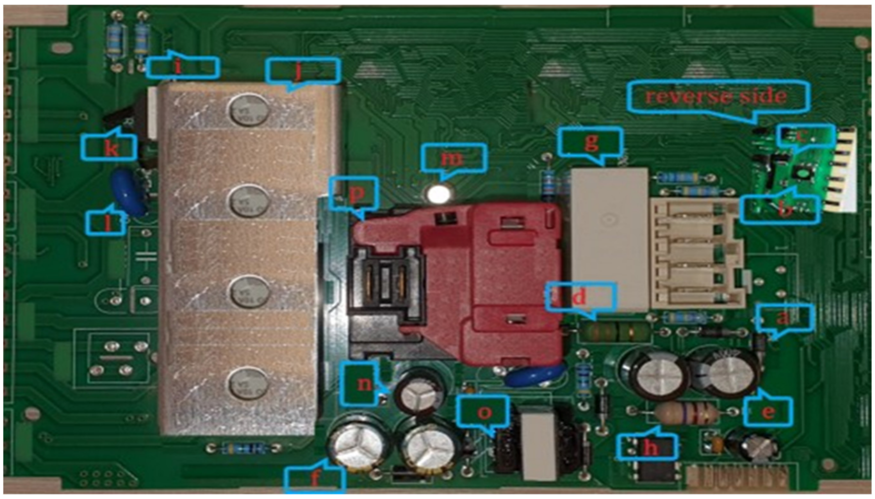

Figure 1. Washing machine PCB and its components.

Table 2. Number and cost of PCB components.

Category	PCB Components	Cost (€/Component)	No. of Components	
			Washing Machine	Dishwasher
a	Diode Rectifier	0.09	8	4
b	Push-Button Microswitch	1.65	8	4
c	A.C-Micro Switch-Thyristor	0.18	7	–
d	Resistor {22 Ohm}	0.08	6	2
e	Capacitor {4.7 μF}	0.46	4	–
f	Capacitor {1000 μF}	0.12	4	–
g	H. Power Relay {250 V D.C}	2.20	4	4
h	Choke	0.28	4	–
i	Resistor {100 Ohm}	0.09	4	–
j	H. Power Relay {12 V D.C}	2.40	3	–
k	Triac	1.25	3	6
l	Leaded Varistor	0.69	3	–
m	Capacitor {22 μF}	0.08	2	4
n	Capacitor {330 μF}	0.10	2	–
o	Autotransformer	2.30	2	1
p	Rotary Modular Selector	18.00	1	1

Considering the case of a washing machine's PCB, the different factors calculation of Equations (1)–(11) are presented in Table 3, while Table 4 presents the calculated aging factors and the corresponding junction and ambient temperatures.

Table 5 presents the corresponding voltages, currents and power used in the calculations of the aging factors measured in voltage (V), ampere (A) and watt (W), respectively.

Table 3. Values of factors used for each PCB component.

Category	λ_b	π_T	π_S	π_C	π_Q	π_E	π_{CYC}	π_L	π_R	π_{CV}	π_F	π_{TAPS}	π_V
a	0.069	21.00	1.00	2.00	8.00	1.00	-	-	-	-	-	-	-
b	0.04	-	-	3.00	-	1.00	4.00	4.77	-	-	-	-	-
c	0.0022	13.00	0.97	-	8.00	1.00	-	-	2.64	-	-	-	-
d	0.0018	-	-	-	15.00	1.00	-	-	1.00	-	-	-	-
e	1.99	-	-	-	10.00	1.00	-	-	-	0.45	-	-	-
f	1.99	-	-	-	10.00	1.00	-	-	-	2.19	-	-	-
g	0.016	-	-	4.25	3.00	2.00	10.00	4.77	-	-	6.00	-	-
h	0.014	-	-	2.00	20.00	1.00	-	-	-	-	-	-	-
i	0.0018	-	-	-	15.00	1.00	-	-	1.00	-	-	-	-
j	0.016	-	-	4.25	3.00	2.00	10.00	4.77	-	-	6.00	-	-
k	0.0022	21.00	0.91	-	8.00	1.00	-	-	1.9	-	-	-	-
l	0.05	-	-	-	10.00	1.00	-	-	2.00	-	-	2.25	2.00
m	1.99	-	-	-	10.00	1.00	-	-	-	1.89	-	-	-
n	2.00	-	-	-	2.20	1.00	-	-	-	10.00	-	-	-
o	0.076	-	-	-	30.00	1.00	-	-	-	-	-	-	-
p	1.42	-	-	-	-	1.00	7.00	15.96	-	-	-	-	-

Table 4. Aging factors of PCB components and corresponding junction and ambient temperatures.

Category	$\lambda_p(\frac{failures}{10^6\ h})$	Junction Temperature (°C)	Ambient Temperature (°C)
a	23.1840	150	-
b	2.2900	-	-
c	0.5880	125	-
d	0.0027	-	90
e	8.9840	-	80
f	43.8000	-	80
g	116.7700	-	80
h	0.5600	-	83.9
i	0.0270	-	90
j	116.7700	-	80
k	0.6400	150	-
l	4.5000	-	80
m	37.8000	-	80
n	44.0000	-	100
o	2.4000	-	83.9
p	158.6400	-	-

Table 5. Corresponding voltages, currents and power used in the calculations of the aging factors.

Category	V_1	V_2	V_3	V_4	V_5	V_6	I_1	I_2	P_1	P_2
a	36.00	36.50	-	-	-	-	-	-	-	-
b	-	-	-	-	-	-	0.00005	0.00005	-	-
c	-	-	36.00	36.50	-	-	-	-	-	-
d	-	-	-	-	-	-	-	-	0.60	0.60
e	-	230.00	-	-	5.00	220.00	-	-	-	-
f	-	230.00	-	-	5.00	220.00	-	-	-	-
g	-	-	-	-	-	-	1.45	1.45	-	-
h	-	-	-	-	-	-	-	-	-	-

Table 5. *Cont.*

Category	V_1	V_2	V_3	V_4	V_5	V_6	I_1	I_2	P_1	P_2
i	-	-	-	-	-	-	-	-	0.60	0.70
j	-	-	-	-	-	-	1.45	1.45	-	-
k	-	-	20.00	21.00	-	-	-	-	-	-
l	24.00	25.00	-	-	-	-	-	-	2.16	2.40
m	-	50.00	-	-	5.00	48.00	-	-	-	-
n	-	25.77	-	-	5.00	25.00	-	-	-	-
o	-	-	-	-	-	-	-	-	-	-
p	-	-	-	-	-	-	0.80	0.60	-	-

Note, that all AC/DC voltage and current measurements were conducted using a measuring arrangement such as the one shown in Figure 2.

Figure 2. Experimental arrangement for AC/DC voltage and current measurements considering a PCB of a washing machine.

Table 6 shows the calculated values of the part failure rate, λ_p, for the components of the two PCBs examined.

Table 6. Failure rate values for PCB components.

Category	PCB Components	λp (Failures/10^6 h)	
		Washing Machine	Dishwasher
a	Diode Rectifier	23.184	23.184
b	Push-Button Microswitch	2.290	2.290
c	A.C-Micro Switch-Thyristor	0.588	-
d	Resistor {22 Ohm}	0.027	0.027
e	Capacitor {4.7 μF}	8.984	-
f	Capacitor {1000 μF}	43.800	-
g	H. Power Relay {250 V D.C}	116.770	116.770

Table 6. *Cont.*

Category	PCB Components	λp (Failures/10^6 h)	
		Washing Machine	Dishwasher
h	Choke	0.560	-
i	Resistor {100 Ohm}	0.027	-
j	H. Power Relay {12 V D.C}	116.770	-
k	Triac	0.639	0.639
l	Leaded Varistor	4.500	-
m	Capacitor {22 µF}	37.800	37.800
n	Capacitor {330 µF}	44.000	-
o	Autotransformer	2.400	2.400
p	Rotary Modular Selector	158.642	158.642

4. Proposed Algorithm for PCBs Maintenance

Let a PCB that has n different types of components which can be replaced and assume that $x = (x_1, \ldots, x_n)^T$ is the decision variable vector, with each x_i permitted to take non-negative integer values up to a maximum of m_i, representing the total number of components of type x_i on the PCB.

Given a customer-specified budget, B, the purpose of the algorithm is to determine the optimal number of components of each type to be replaced, so as to maximize an objective function, related to the benefit to the health of the appliance. This is formulated as an integer linear programming (ILP) problem:

$$\begin{aligned} &\text{maximize} \sum w_i \times x_i \\ &f(x) \leq B \end{aligned} \tag{32}$$

where $w_i = h_i \cdot a_i$ is a weight related with the health benefit h_i of ith component. The health benefit expresses the percentage of aging of a component, based on its life expectancy, L_i, and the total hours of real operation, t_i, after a certain period of years elapsed. It can be written as:

$$h_i = \frac{t_i}{L_i} \times 100\% \tag{33}$$

where $L_i = 1/\lambda_i$ and λ_i is the part failure rate of the ith component which is calculated as the product of the corresponding aging factors.

The value of the constant a_i is empirically selected equal to 0.2, B is the maximum budget to be spent for PCB maintenance, taking a value, e.g., in the range of EUR 30 to 90 and the cost function $f(x)$ is defined by:

$$f(x) = S + \sum b_i \times x_i \tag{34}$$

where b_i is the cost of each component and S is the service fee, e.g., S = EUR25.

Moreover, we introduce the following metric, namely the "replacement ratio", to further quantify the results.

$$Replacement\ ratio\ (\%) = \frac{\sum h_i \times x_i}{\sum h_i \times m_i} \times 100\% \tag{35}$$

The "replacement ratio" shows the benefit to the health of the appliance, in terms of PCB aging, after the replacement of the components proposed by the solution of the system through the ILP algorithm. Note that the denominator of Equation (22) represents the total aging of the PCB (sum of the aging percentages of all its components) whereas the numerator is equivalent to the total health benefit from the replacement of certain components, i.e., the reduction of the aging percentage that corresponds to the replaced components.

5. Results

The proposed method, implemented in an algorithm developed in a MATLAB environment, was applied and tested for the washing machine PCB described in the previous section. This paper showcased a simple, flexible, and easy-to-implement ILP-based method, which maximizes a linear objective function related to the components included in a PCB, subjected to an inequality constraint, ensuring that the total cost of repair does not exceed a predefined value. The proposed methodology is successfully tested on a PCB related to a washing machine, while the proposed algorithm was developed in MATLAB on a 3.4 GHz Intel (R) Core (TM) i7-2600 processor with 16 GB of RAM.

For the purpose of this application, the following assumptions are made for both types of PCB:

(a) A special coefficient referred hereon as the "age factor", is introduced to impose the servicing of a certain component type when its aging surpasses a certain percentage. Specifically, this factor multiplies the weight (w_i) by 100 when its aging reaches 80%, thus modifying its significance relative to other components with a lower aging percentage.
(b) Supposing that the annual operating time of the appliance is 1872 h per year (specifically, considering 20 washing cycles/week × 3 h/cycle × 52 weeks/year), an extra coefficient is applied to the life expectancy, L_i, of each component type, to account for its actual operational life, e.g., 8760/3120 = 2.8 (with a year having 8760 h).
(c) A minimum aging percentage is required for a component to be added to the system for a potential replacement. This is specified to 20% of its formal life expectancy, L_i, (for continuous operation). The threshold is then modified to a lower value when the coefficient for actual operational hours/year is taken into account. Specifically, the minimum aging percentage is lowered to 7.14% for the assumption of 3120 operational hours/year.
(d) Once a type of component reaches its 100% operational life expectancy, L_i, its weight remains fixed to a maximum value.

Through the proposed ILP algorithm and assumptions, we perform several tests for different values of B (maximum budget of the customer) to maximize the health gain, for a range of actual time elapsed since the purchase of the appliance, up to 10 years. The number and types of components to be replaced varies with the time elapsed due to the introduction of the above-mentioned assumptions. The minimum aging percentage defines which components enter the system, introducing new variables as time progresses. The "age factor" forces the urgent replacement of a component that is more likely to fail after it surpasses its 80% life expectancy, L_i. Lastly, the weight clipping at 100% of a component's life expectancy, L_i, permits the weight of other components to change in relation to those which have reached their maximum value. Without these parameters, considering only a constant aging rate, the results of the ILP algorithm would only depend on the maximum budget of the customer and not the time elapsed since the purchase of the appliance. Table 7 presents the number of PCB components to be replaced considering the maximum client budget. Figure 3 shows a graphical representation of PCB components considering different maximum client budgets for a dishwasher machine, while Figure 4 depicts how the cost of components affects the simulation results in terms of components to be replaced assuming that the cost of Diode Rectifiers, H. Power Relays, Capacitors and Rotary Modular Selectors changed to 1.60 EUR, 6.30 EUR, 2.65 EUR and 26.58 EUR, respectively. Figures 5 and 6 show how the weight of components to be replaced changes with time.

Table 7. Number of PCB components of a washing machine to be replaced considering the maximum client budget.

Category	PCB Components	Number of Components to Be Replaced						
		Maximum Client Budget						
		30	40	50	60	70	80	90
a	Diode Rectifier	8	6	8	8	8	8	8
e	Capacitor {400 V/4.7 µF}	2	2	2	2	2	2	2
f	Capacitor {16 V/1000 µF}	4	4	4	4	4	4	4
g	H. Power Relay {250 V D.C-250 V A.C}	1	4	4	4	4	4	4
j	H. Power Relay {12 V D.C-250 V A.C}	0	2	3	2	3	3	3
n	Capacitor {25 V/330 µF}	2	2	2	2	2	2	2
p	Rotary Modular Selector	0	0	0	1	1	1	1

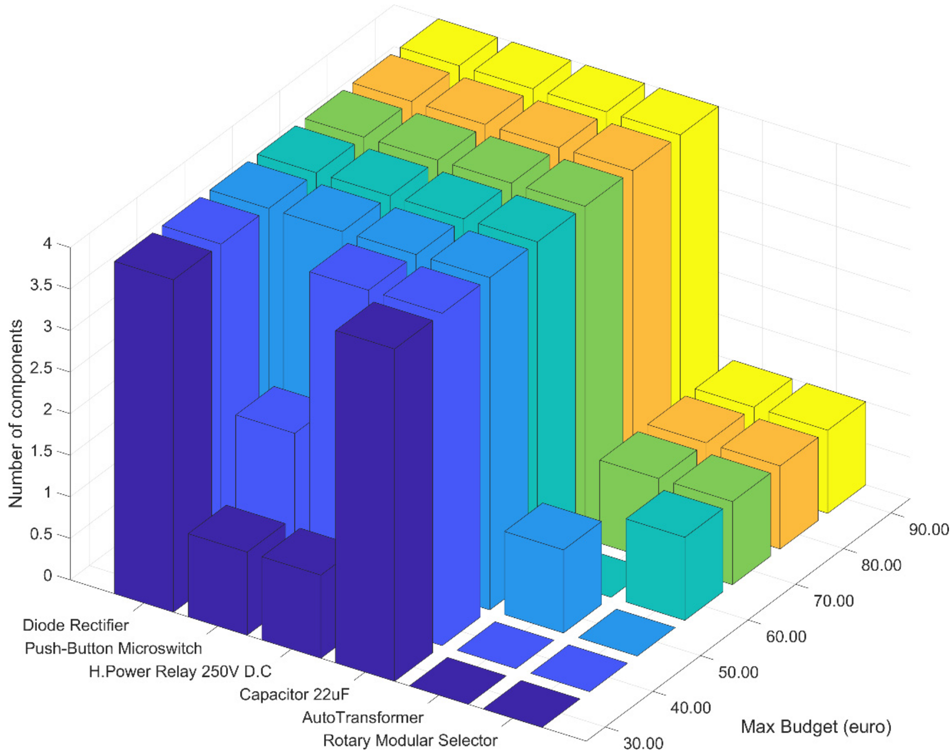

Figure 3. Graphical representation of PCB components considering different maximum client budgets for a dishwasher machine.

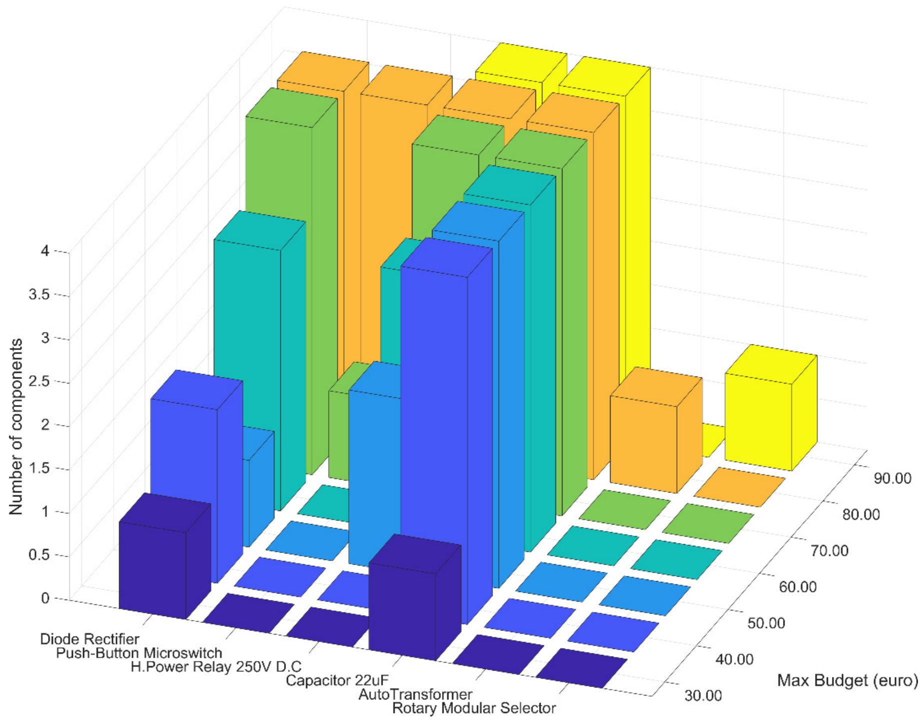

Figure 4. Graphical representation of PCB components considering different maximum client budgets for a dishwasher machine and differentiating the cost of Diode Rectifiers, H. Power Relays, Capacitors and Rotary Modular Selectors to 1.60 EUR, 6.30 EUR, 2.65 EUR and 26.58 EUR, respectively.

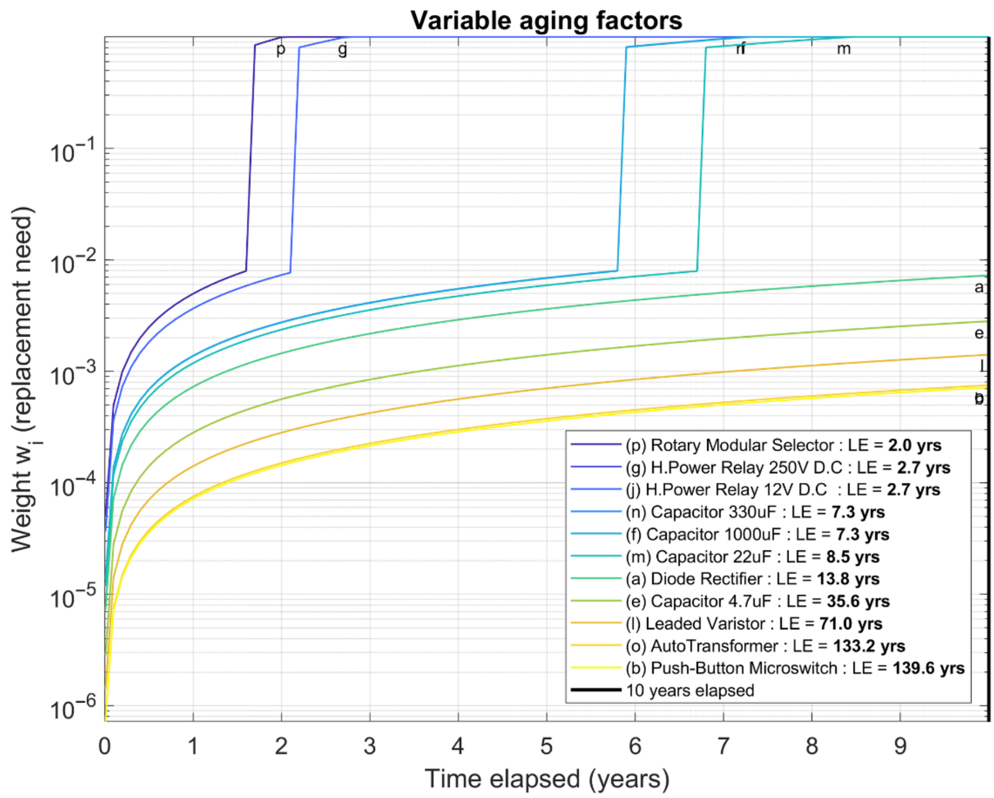

Figure 5. Weight of components to be replaced versus time elapsed for a washing machine's PCB.

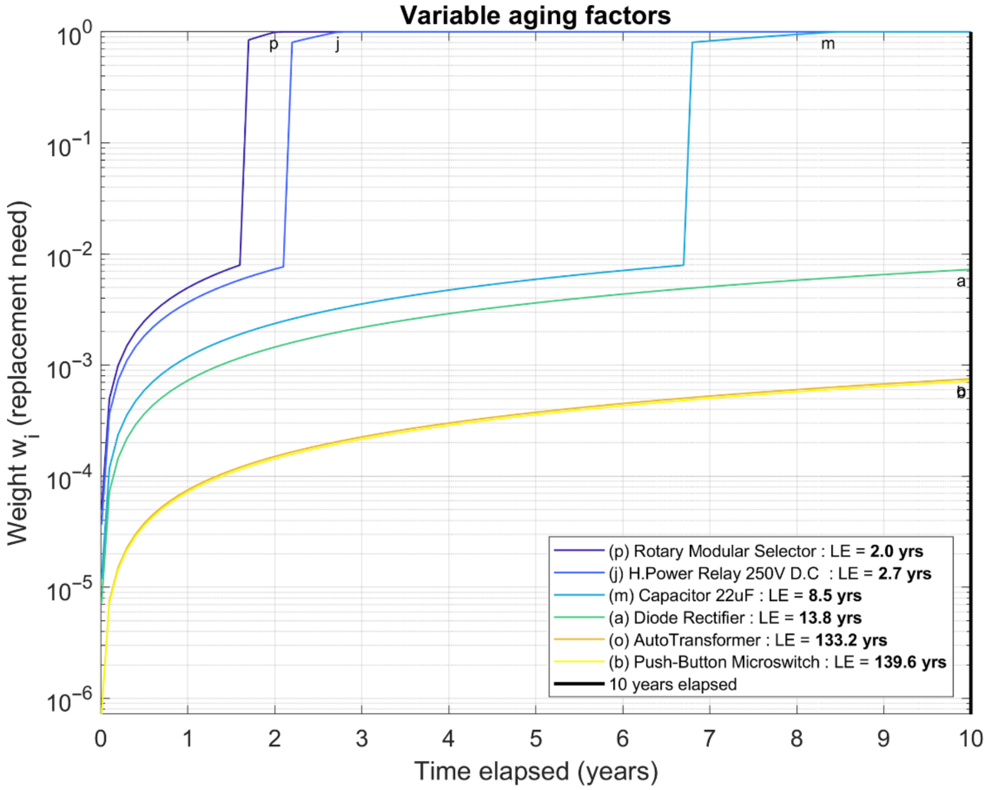

Figure 6. Weight of components to be replaced versus time elapsed for a dishwasher's PCB.

From the results of Figures 7 and 8, it can be observed that as the customer's budget increases, the replacement ratio for the maintenance of the PCB also increases. The benefit of replacement for a low budget varies, depending on the time elapsed. This is because it seems more beneficial to replace certain cheaper components after a few years than replace some more expensive components earlier. This takes into consideration that any part of the PCB is essential for its operation and a replacement of a single part increases the PCB's health by an amount equal to the aging percentage of the replaced component. Note that, in the first two years, three PCB components need to be replaced due to their aging, namely, the Rotary Modular Selector, the H. Power Relay {250 V D.C-250 V A.C} and the H. Power Relay {12 V D.C-250 V A.C}. After the replacement of this set of components in the first two years and assuming a maximum budget of 50 EUR, the replacement ratio, expressing the benefit to the health of the appliance, is rapidly increased. As a result, for a washing machine, at a budget of only 50 EUR, it is manageable to achieve a health benefit of 92.4% after 3 years, while for a dishwasher, with the same budget, the health benefit reaches 86.3%. However, assuming the same budget, the replacement ratio drops to 61.1% after 2 years for the washing machine, while it rises to 73.1% for a dishwasher, respectively. It seems more beneficial to perform maintenance of the PCB at 3 years with a budget of 65 EUR achieving a replacement ratio of 92.5% for the washing machine's PCB, while a budget of 54.5 EUR is needed for the dishwasher. Figures 9 and 10 present the replacement ratio % versus the maximum client budget expressed in EUR considering the operational years. As was expected, the replacing of the PCB components extends the PCB's lifespan, and the lifespan of the appliance is also extended.

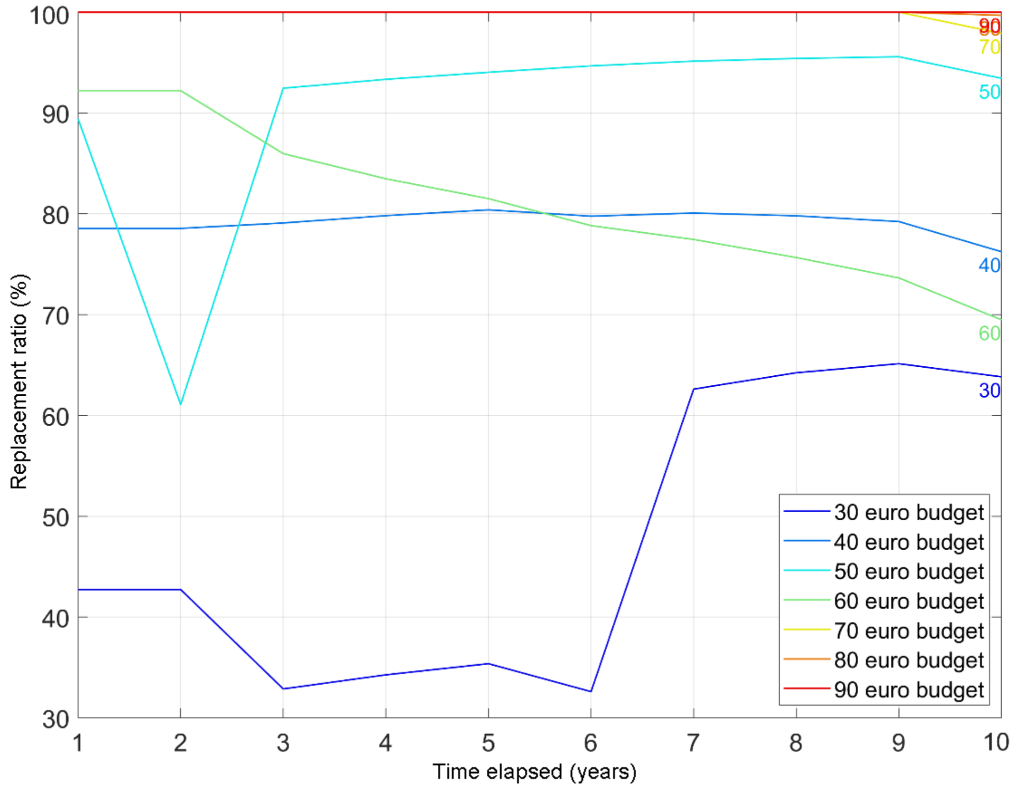

Figure 7. Replacement ratio % versus time elapsed for a washing machine's PCB.

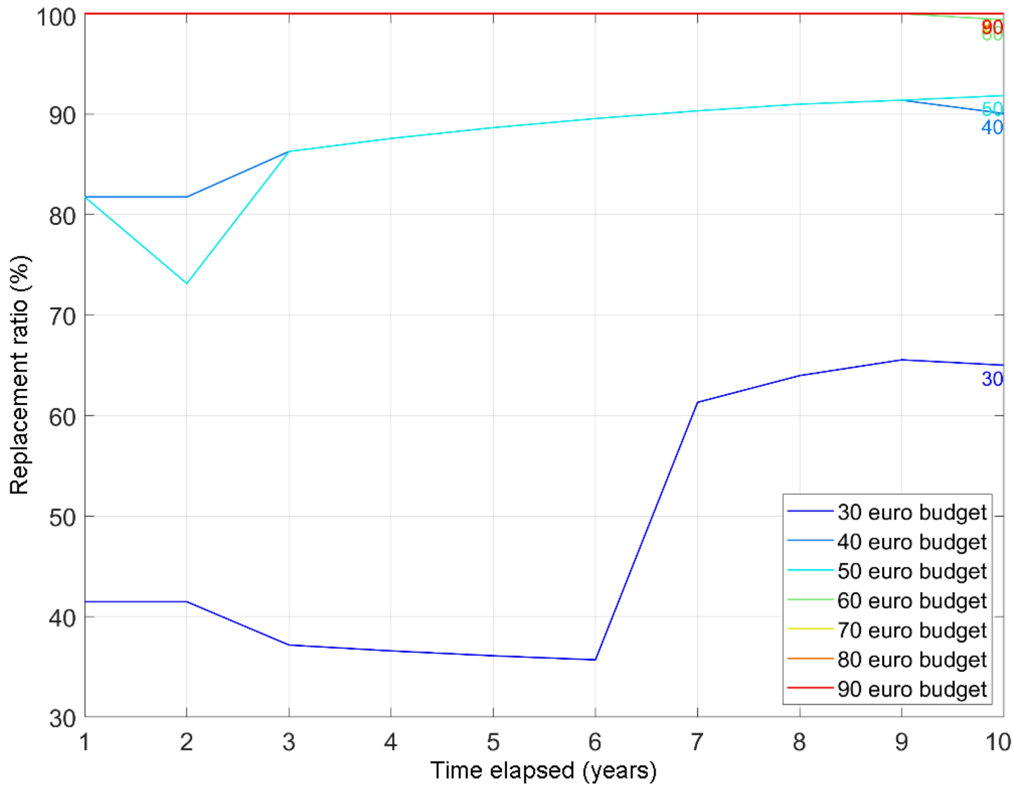

Figure 8. Replacement ratio % versus time elapsed for a dishwasher's PCB.

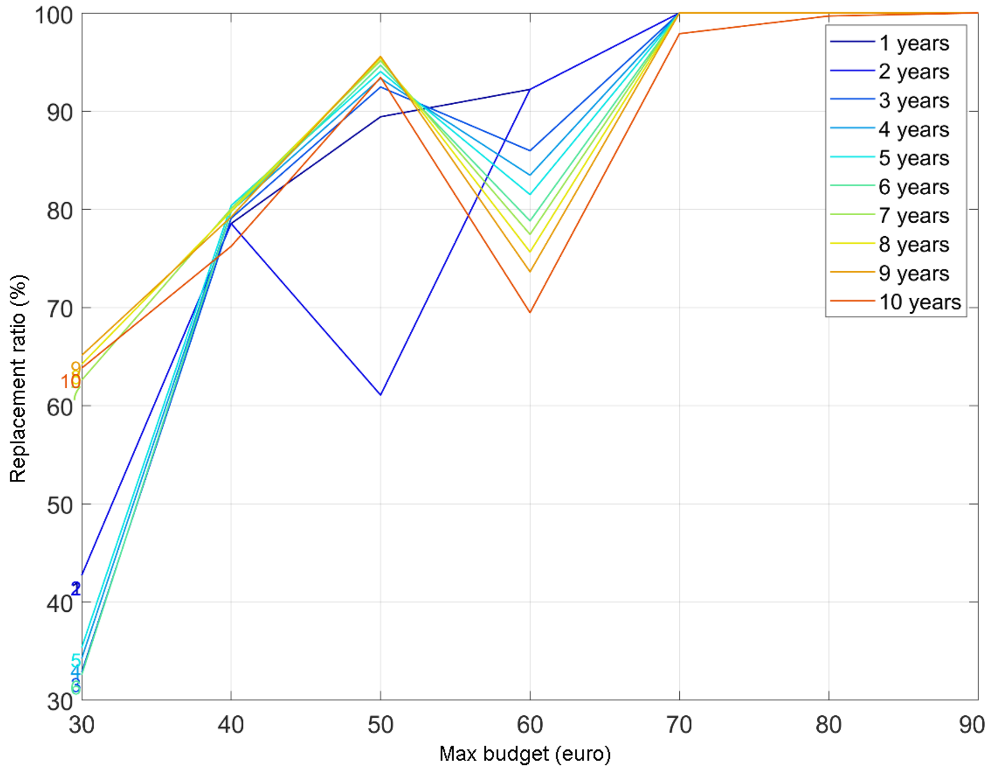

Figure 9. Replacement ratio % versus maximum client budget expressed in euros considering the operational years for a washing machine's PCB.

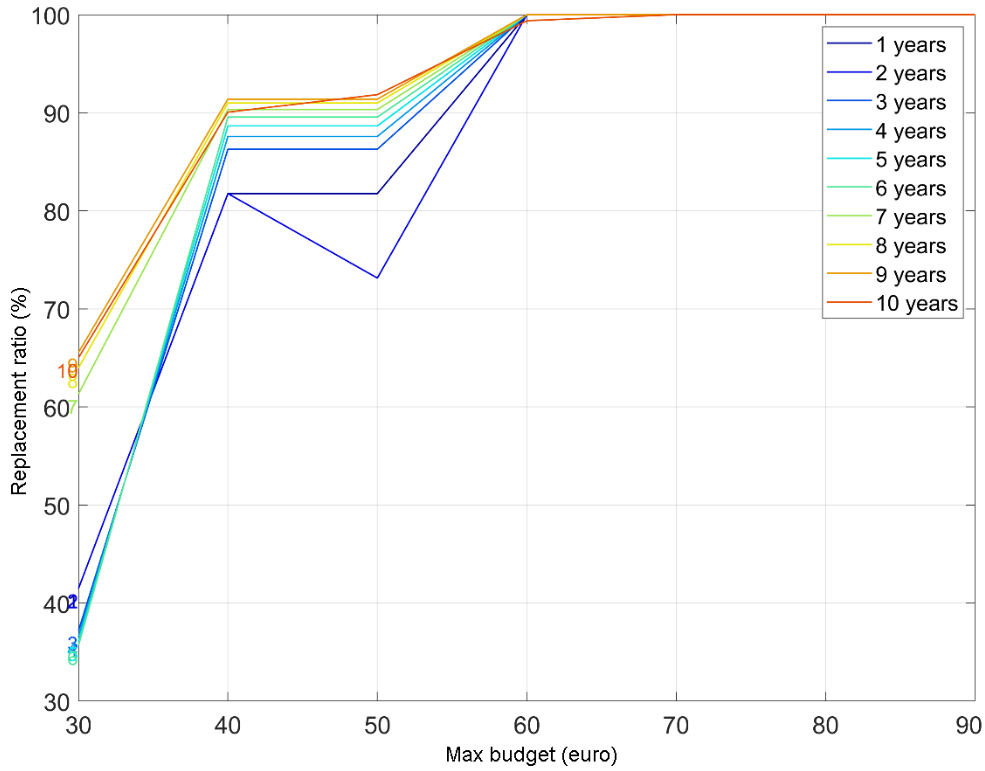

Figure 10. Replacement ratio % versus maximum client budget expressed in EUR considering the operational years for a dishwasher's PCB.

6. Conclusions

In recent years, many countries and especially the members of the EU seek to promote sustainability by encouraging reuse and repair, as well as addressing behaviors that increase product lifespans. The target of the European Commission is to support the "Right to Repair" movement and also to motivate customers to adopt this concept by making repairs more attractive, methodical, and cost-effective, whether by extending warranties, offering guarantees for replacement components, or improving access to repair and maintenance information. This article proposes a simple, flexible, and straightforward ILP-based method for optimizing a linear objective function associated with the components on a printed circuit board, subject to an inequality constraint while ensuring that the total cost of repair does not exceed a predefined value. The proposed methodology focuses on the maintenance of printed circuit boards, taking also into account the effect of their aging failures as determined by measurements, and optimizes the benefit to the appliance's life expectancy, while adhering to a customer's restricted budget, as well as the repair and replacement costs of their components. The proposed approach is systematic, easy to be implemented, and it adheres to the "Right to Repair" in terms of longer-lasting products. It can be used for any printed circuit board, type of component and client's budget. Case studies where PCBs from different domestic appliances are examined to determine the solutions' dependence on the aging rate of their different components. From the results, it can be seen that when the customer's budget increases, the replacement ratio for PCB maintenance increases as well. The cost-effectiveness of replacing for a modest budget varies based on the amount of time that has passed. Generally, from the simulation results of the proposed methodology, it can be concluded that the replacement ratio for PCB maintenance increases, the customer's budget also grows. Replacement benefits for a limited budget vary based on the amount of time that has passed due to the fact that it appears to be more cost-effective to replace certain lower-cost components after a few years rather than replacing some higher-cost components sooner. This takes into consideration the requirement that any component of the PCB is essential for its operation, and that replacing a single part improves the PCB's health by the same proportion as the aging percentage of the replaced component.

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