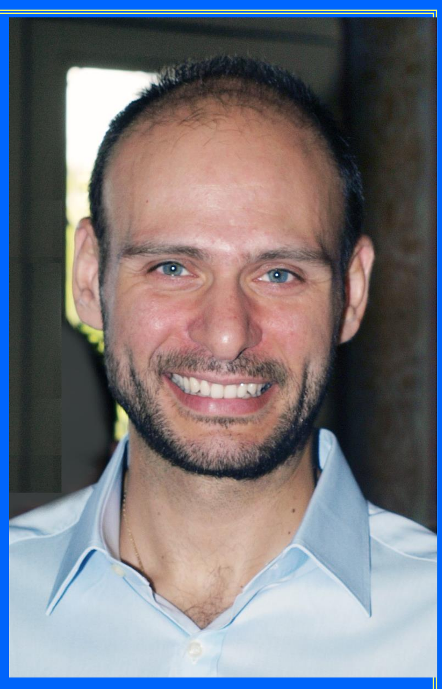
Repair and recycling of PCBs and their components considering energy consumption



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Introduction

Energy consumption studies predict a 50% worldwide demand rise in 30 years (Figure 1). Solar and wind will expand as fast as petroleum and other liquid fuels in 2050. Falling technology costs and resource-friendly government measures will expand sustainable energy production to meet power needs. All economies will flourish fastest with renewable energy. Some nations will reduce carbon and nuclear use, while others will expand.

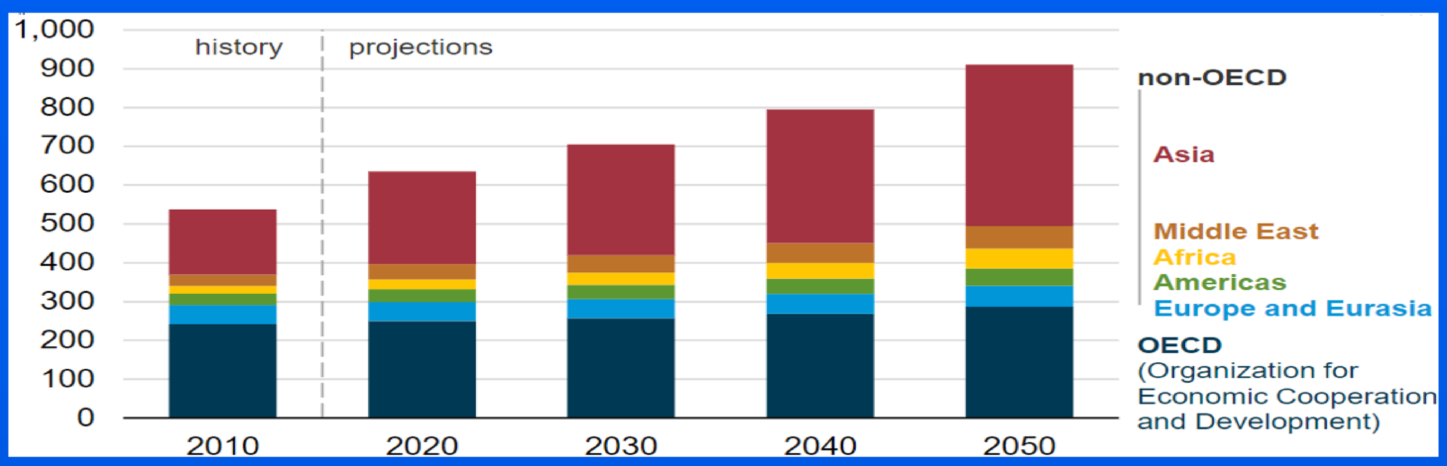

Figure 1: Global primary energy consumption by energy source (2010-2050) expressed in 10^{15} British thermal units (BTUs)

Domestic or electric appliances help in food preparation, cleaning, and storage. Small appliances, large appliances, and consumer electronics comprise household appliances. These devices are diverse, making the industry fast increasing. The global household appliance market grew 10% from $551.29 billion in 2022 to $606.58 billion in 2023. Figure 2 shows the top global manufacturers by sales.

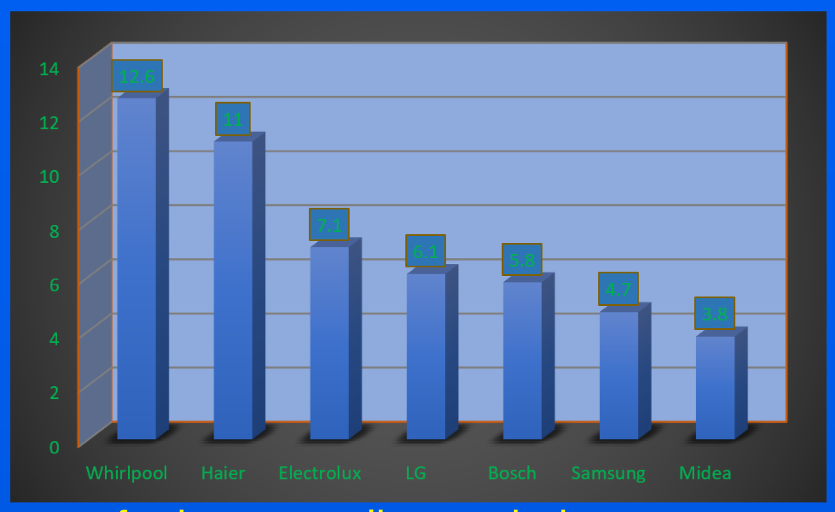

Figure 2: Total sales percentage for home appliances industry

Results & Discussion

This work optimizes an obsolescence-related linear objective function for home equipment. An ILP-based technique is simple and adaptable. This optimization keeps energy usage below a predefined threshold under an inequality constraint. The proposed methodology was tested using a household with five appliances: a washing machine, dishwasher, refrigerator, tumble dryer, and oven.

Table 1 displays the average power rating associated with using certain typical domestic appliances. The actual power rating will vary depending on the size and features of each appliance; we have averaged their power ratings.

Table 1: Domestic appliances and corresponding average power ratings.

Appliance	Average power rating (W)
Washing machine	2100
Dishwasher	2000
Refrigerator	300
Tumble-dryer	2500
Oven	2100

The proposed formulation is as follows:

$$\text{maximize} \sum 1 \cdot x \qquad \text{s.t. } f(x) = \sum w_i \cdot x_i \leq B \tag{1}$$

where $x = (x_1, \ldots, x_n)^T$ is the vector of the decision variables, x_i is the decision variable corresponding to ith electrical device of a household, 1 is the unity vector assuming that all variables have equal importance and n is the number of household devices. $f(x)$ is an energy consumption function, B is the total energy consumption of a household for a specific time interval and $w_i = \alpha_i \cdot b_i$ is a weight related with the obsolescence of the ith device. Note that α_i and b_i express the mean energy consumption and the failure factor of the ith device, respectively. To further quantify the most vulnerable device selected from the procedure described on (1), we adopted the following ILP formulation for the PCB maintenance.

$$\text{maximize} \sum_{i=1}^{N} k_i \cdot y_i \qquad \text{s.t. } t + \sum_{i=1}^{N} J_i \cdot y_i \leq BC \tag{2}$$

The variable decision vector related with a PCB comprising N distinct types of electronic components that require replacement. In the context of variable vector y, k_i represents the weight assigned to each variable denoting the frequency of replacement for different parts of the PCB. On the other hand, J_i refers to the purchase price of each part, expressed in (€), while t and BC are the fixed repair cost and maximum customer budget also expressed in (€).

The issue of PCB maintenance can be expressed as a comprehensive linear programming problem, with a fixed repair cost t, while the variable BC represents the maximum available customer's budget. Table 2 shows the simulation appliances' mean energy consumption in kWh, failure factor, and weight. These values are experimentally measured. We assume 500 (€) monthly energy consumption for simulation purposes.

Table 2: Mean energy consumption, failure factor and weight of the household appliances.

Appliance	α_i	b_i	w_i
Washing machine	132.300	0.153	20.193
Dishwasher	46.875	0.230	10.802
Refrigerator	60.000	0.036	2.1474
Tumble-dryer	112.500	0.267	30.089
Oven	117.000	0.310	36.110

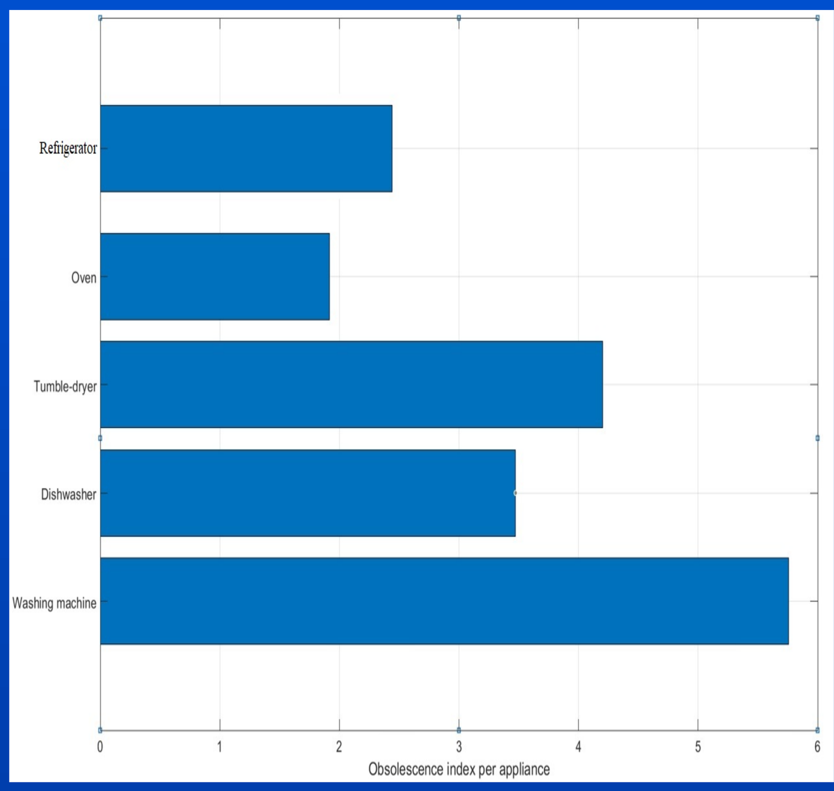

Figure 3: Obsolescence index per appliance for the simulated case.

Figure 3 shows eq. (1) simulation results. Washing machines are the most vulnerable. PCB maintenance used the ILP formulation of eq. (2) to quantify the device with the highest vulnerability. Since the washing machine has three PCBs, Table 3 shows the type, number, and cost of components per PCB. The maximum customer budget, BC, is 60 €, and the fixed repair cost, t, is 25 €. Figure 4 depicts PCB components based on the maximum washing machine budget. "Relay" is the most often replaced PCB component.

Table 3: Type, no. and cost of components per PCB

Type of component	Number of components	J_i (€/item)	k_i	PCB
Capacitor	3	1.27	0.78	
Resistor	4	2.23	0.75	#1
Triac	3	3.18	0.75	
Push-ButtonMicroSwitch	7	0.72	0.78	
Relay	4	1.57	0.75	#2
A.C-Thyristor	6	1.72	0.78	
Diode Rectifier	3	0.82	0.75	#3
Capacitor	3	1.27	0.76	

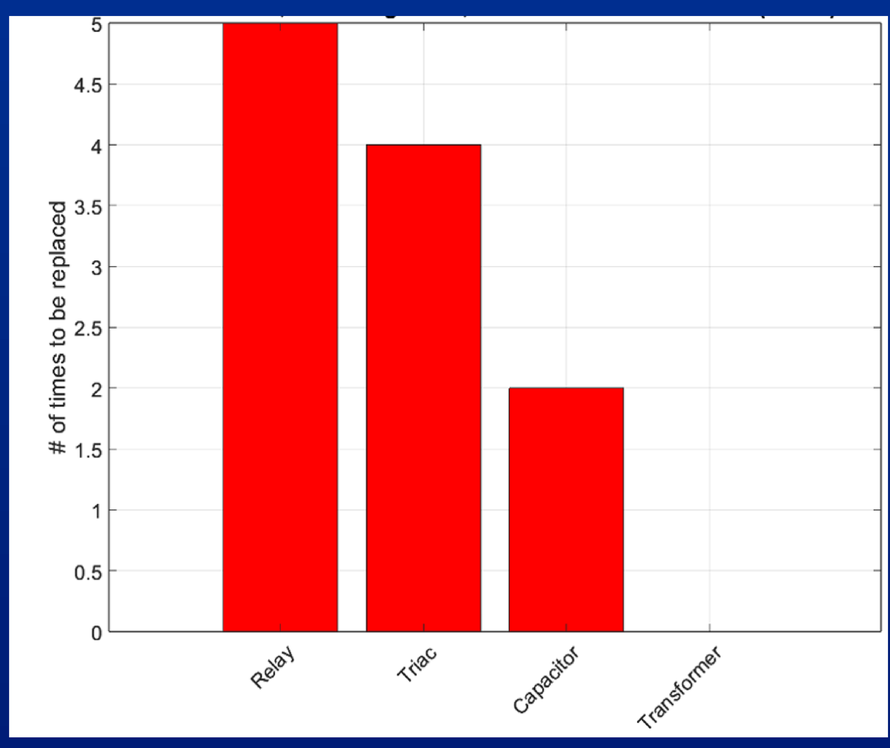

Figure 4: Graphical representation of PCB components considering the max. consumer budget for the washing machine.

Conclusions

This work uses a simple and extensible ILP-based strategy to optimize a linear objective function related to a household's obsolescence of home equipment. This inequality-constrained optimization keeps energy usage below a threshold. A washing machine, dishwasher, refrigerator, tumble-dryer and oven were used to test the proposed procedure. The washing machine was shown to be the most vulnerable household device. The current method focuses on PCB maintenance, taking into account the impact of deterioration-related malfunctions as measured by measurements, and aims to maximize the device's longevity while complying with a client's limited financial resources and the costs of repairing and replacing its parts.