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Investigation of home appliances industry and devices obsolescence considering energy consumption

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The objective of this study is to optimize a linear objective function that pertains to the obsolescence of home appliances in a household. The approach introduced is an ILP-based method that is both simple and adaptable. This optimization guarantees that the total energy consumption remains below a predetermined energy threshold, while also adhering to an inequality constraint. The proposed methodology was effectively tested using a household containing four home appliances: a washing machine, a dishwasher, a refrigerator, and an oven. The findings indicate that the refrigerator is the most hazardous and inexpensive home appliance. The current formulation aims to optimize the device's lifespan considering the customer's financial constraints and the expenses associated with repairing and replacing its parts. This study centers on the maintenance of printed circuit boards (PCBs) and considers the effects of degradation-related malfunctions, as assessed through testing. Moreover, we employ an additional ILP approach to assess the vulnerability of refrigerator's PCB components by determining which ones should be replaced when a customer has limited financial resources.

List of symbols

x	Decision variable vector including the integer elements x_i
x_i	Number of the electrical home appliance in a household
n	Total number of home appliances
$J_1(x)$	Objective function corresponding to the set of home appliances included in the household
$f(x)$	Energy consumption constraint
O_i	Obsolescence index
w_i	Obsolescence of the *ith* home appliance
a_i	Mean energy consumption of the *ith* home appliance
b_i	Probability of survival of the *ith* home appliance
E	Total energy consumption of a household
L_n	Number of PCB components in a home appliance PCB
$b_{i,k}$	Influence of the *kth* component on the probability of survival
t_{LT}	Lifetime of the home appliance
λ_k	Total failure rate of the *kth* component included in home appliance
n_{ea}	Total number of PCBs per home appliance
N_k	Total number of the *kth* component per PCB
$w_{f,i}$	Frequency of replacement for different components of the PCB
PP_i	Purchase price of each component
FRC	Fixed repair cost
CB	Customer's maximum budget
$J_2(x_c)$	Number of components of each type to be replaced
x_c	Variable vector for PCB components

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Energy consumption and product labelling

Energy consumption models predict a potential 50% increase in global demand over the next three decades, unless substantial policy or technological advancements occur. In 2050, petroleum and other liquid fuels will continue to be the primary energy sources globally. However, renewable energy sources such as solar and wind will also experience significant growth, expanding at a comparable pace. The declining costs of technology and government initiatives aimed at meeting growing energy demands will drive the expansion of sustainable energy generation. Renewable energy is projected to be the fastest-growing energy source across all economies. While certain countries are projected to decrease their usage of carbon and nuclear energy, the remaining nations are expected to witness an increase in the consumption of coal and nuclear energy[1]. The yearly increase of one million tons in the global consumption of electronic and electrical appliances contributes significantly to global energy usage. The proliferation of technological advancements and expansion in various fields has led to a substantial increase in the number of public and commercial electrical items per person over the past three decades.

Europe is currently confronted with a significant issue stemming from heightened energy consumption and the subsequent rise in greenhouse gas emissions. The European Union (EU) has established the EU 20-20-20 target, which seeks to achieve a 20% decrease in Europe's yearly energy consumption, a minimum 20% reduction in EU greenhouse gas emissions, and a 20% share of renewable energy sources in EU energy consumption by 2020[2]. With the rising costs of energy, an increasing number of consumers are displaying a growing interest in actively reducing their energy consumption. Some new technologies have been suggested to potentially reduce residential electricity consumption by at least 40% in various types of appliances[3]. However, not all consumers are willing or able to purchase these appliances while their current ones are still functional.

When purchasing home appliances, it is crucial to consider their energy consumption. Customers will experience improved navigability of the process due to the implementation of labelling regulations. Starting from Monday, 1 March 2021, a revised version of the EU energy label was implemented in both physical stores and online retail platforms. This updated label aims to assist EU consumers in reducing their energy expenses and carbon emissions. The new labels were initially be implemented for four product categories: refrigerators and freezers, dishwashers, washing machines, and television sets (including other external monitors). Similar labelling requirements will be introduced for other products in the future.

The increasing prevalence of products receiving A +, A + +, or A + + + ratings necessitate a shift towards a simplified A-G scale as the most significant change as mentioned in Fig. 1.

The scale is designed to be stringent, allowing only a small number of products to initially attain an "A" rating. This allows for the inclusion of more efficient products. Energy efficient products currently available in the market are commonly labelled as "B," "C," or "D" to indicate their high energy efficiency. The labels featured additional elements, such as a QR link to an EU-wide database, enabling consumers to access more information about the product. Several eco-design rules implemented, particularly regarding reparability and the requirement for manufacturers to maintain a supply of spare parts for a specified period after products are discontinued[4].

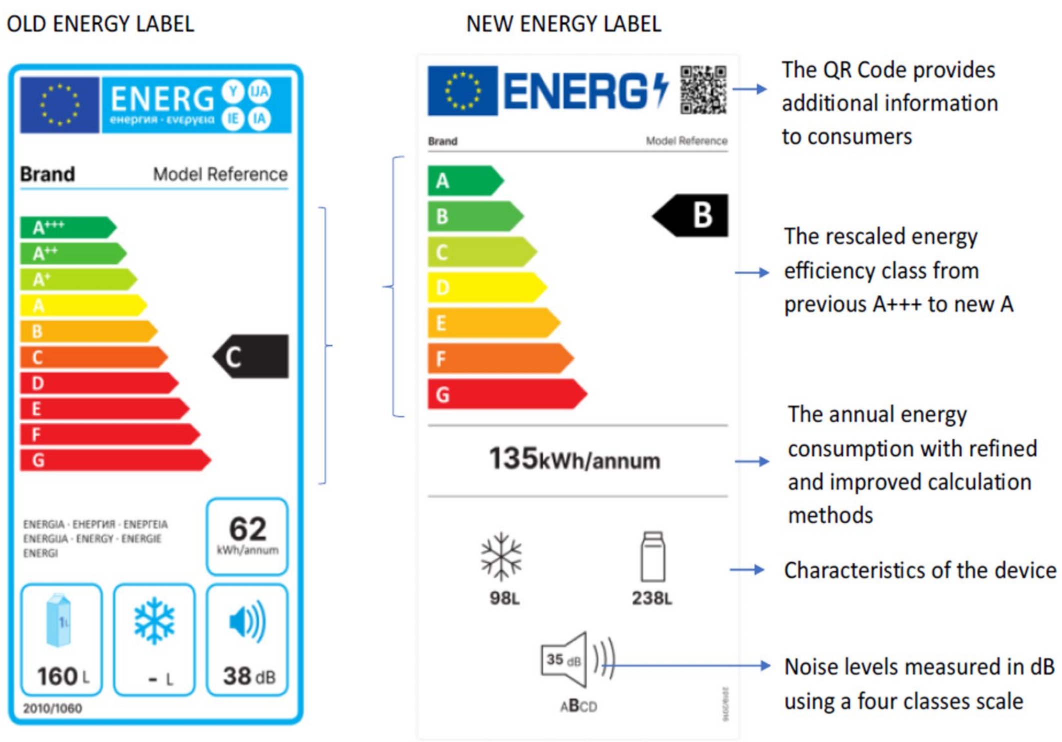

Figure 1. Comparison of old and new home appliance energy labels (source for data [4]).

Literature review

To mitigate the environmental impact, it is advantageous for appliances and industries to adopt strategies such as reduction, reuse, recycling, and recovery[5,6]. Manufacturers of electrical household appliances, in order to satisfy these strategies, have to address the repair and replacement of home appliances. This involves striking a balance between ensuring high reliability and meeting budgetary limitations within a fiercely competitive business landscape. Most manufacturers are currently upgrading their appliances and placing significant emphasis on the need for a long-term strategy to manage obsolescence of electrical parts of appliances. Conducting cost–benefit analysis for improvement projects at the component or system level, remains challenging in contemporary corporate settings[7]. The obsolescence of appliances' spare parts, such as printed circuit boards (PCBs) is influenced by temperature and humidity, as well as the efficiency of the manufacturing process in improving board cleanliness[8].

The reliability of electronic assemblies is crucial for all applications and must be thoroughly assessed during the equipment's design, implementation, and operation stages. Accelerated ageing testing is widely recognized as an effective method for estimating the lifespan and reliability of diverse products. This method in the electronics industry offers the advantage of expediting the ageing process, enabling the assessment of electronic modules' durability against specific climatic conditions such as heat, vibrations, radiations, and humidity within a reasonable timeframe. This strategy is especially beneficial in the prototype phase, when the newly developed equipment has not been used for a sufficient duration to encounter unexpected failure at the end of its lifespan. Temperature is a significant external factor that affects electronic PCBs. It leads to related stresses that can also be observed at the mechanical level[9]. The objective of[10] is to investigate the impact of ageing on electronic instrument and control (I&C) circuit boards. There is a concern regarding the potential for ageing failures in circuit boards used in I&C systems. These failures have the potential to cause a plant trip or render the system unavailable. The primary objective is to determine methods for quantifying failure precursors in I&C circuit boards and utilizing these measurements to estimate the probability of failure in the upcoming operational period, with a specified level of statistical confidence. Various methods have been proposed to ascertain the statistical confidence level of a circuit. The MIL-HDBK-217 provides methods for predicting system reliability[11].

There are also many works that have been published in the literature focused on the obsolescence of specific parts of home appliances. The study in[12] examines the obsolescence of appliances in German households through an empirical survey. Work[13] concentrated on the repair and recycling of printed circuit boards (PCBs) and their components in the context of the obsolescence index. The case study specifically examines home electrical appliances. Study[14] aims to explore the potential benefits of product remanufacturing in enhancing the environmental and economic aspects of sales functionality. Multiple case studies on the use of environmentally friendly supply chain management practices in Brazil's home appliance sector focused on obsolescence is presented in[15]. In[16], a comprehensive survey on the topic of disassembly sequence planning referred to the process of determining the optimal order in which to disassemble a product or system is discussed.

Study[17] focuses on the design of a remanufacturing platform as a strategic response to the Directive on Waste Electrical and Electronic Equipment, while the application of the "6R" principles in the sustainable supply chain design of white goods in Western Australia is studied in[18].

In recent years, there has been a considerable body of research dedicated to examining the remanufacturing and reparability of electrical appliances, with a particular emphasis on energy conservation. More specifically, a method to determine the best end-of-life scenario for electric and electronic equipment that prematurely malfunctions, with a focus on environmental factors considering, the environmental impacts of the equipment's life cycle, as well as, the repair and reuse versus replacement is discussed in[19]. Work[20] demonstrates the reuse of electric and electronic equipment in a developed industrial economy reduces total resource consumption, including materials and energy, by less than 1%. There is a consensus among both industry stakeholders and consumers that enhancing the quality of products serves as a fundamental step toward extending product lifespans. This, in turn, is expected to stimulate the demand for repairs that are economically viable and energy-efficient, thereby fostering motivation in this regard[21]. The implementation of remanufacturing practices presents a feasible approach within the realm of electronic waste management, as it effectively mitigates the generation of e-waste while simultaneously promoting the reuse of electronic equipment and its constituent components reducing the energy footprint[22]. The comprehensive survey[23] was conducted to investigate environmental attitudes and beliefs, energy consumption patterns, appliance ownership, and usage within residential households. The results suggest that there is a significant level of public interest in the consumption of energy within households and the subsequent environmental consequences. The objective of[24] is to analyze the trend of energy consumption in building appliances and identify the factors that contribute to this trend. It is important to consider that the increasing demand for new large and small appliances, which often come with additional features, is leading to a rise in electricity usage in residential and service sectors. A study[25] introduces a Home Energy Management System (HEMS) with a focus on environmental sustainability. The system employs energy comparison as its fundamental principle and primarily offers insights into the energy usage of both the entire household and individual home appliances. The focus of[26] is specifically on refrigerators, as their energy consumption is anticipated to comprise over 30% of the total average domestic electricity expenditure in Brazilian households. If all newly produced refrigerators in Brazil were engineered to adhere to energy efficiency standards that optimize the overall cost of ownership over their lifespan, potential advantages would encompass an annual cost reduction of 2.8 billion US dollars in electricity expenses, a decrease in electricity demand by 45 terawatt-hours (TWh), and a decline in carbon dioxide (CO2) emissions by 18 million metric tons (Mt). Work in[27] conducts a qualitative analysis of Spain's household and service sectors, with a specific focus on accommodation and private service companies. The findings of this analysis reveal a lack of comprehension regarding energy labels, indicating a limited understanding among individuals and organizations. Moreover, the adoption of energy-efficient products in Spain is hindered by the presence of bounded rationality and end-user behavior, which impose constraints on the extent to which such products are embraced. Research[28] utilizes a multi-case study methodology to establish a correlation between the realms of remanufacturing, product design, and automation. The objective of this study is to investigate the potential of circular product design in improving the efficiency of automation-driven remanufacturing processes, with the ultimate goal of minimizing energy consumption.

This work concentrates on repairing home appliances and their printed circuit boards, with a specific emphasis on energy consumption within a household. The MATLAB environment is used to implement an Integer Linear Programming (ILP) method[29], which considers various home appliances and PCBs for customers with fixed energy consumption and repairing budget.

The main contributions of this work are summarized as follows:

- This work is an extension of our previous study[30]. The primary distinction between reference[30] and the suggested technique is in the computation of the obsolescence w_i. More specifically, in[30], the obsolescence was established using predefined experimental values for the probability of survival. However, the proposed methodology utilized a mathematical procedure to estimate the obsolescence considering the failure factors of the components each PCB included into the home appliances.
- A proposed systematic and efficient procedure is presented, which takes into account obsolescence and aims to produce more durable products.
- The problem is addressed using an ILP method that is straightforward, adaptable, and easy to implement. This method considers all components of home appliances, regardless of their number.
- The suggested strategy is applicable to both client energy consumption and budget.

The paper is organized as follows: Sect. "Home appliances industry analysis in the context of sales and energy consumption" presents the home appliances industry analysis in the context of sales and energy consumption, while Sect. "Proposed methodology" defines the proposed methodology. Section "Solution technique for the proposed ILP model" provides the solution technique for the proposed ILP model, Sect. "Simulation results" presents the simulation results of the proposed methodology. Section "Comparison with other works in the literature" qualitative compares our methodology with other works in the literature, and finally Sect. "Conclusions" concludes the paper.

Home appliances industry analysis in the context of sales and energy consumption

The household appliances market undergoes ongoing challenges, innovations, and transformations. The market is influenced by smart technology and the adoption of energy-efficient appliances. A home appliance, is a device created to aid in tasks related to food preparation, cleaning, and food preservation. The three main categories are small appliances, large appliances, and consumer electronics. The wide range of these devices establishes the related field as a rapidly growing industry. The global market has witnessed a 10% compound annual growth rate (CAGR), leading to a rise in market value from \$551.29 billion in 2022 to \$606.58 billion in 2023[31]. The manufacturers with the highest total sales in the global market are detailed in reference[32], as depicted in Fig. 2.

The large appliances segment represents the largest proportion of the overall revenue. The refrigerator segment accounts for 21%, closely followed by the small appliances segment, which represents 18% of the total revenue. A mere 22% of consumers intend to purchase a new appliance in the upcoming year. Online shopping has been widely embraced by consumers, and the household appliances market has already established a strong presence in the realm of eCommerce.

The market is characterised by a concentration of major players who have consolidated well-known brands within their portfolio. Whirlpool emerged as the leading manufacturer, generating a substantial revenue of US\$19 billion in the year 2020. Whirlpool is the parent company of seven brands, including KitchenAid, Maytag, and Bauknecht, each generating annual sales exceeding US\$1 billion. Bosch, through its Home Appliances division BSH, held the second largest market share in 2019, amounting to a total of US \$15.6 billion. Haier Electronics, a Chinese manufacturer, exhibits the most substantial growth rates in the appliance industry compared to other prominent companies, achieving up to a 50% increase in certain segments[33].

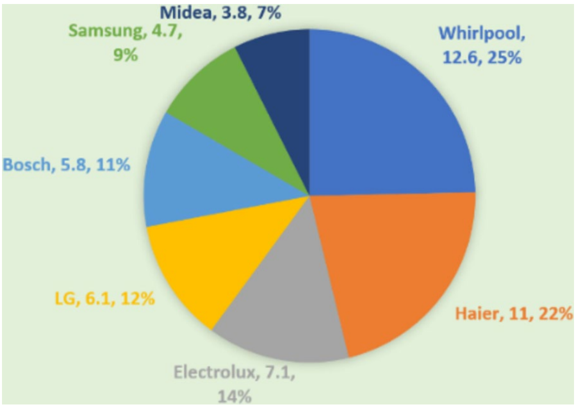

Figure 2. The overall sales percentage for the home appliances industry.

The electricity cost for most households is primarily attributed to the energy consumption of home appliances such as washing machines, dishwashers, refrigerators, and ovens. Each appliance is assigned a power rating, usually measured in watts (W). It requires a specific amount of electricity to function. The duration of device persistence impacts the energy consumption. The refrigerator's continuous usage results in high energy consumption despite its low wattage. Despite infrequent usage, ovens consume substantial amounts of electricity due to the high energy requirement for heating. Figure 3 presents the average power ratings of various common home appliances[34]. The power rating of each appliance may vary depending on its size and features. However, we have provided an average power rating for each appliance.

To quantify the home appliances in terms of energy consumption, we expanded the analysis of work[31] incorporating also data related with energy classes of the appliances[35]. In order to measure the energy consumption of household appliances, we extended the study conducted by[31] to include data on the energy classes of the appliances. This additional information was obtained from[35]. Based on the findings of the study conducted[31] in the field of household appliances, specifically washing machines, dishwashers, electric ovens and refrigerators, we have expanded upon the results to estimate the mean energy consumption per appliance and energy class (MECPAEC) measured in kilowatt-hours (kWh). The study was based on a sample size of 1511 appliances. Table 1 presents data on the dominant energy efficiency class of household appliances per manufacturer, along with the corresponding mean number of appliances (MNA).

Figure 4 presents the graphical representation of MECPAEC per manufacturer. Combining the results of Table 1 and Fig. 4, it can be concluded that considering the energy consumption per energy class and manufacturer, the most environmentally friendly manufacturer per energy class, in terms of mean energy consumption, is the Samsung Electronics Co., Ltd. having 75.23 kWh in energy class A, the LG Electronics having 159.20 kWh in energy class D, and the Robert Bosch GmbH having 164.81 kWh in energy class E.

Proposed methodology

This study presents a methodology for evaluating the obsolescence of electrical appliances by taking into account factors related to failure and energy consumption. We propose an integer linear programming (ILP) formulation for classifying the obsolescence of household electrical devices. The objective of this problem is to determine the household appliances with the highest obsolescence index, O_i, considering the energy consumption of a household, the mean energy consumption spent by each appliance and the probabilities of survival of the appliances.

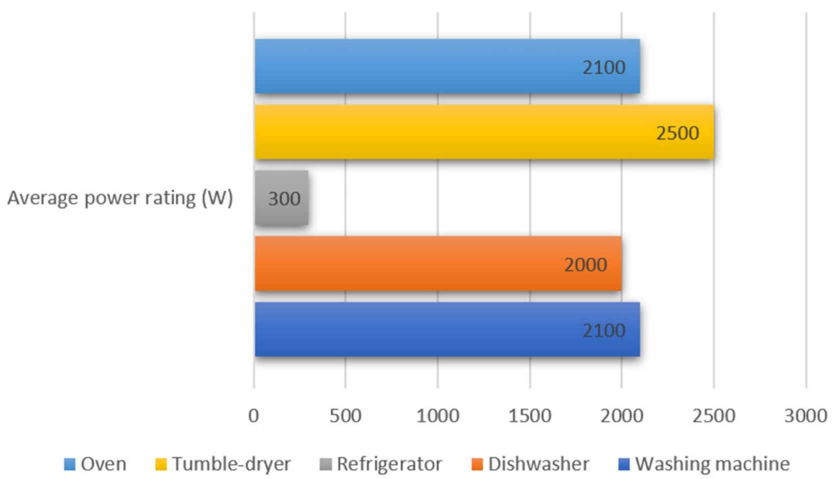

Figure 3. Home appliances and average power ratings.

Manufacturers	MNA	Energy class	MECPAEC
Whirlpool Corp	1.14	A	110.84
Haier Smart Home Co. Ltd	7.00	D	175.00
Electrolux AB	1.06	E	219.00
LG Electronics	1.27	D	159.20
Robert Bosch GmbH	0.99	E	164.81
Samsung Electronics Co. Ltd	0.96	A	75.23
Midea Group co Ltd	1.32	E	219.00
Rest	1.15	A	100.49

Table 1. MNA, energy class, and MECPAEC per manufacturer.

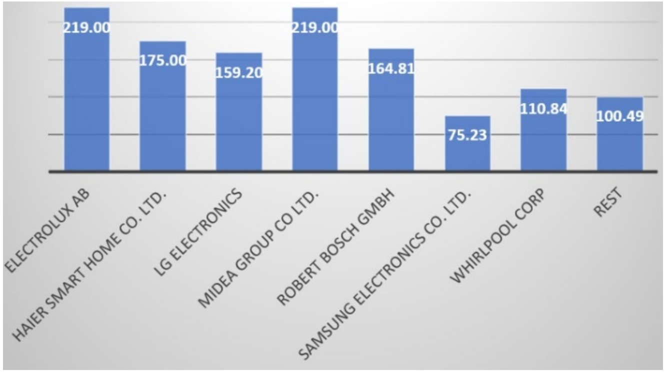

Figure 4. Graphical representation of MECPAEC.

$$\begin{aligned} \max_x J_1(x) &= \sum_{i=1}^{n} x_i \\ s.t. f(x) = \sum_{i=1}^{n} \mathrm{O}_i &= \sum_{i=1}^{n} w_i \cdot x_i \leq E \end{aligned} \tag{1a}$$

$$\begin{aligned} \max_x J_1(x) &= \sum_{i=1}^{n} x_i \\ s.t. f(x) = \sum_{i=1}^{n} \mathrm{O}_i &= \sum_{i=1}^{n} (a_i \cdot b_i) \cdot x_i \leq E \end{aligned} \tag{1b}$$

where x is the decision variable vector. Each one integer element of x, namely x_i, corresponds to the number of the *ith* appliance, while n is the number of household appliances. $J_1(x) : I^n \rightarrow R$ is an objective function corresponding to the set of home appliances included in the household and $f(x)$ is an energy consumption constraint. O_i is the obsolescence index of the *ith* device,w_i is the *ith* device obsolescence expressed as the product of the mean energy consumption, a_i, and the probability of survival of the *ith* appliance $b_i = \prod_{k=1}^{Ln} e^{-\left[\sum_{k=1}^{n_{eq}} N_k \cdot (\lambda_p \cdot \pi_Q)_k\right] \cdot t_{LT}}$. The variable x_i takes on non-negative integer values.

E is the total energy consumption of a household for a specific time interval expressed in kWh.

To estimate the failure factor of the *ith* device, we adopted the probability of survival of the *ith* device[36].

$$b_i = \prod_{k=1}^{L_n} b_{i,k}(t) \tag{2}$$

where L_n is the number of PCB components included in *kth* PCB of a domestic appliance and $b_{i,k}$ is the influence of the component k on the probability of survival.

The influence of the component k is determined by:

$$b_{i,k}(t) = e^{-\lambda_k \cdot t_{LT}} \tag{3}$$

where t_{LT} is the lifetime of the device.

The total failure rate of the *kth* component included in electrical devices, λ_k is as follows:

$$\lambda_k = \sum_{k=1}^{n_{ea}} N_k \cdot (\lambda_p \cdot \pi_Q)_k \tag{4}$$

where n_{ea} is the total number of PCBs per home appliance, N_k is the total number of the *kth* component per PCB, while λ_p and π_Q are the failure rate and the quality factor for the *kth* component, respectively.

To quantify the vulnerability of the selected device from the procedure described in (1), we used the following Integer Linear Programming (ILP) formulation for PCB maintenance[30].

$$\begin{aligned} \max_{x_c} J_2(x_c) &= \sum_{i=1}^{n_{PCB}} w_{f,i} \cdot x_{c,i} \\ s.t. f_2(x_c) &= FRC + \sum_{i=1}^{n_{PCB}} PP_i \cdot x_{c,i} \leq CB \end{aligned} \tag{5}$$

The decision vector variable is associated with a PCB that consists of n_{PCB} different types of electronic components that need to be replaced. In relation to the variable vector x_c, the symbol $w_{f,i}$ represents the assigned weight for each variable, indicating the frequency of replacement for different components of the PCB. PP_i represents the euro (€) denominated purchase price of each component. The problem of PCB maintenance can be formulated as a linear programming problem, where the repair cost is fixed at *FRC* and the variable *CB* represents the customer's maximum budget.

Solution technique for the proposed ILP model

The proposed ILP model is solved considering the Branch and Bound method[37]. The Branch-and-Bound method is highly efficient in addressing mixed-integer linear and nonlinear programming problems. The technique was initially adapted for resolving integer linear programming issues and then was expanded to address nonlinear mixed-integer programming issues. The primary solution process analyzes the provided nonlinear mixed-integer programming problem:

$$\begin{gathered} \text{Minimize}\, f(X) \\ \text{s.t.} \\ g_j(X) \geq 0,\; j = 1, 2, \ldots, \text{m} \\ h_k(X) = 0,\; k = 1, 2, \ldots, \text{p} \\ x_j = \text{integer}, j = 1, 2, \ldots, n_0 (n_0 \leq n) \end{gathered} \tag{6}$$

It should be noted that in the design vector X, the initial n_0 variables are specifically designated as the integer variables. If the initial value n_0 is equal to n, the problem transforms into an all-integer programming problem. The design vector X is a continuous viable solution if it adheres all the problem's constraints.

Simulation results

To demonstrate the effectiveness of the proposed formulation, we conducted a study using common home appliances as a scenario. The suggested technique was implemented in[38] using an Intel Core i7-2600K CPU operating at 3.4 GHz and 16 GB of RAM. We assume a household that includes four home appliances namely washing machine, dishwasher, refrigerator and oven.

It is also assumed that the combined monthly energy consumption of all devices is 350kWh, with a cost of 0.155€ per kWh. Moreover, the number of PCBs per appliance is presented in Table 2. For the implementation of the proposed methodology in order to calculate the probability of survival of the *ith* appliance, we adopted the procedure described in Eqs. (2)–(4).

More specifically, the probability of survival of each appliance is calculated from Eq. (2) considering the influence of the electronic components included in PCBs of the specific appliance, Eq. (3), and the total failure rate of the corresponding components included in the electrical appliance as described by Eq. (4). Tables 3, 4, 5 and 6 provide an analytical presentation of the findings obtained from the process described above and considering the inputs related with the total number of components per PCB, N_k, as well as λ_p, π_Q, which are given in[11]. Note that the first column of these matrices describes the PCB components per home appliance and the fourth column their corresponding total number per home appliance. This procedure was used to calculate the impact of electronic components in the PCBs of a given appliance, as well as the overall number of components in each electrical appliance (Table 7).

Figure 5 shows the simulation results considering the formulation as described by Eqs. (1)–(4), whereas Fig. 6 presents the corresponding simulation results considering the formulation as described in[30].

From the results, it is obvious that the most vulnerable appliance in both cases is the refrigerator.

The ILP formulation of Eq. (5) was applied for PCB maintenance in order to provide additional quantification regarding the refrigerator which is the home appliance with the highest level of vulnerability. The parameters for this simulation are presented in Table 8. Considering that the values of *FRC* and *CB* are equal to 25€ and 60€, respectively, the simulation results based on Eq. (5) are as follows:

Figure 7 depicts a graphical representation of the printed circuit board (PCB) components, taking into account the maximum budget allocated by the customer for the refrigerator. For example, considering the diode rectifier, although the refrigerator as a home appliance consumes a relatively low amount of energy per unit of time, given that it operates for many hours during the year (or even continuously), many of the electronic elements on the board are particularly burdened. As can be seen from the simulation results, one of them is the rectifier diode which is directly related to the maximum repeated reverse voltage which stresses the specific electronic element during the operation of the PCB. Additionally, Fig. 7 shows that the component that is most commonly replaced on PCBs is the "22 Ohm Resistor".

Table 7 presents the values for mean energy consumption in kWh, probability of survival and weight of the household appliances used for simulation purposes. Moreover, in order to enhance the outcomes presented in the research, we made further adjustments to the parameters of the utilized model. For further clarification,

Home appliance	Number of PCBs per home appliance (n_{ea})
Washing machine	3
Dishwasher	3
Refrigerator	2
Oven	2

Table 2. Number of PCBs per appliance.

PCB components	Inputs			λ_k	$b_{i,k}$
	π_Q	λ_p	N_k		
Diode rectifier	8.00	23.18	19	3523.97	0.95859
Push-button MicroSwitch	7.00	17.46	5	611.18	0.99269
A.C-micro switch-thyristor	8.00	0.60	11	53.13	0.99936
Resistor {22 Ohm}	15.00	0.23	21	70.88	0.99915
Capacitor {400 V/4.7uF}	10.00	8.98	6	539.04	0.99355
Capacitor {16 V/32mF}	10.00	23.58	10	2357.80	0.97210
H.Power Relay {250 V D.C–250 V A.C}	3.00	45.85	10	1375.48	0.98363
Choke {0.47mH}	20.00	0.04	9	7.92	0.99990
Resistor R100	15.00	0.07	12	12.69	0.99985
H.Power Relay {12 V D.C–250 V A.C}	3.00	82.43	4	989.11	0.98820
Triac {BTA316}	8.00	1.20	10	95.92	0.99885
Leaded varistor {11–1000VRMS}	10.00	4.60	8	368.00	0.99559
Capacitor {50 V/14mF}	10.00	11.86	5	593.10	0.99291
Capacitor {25 V/32mF}	10.00	19.31	8	1544.96	0.98163
AutoTransformer {1–200 kHz}	30.00	2.25	2	135.00	0.99838
Rotary modular selector	6.00	17.27	1	103.63	0.99876

Table 3. Inputs, total failure rate and influence for washing machine.

PCB components	Inputs			λ_k	$b_{i,k}$
	π_Q	λ_p	N_k		
Diode rectifier	8.00	23.18	12.00	2225.66	0.96717
Push-button MicroSwitch	7.00	17.46	4.00	488.95	0.99269
A.C-micro switch-thyristor	8.00	0.60	7	33.81	0.99949
Resistor {22 Ohm}	15.00	0.23	17	57.38	0.99914
Capacitor {400 V/4.7uF}	10.00	8.98	5	449.20	0.99328
Capacitor {16 V/32mF}	10.00	23.58	7	1650.46	0.97555
H.Power Relay {250 V D.C–250 V A.C}	3.00	45.85	8	1100.38	0.98363
Choke {0.47mH}	20.00	0.04	6	5.28	0.99992
Resistor R100	15.00	0.07	9	9.52	0.99986
H.Power Relay {12 V D.C–250 V A.C}	3.00	82.43	3	741.83	0.98893
Triac {BTA316}	8.00	1.20	7	67.14	0.99899
Leaded varistor {11–1000VRMS}	10.00	4.60	4	184.00	0.99724
Capacitor {50 V/14mF}	10.00	11.86	3	355.86	0.99468
Capacitor {25 V/32mF}	10.00	19.31	5	965.60	0.98562
AutoTransformer {1–200 kHz}	30.00	2.25	3	202.50	0.99697
Rotary modular selector	6.00	17.27	1	103.63	0.99845

Table 4. Inputs, total failure rate and influence for dishwasher.

we performed a sensitivity investigation to identify the parameter which had the greatest influence in both our current study and the earlier study conducted by the same authors[30]. Specifically, we conducted a comparison determining the impact of the parameter b_i on the obsolescence w_i in terms of the sensitivity index S_i as described in the last column of Table 7. Based on the Si results, it is obvious that the proposed methodology provides higher values of S_i due to the systematic calculation of b_i. Note that the values of b_i were based on either experimental tests [30] or systematic calculations (Eqs. (2)–(4)).

Comparison with other works in the literature

In order to assess the benefits of our article, Table 9 provides a qualitative analysis between our proposed methodology and other studies found in the literature. This analysis takes into account various perspectives, including the solution algorithm, the devices and appliances involved, energy consumption, repair costs, electricity costs, and other relevant variables. Our methodology takes into account various factors, including repair costs in comparison to work[39] and electrical costs in comparison to work[40]. The primary advantage of comparing the perspectives in Table 9, is that our work outperforms the other works in the field of home appliance maintenance. Specifically, it pertains to the costs related to repairing, the cost of power, the amount of energy consumed, and

PCB components	Inputs			λ_k	$b_{i,k}$
	π_Q	λ_p	N_k		
Diode rectifier	8.00	23.18	6	1112.83	0.98017
Push-Button MicroSwitch	7.00	17.46	4	488.95	0.99124
A.C-micro switch-thyristor	8.00	0.60	6	28.98	0.99948
Resistor {22 Ohm}	15.00	0.23	9	30.38	0.99945
Capacitor {400 V/4.7uF}	10.00	8.98	4	359.36	0.99355
Capacitor {16 V/32mF}	10.00	23.58	6	1414.68	0.97486
H.Power Relay {250 V D.C–250 V A.C}	3.00	45.85	7	962.83	0.98282
Choke {0.47mH}	20.00	0.04	5	4.40	0.99992
Resistor R100	15.00	0.07	5	5.29	0.99990
H.Power Relay {12 V D.C–250 V A.C}	3.00	82.43	5	1236.38	0.97799
Triac {BTA316}	8.00	1.20	7	67.14	0.99879
Leaded varistor {11–1000VRMS}	10.00	4.60	4	184.00	0.99669
Capacitor {50 V/14mF}	10.00	11.86	5	593.10	0.98938
Capacitor {25 V/32mF}	10.00	19.31	4	772.48	0.98619
AutoTransformer {1–200 kHz}	30.00	2.25	1	67.50	0.99879
Rotary modular selector	6.00	17.27	0	0.00	1.00000

Table 5. Inputs, total failure rate and influence for refrigerator.

PCB components	Inputs			λ_k	$b_{i,k}$
	π_Q	λ_p	N_k		
Diode rectifier	8.00	23.18	8	1483.78	0.97944
Push-Button MicroSwitch	7.00	17.46	0	0.00	1.00000
A.C-micro switch-thyristor	8.00	0.60	5	24.15	0.99966
Resistor {22 Ohm}	15.00	0.23	14	47.25	0.99934
Capacitor {400 V/4.7uF}	10.00	8.98	6	539.04	0.99248
Capacitor {16 V/32mF}	10.00	23.58	6	1414.68	0.98039
H.Power Relay {250 V D.C–250 V A.C}	3.00	45.85	6	825.29	0.98851
Choke {0.47mH}	20.00	0.04	6	5.28	0.99993
Resistor R100	15.00	0.07	8	8.46	0.99988
H.Power Relay {12 V D.C–250 V A.C}	3.00	82.43	8	1978.21	0.97268
Triac {BTA316}	8.00	1.20	7	67.14	0.99906
Leaded varistor {11–1000VRMS}	10.00	4.60	4	184.00	0.99743
Capacitor {50 V/14mF}	10.00	11.86	4	474.48	0.99338
Capacitor {25 V/32mF}	10.00	19.31	5	965.60	0.98657
AutoTransformer {1–200 kHz}	30.00	2.25	1	67.50	0.99906
Rotary modular selector	6.00	17.27	0	0.00	1.00000

Table 6. Inputs, total failure rate and influence for oven.

Appliance	Methodology	α_i	b_i	w_i	S_i	
Washing machine	A (Proposed)	132.300	0.862	114.043	0.850	$\frac{w_{i,A}}{w_{i,A}+w_{i,B}}$
Dishwasher		46.875	0.543	25.453	0.702	
Refrigerator		60.000	0.876	52.560	0.961	
Oven		117.000	0.893	104.481	0.743	
Washing machine	B ([30])	132.300	0.153	20.193	0.150	$\frac{w_{i,B}}{w_{i,A}+w_{i,B}}$
Dishwasher		46.875	0.230	10.802	0.298	
Refrigerator		60.000	0.036	2.147	0.039	
Oven		117.000	0.310	36.110	0.257	

Table 7. Mean energy consumption, probability of survival and weight of the household appliances.

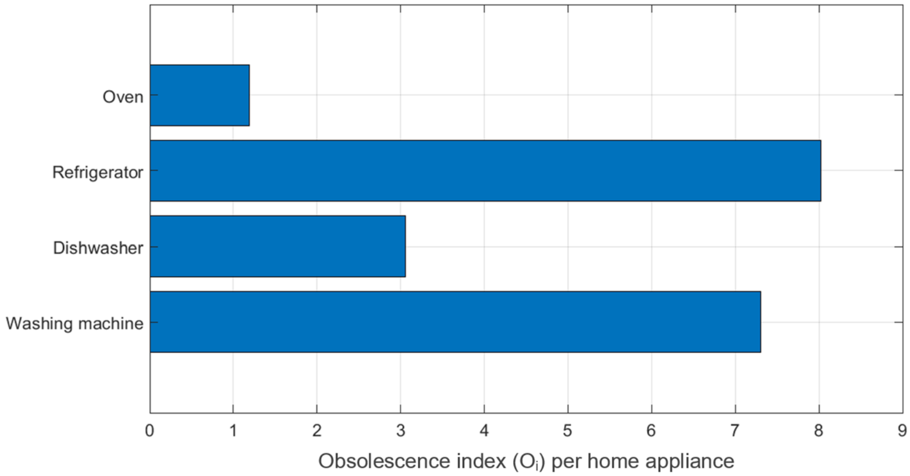

Figure 5. Obsolescence index per appliance for the simulated case based on the proposed methodology.

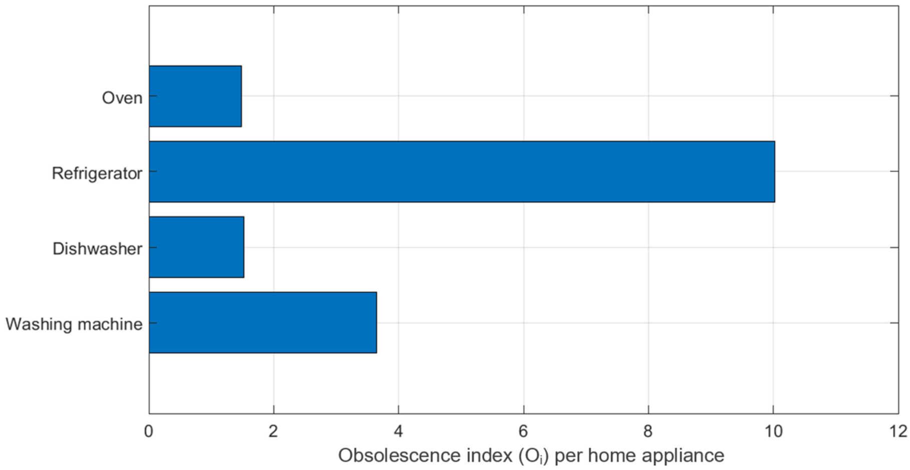

Figure 6. Obsolescence index per appliance for the simulated case based on [30].

Type of component	PCB #1	PCB #2	PP_i(€/item)	$w_{f,i}$
	n_{PCB}			
Diode rectifier	2.00	4.00	0.20	0.75
Push-Button MicroSwitch	1.00	3.00	2.00	0.55
A.C-micro switch-thyristor	1.00	5.00	0.30	0.80
Resistor {22 Ohm}	2.00	7.00	0.15	0.70
Capacitor {400V/4.7uF}	1.00	3.00	0.22	0.90
Capacitor {16V/32mF}	1.00	5.00	1.25	0.90
H.Power Relay {250V D.C-250V A.C}	1.00	6.00	1.55	0.85
Choke {0.47mH}	2.00	3.00	0.65	0.75
Resistor R100	2.00	3.00	0.25	0.70
H.Power Relay {12V D.C -250V A.C}	2.00	3.00	2.30	0.85
Triac {BTA316}	2.00	5.00	1.50	0.80
Leaded varistor {11-1000VRMS}	1.00	3.00	0.85	0.65
Capacitor {50V/14mF}	1.00	4.00	1.15	0.90
Capacitor {25V/32mF}	1.00	3.00	1.45	0.90
AutoTransformer {1–200kHz}	0.00	1.00	5.60	0.55

Table 8. Parameters for simulation focused on PCB maintenance of the refrigerator.

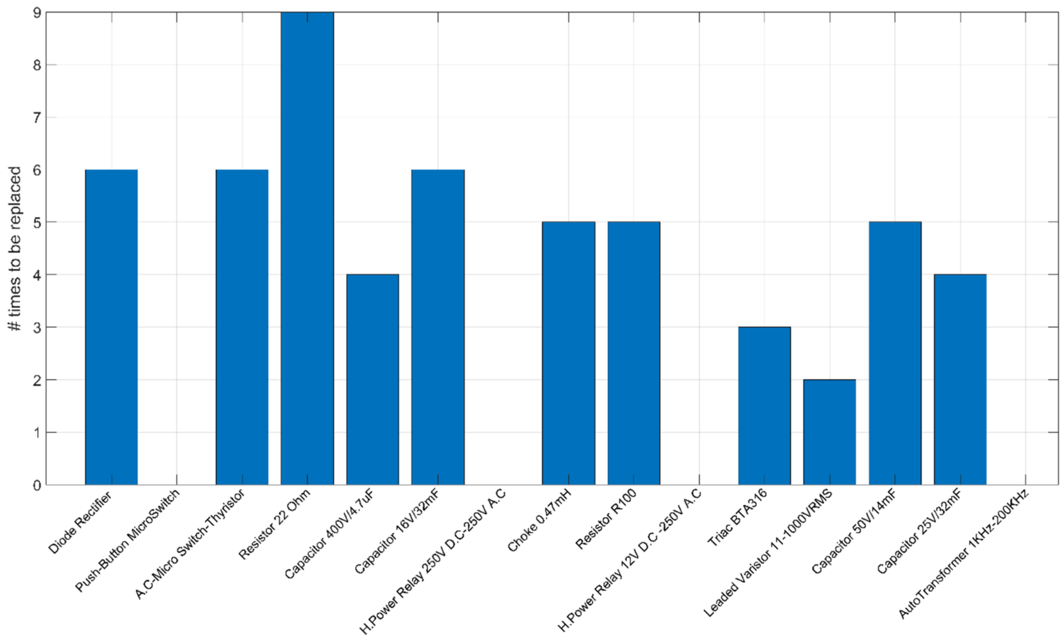

Figure 7. Graph of the refrigerator's PCB components considering based on maximum customer's budget.

Perspectives	Proposed methodology	[39]	[40]
Algorithm	ILP (Branch and Bound)	MILP	Machine learning
Devices-appliances	Oven Refrigerator Dishwasher Washing machine	Dishwasher Washing machine Dryer	Washing machine Refrigerator
Energy consumption	Yes	Yes	Yes
Repair cost	Yes	No	Yes
Electricity cost	Yes	Yes	No
Variables	PCB elements	Power profiles	Appliances' working errors

Table 9. Qualitative comparison of the proposed methodology with other works in the literature considering different perspectives.

the failures in electronic components. It ultimately leads to the development of a more organized approach to maintaining household appliances.

Conclusions

This study presents a simple and adaptable ILP-based approach for optimizing a linear objective function related to the obsolescence of home appliances in a household. This optimization problem incorporates an inequality constraint to ensure that the total energy consumption remains below a predetermined energy threshold. The proposed methodology was tested successfully on a household with four home appliances: washing machine, dishwasher, refrigerator, and oven. The findings demonstrate that the refrigerator is the appliance most susceptible to damage or malfunction. This study focuses on maintaining printed circuit boards and assessing the impact of deterioration-related malfunctions through measurements. The objective is to maximize the device's lifespan while considering the customer's limited financial resources and the costs of repairing or replacing its parts. To assess the vulnerability of the refrigerator's PCB components, we employ an additional ILP methodology. This approach aids in identifying the specific components that should be replaced when a customer has limited financial resources at his disposal. While the proposed methodology is relatively simple to implement, there are several limitations associated with global trends in the home appliances industry, the accuracy of energy consumption data and device obsolescence, the inconsistent standards and regulations for energy consumption and appliance manufacturing, the rapid pace of technological innovation, the diverse behaviors and preferences of consumers, economic factors such as income levels and market prices, the overall environmental impact, the carbon footprint of supply chains, and the impact of electronic waste. In order to expand our research efforts, it is imperative to gather and analyze data from a broader array of geographic regions and manufacturers. This will enable us to achieve a more holistic understanding of global trends, monitor shifts in energy usage and product longevity patterns over time, incorporate the latest advancements in energy-efficient technologies and smart home appliances into our analysis, explore the impact of smart home technologies and the Internet of Things (IoT) on reducing energy consumption and prolonging appliance lifespan, assess the interplay between energy usage and product obsolescence, examine the influence of economic factors such as subsidies, energy costs, and income levels on the adoption of energy-efficient home appliances, conduct thorough life cycle assessments (LCAs) that encompass all stages of an appliance's lifecycle to better comprehend its overall environmental footprint. Also, we have to investigate strategies for managing and diminishing electronic waste (e-waste) through improved recycling practices, develop and implement more sophisticated models capable of capturing the complexities of energy usage and product obsolescence, and evaluate the efficacy of existing regulations and policies aimed at curbing energy consumption and fostering sustainability in the home appliance sector.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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