Repair and recycling of PCBs and their components considering energy consumption

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Abstract

The goal of the current study is to optimize a linear objective function related to the domestic appliances of a home in terms of their obsolescence. It introduces an ILP-based approach that is both straightforward and extensible. This optimization ensures that the overall energy usage stays below a predetermined level while being subject to an inequality constraint. A household with five domestic appliances a washing machine, a dishwasher, a refrigerator, a tumble dryer, and an oven—was used to effectively test the proposed methodology. The washing machine is clearly the most dangerous residential equipment, according to the findings. The goal of the current methodology is to maximize the benefit to the device's longevity while taking into account the client's limited financial resources and the costs involved in repairing and replacing its component parts. It focuses on the maintenance of printed circuit boards and takes into account the impact of their degradation-related malfunctions as measured by tests. In a subsequent phase, we apply another ILP approach to determine which of the components should be replaced if a customer has a restricted budget to work with in order to further quantify the vulnerability of these washing machine PCB components.

Keywords: domestic appliances, energy consumption, failure factors, obsolescence.

1. Introduction

Energy consumption models suggest that during the next 30 years, global demand would rise by about 50%, barring significant policy or technology advancements. The world's main energy sources will still be petroleum and other liquid fuels in 2050, but renewable energy sources like solar and wind will grow at a similar rate. The generation of sustainable energy will increase as a result of falling technology costs and government initiatives that support resources in order to fulfil rising energy demands. The fastest-growing energy source for all economies will therefore be renewable energy. Although it is anticipated that some countries will use less carbon and nuclear energy, consumption of coal and nuclear energy is expected to increase in the remaining nations [1]. The annual million-ton growth in the total global consumption of electronic and electrical appliances accounts for a significant portion of the energy used globally. Because of extraordinary technological advancements and rapid expansion in numerous fields, the amount of public and commercial electrical items per inhabitant has expanded significantly during the past three decades. Electric and electronic output have significantly increased as a result of the rapid decline in the average life expectancy of electrical gadgets. The United Nations University (UNU) estimates that 41.8 million metric tons of waste electrical and electronic equipment (WEEE) were produced globally in 2014. (Mt). EEE manufacturing is a demanding industry for both expensive and precious metals, which are used in a variety of combinations and in smaller amounts per unit. The precious metals included in these outdated household appliances should be recovered by both developed and developing countries [2]. With a projected yearly growth rate between 3% and 5%, WEEEs are currently regarded as one of the fastest waste streams on the planet, necessitating significant disposal techniques. Techniques for reducing business and industry environmental effect include reducing, reusing, recycling, and recovering [3], [4]. Recycling household electrical appliances may result in a decrease in the production use of natural resources, hence reducing the impact on the environment [5]. Recycling is widely acknowledged as a key component of the shift toward ecological sustainability in waste management activities in the European Union (EU). As a result, many governmental initiatives, such as the WEEE rules, have been created to establish weight-based requirements for recovery, reuse, and recycling. Furthermore, a more comprehensive approach is required to increase efficiency due to the rising relevance of raw material acquisition [6]. In addition, due to the startlingly quick increase in the volume of waste produced each year, management of electronic waste (or "E-waste") has been emphasized as a significant global concern [7]. A method for developing sustainable production and consumption, the circular economy (CE) is touted as a replacement for the previous linear economic structure. The CE strategy is a method for increasing the longevity of consumer preferences by optimizing product lifespans. A recent legislative proposal in the EU made an effort to address this problem by promoting resource reuse, trash minimization, and extensive recycling. This method of treating WEEE, which is thought of as an urban storehouse of diverse metals, particularly valuable metals and elements of rare earths, is incredibly interesting. The main objective of WEEE management strategies, which have attracted a lot of attention recently due to the waste's rising production, is metal recovery. But there is a lot of room for growth in order to ensure the overall sustainability of WEEE administration [8]. Reusing materials and prolonging the life of equipment are two of the most economical methods for resource preservation. In terms of its benefits to the environment, the economy, and society, reusability may be described as an alternative to recycling or disposing of a given product [9]. Strong statistical hypotheses in favour of home reuse could result in the usage of over 33% fewer raw materials [10]. By recycling old household appliances, energy consumption will drop by 12 percent. The Energy Information Administration (EIA) estimates that 1.8% of all power used in homes in the United States comes from appliances [11]. On the other hand, reducing the lifespan of appliances for social and practical reasons results in more resource depletion and waste [12].

2. Analysis of Domestic appliances Printed Circuit Board’s

A household appliance, also referred to as a domestic or electric appliance, is a device designed to assist with food preparation, cleaning, and food preservation. There exist three primary categories of household appliances, namely small appliances, large appliances, and consumer electronics. The diverse array of these devices positions the associated field as a rapidly expanding industry. In the contemporary era, the worldwide market for household appliances has experienced a compound annual growth rate (CAGR) of 10%, resulting in an increase from $551.29 billion in 2022 to $606.58 billion in 2023. According to reference [13], the manufacturers with the highest total sales are depicted in Figure I, which pertains to the global market.

Considering the energy consumption of domestic appliances, washing machines, dishwashers, refrigerators and ovens, accounts up the largest percentage of the electricity cost for most households. Every appliance has an associated power rating, which is typically expressed in watts (W) or kilowatts (kW) (1 kW = 1000 W). It needs this much electricity in order to operate. The duration of devices’ persistence influences the amount of electrical energy required.

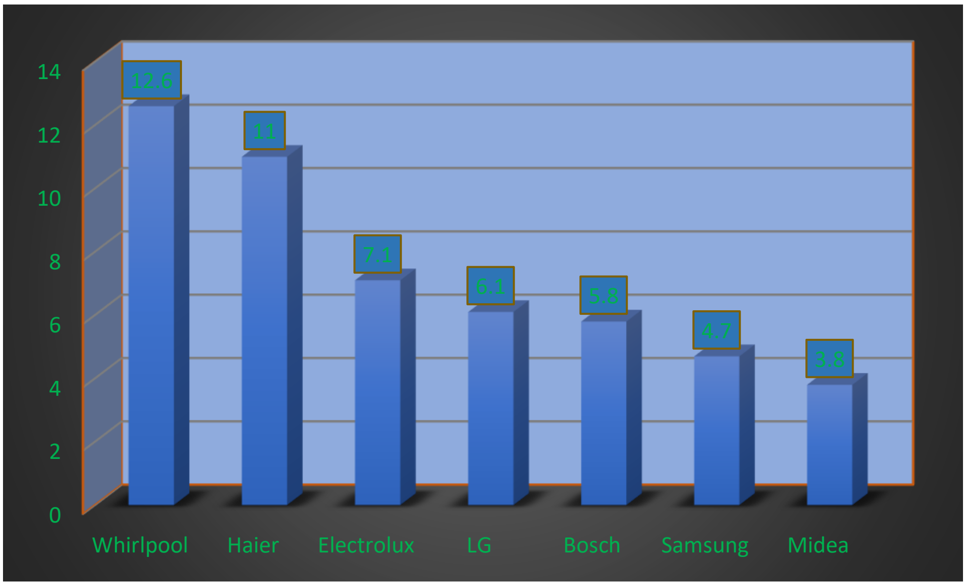

Fig. I. Total sales percentage for home appliances industry.

For example, the refrigerator has a low wattage but consumes a lot of power because it is always in use. And even though an oven is only occasionally used, it will consume a lot of electricity because it takes a lot of energy to heat it up. Table I [14] 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 I. Domestic appliances and corresponding average power ratings.

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

3. Proposed Methodology

This work proposes a methodology for assessing the obsolescence of electrical appliances considering failure factors and energy consumption. More specifically, we introduce the following integer linear programming (ILP) formulation that permits to classify the obsolescence of household electrical devices.

$$\begin{gathered}\text{maximize } \sum \mathbf{1} \cdot \boldsymbol{x} \\ s.t. f(\boldsymbol{x}) = \sum w_i \cdot x_i \leq B\end{gathered} \tag{1}$$

where $\boldsymbol{x} = (x_1, ..., x_n)^{\mathrm{T}}$ 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. $f(\boldsymbol{x})$is an energy consumption function, B is the total energy consumption of a household for a specific time interval and $w_i = a_i \cdot b_i$ is a weight related with the obsolescence of the ith device. Note that a_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.

$$\begin{gathered} \text{maximize } \sum_{i=1}^{N} k_i \cdot y_i \\ st \\ t + \sum_{i=1}^{N} J_i \cdot y_i \leq BC \end{gathered} \tag{2}$$

The variable decision vector related with a printed circuit board 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 euros (€). 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.

4. ILP background

An integer programming problem refers to a type of mathematical optimization or feasibility program that involves constraints on one or more variables, requiring them to take on integer values exclusively. The term is often used to denote the practice of integer linear programming (ILP) within various contexts. In ILP, the objective function and constraints, excluding the integer constraints, are expressed linearly. The problem of integer programming has been proven to be NP-complete. The 0-1 integer linear programming problem is a special case in which the unknowns are binary and only the constraints need to be satisfied.
The canonical form and the standard form are two distinct forms in integer linear programming. The canonical form of an integer linear program is represented as follows (it should be noted that the decision variable is the *x* vector):

$$\begin{aligned} &\max\, c^T x \\ &\quad Ax \leq b \\ &s.t \quad x \geq 0 \\ &\quad x \in \mathbb{Z}^n \end{aligned} \tag{3}$$

where $c \in \mathbb{R}^n$, $b \in \mathbb{R}^m$ are vectors and $A \in \mathbb{R}^{mxn}$ is a matrix.

5. Simulation Results

To prove the efficacy of the proposed formulation, we have implemented a scenario considering the certain typical domestic appliances of a household. An Intel(R) Core (TM) i7-2600K CPU running at 3.4 GHz and 16 GB of RAM was used to construct the suggested technique in MATLAB environment [15].
Table II presents the values for mean energy consumption in *kWh*, failure factor and weight of the household appliances used for simulation purposes. Note that these values based on experimental tests and measurements.
For simulation reasons we also assume that the total energy consumption for one month is equal to 500 €.
Figure II show the simulation results considering the formulation of eq. (1). It is obvious that the most vulnerable appliance is the washing machine.
In order to provide additional quantification regarding the device with the highest level of vulnerability as outlined in step (1), the ILP formulation of eq. (2) was utilized for PCB maintenance purposes.

Table II. 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

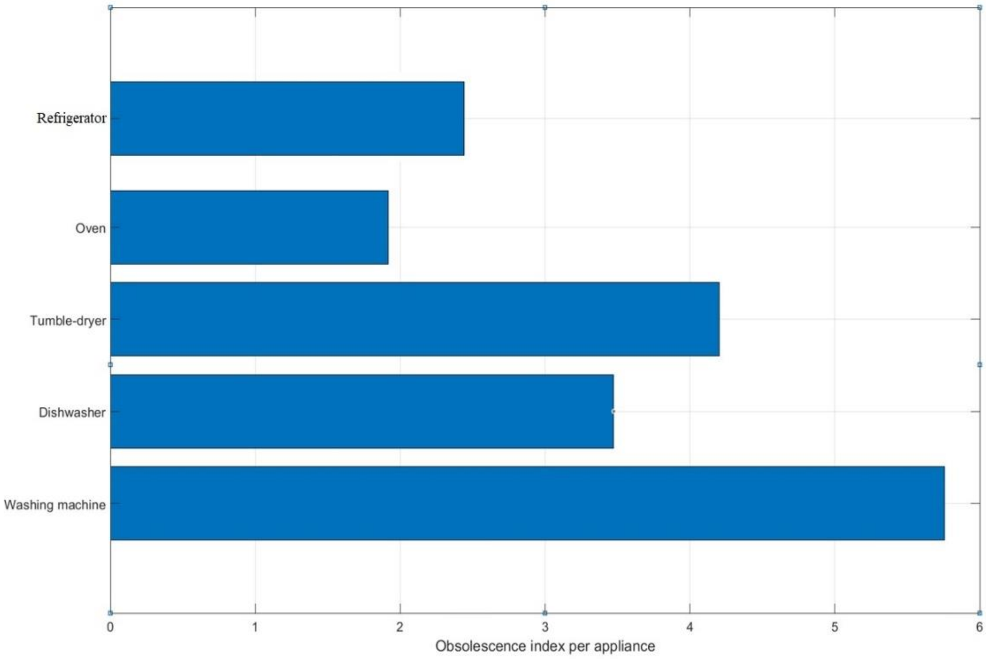

Fig. II. Obsolescence index per appliance for the simulated case.

More specifically, considering that the washing machine includes three PCBs, the Table III presents the type, number and cost of components per PCB. The fixed repair cost, *t*, is selected equal to 25 €, while the maximum available customer's budget, *BC*, is also selected equal to 60 €.

Table III. Type, number and cost of components per PCB

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

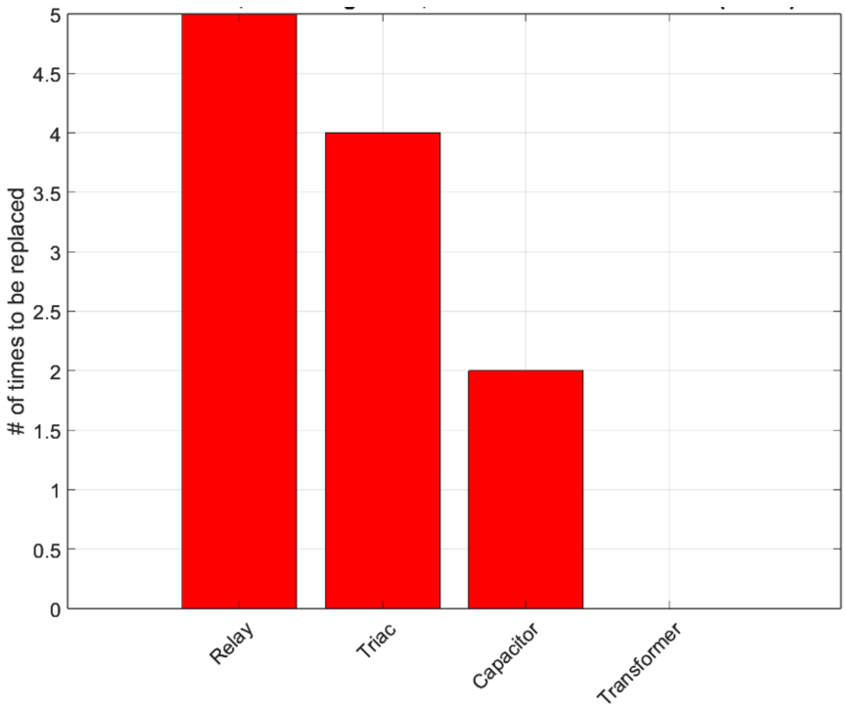

Fig. III. Graphical representation of PCB components considering the maximum consumer budget for the washing machine.

Figure 3 shows a graphical representation of PCB components considering the maximum consumer budget for the washing machine. Moreover, the most frequently PCB component to be replaced is the “relay”.

6. Conclusions

The present study introduces an ILP-based approach that is both simple and adaptable, aimed at optimizing a linear objective function linked to the domestic appliances of a household in terms of their obsolescence. This optimization is subject to an inequality constraint, while simultaneously guaranteeing that the overall energy consumption remains below a predetermined threshold. The proposed methodology was successfully tested considering a household including five domestic appliances, namely washing machine, dishwasher, refrigerator, tumble-dryer and oven. From the results it is proven that the most vulnerable domestic appliance is the washing machine. The present methodology centers on the maintenance of printed circuit boards, with consideration given to the impact of their deterioration-related malfunctions as gauged by measurements, and aims to maximize the advantage to the device's longevity, while complying with a client's limited financial resources, as well as the expenses associated with repairing and replacing its constituent parts. In a next step, to further quantify the vulnerability of this washing machine PCB components, we use another ILP approach to find out which of the components should be changed if a client has a limited budget to work with.

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