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# Decision Support Model for Evaluating Alternative Waste Electrical and Electronic Equipment Management Schemes—A Case Study

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**Abstract:** Waste of electrical and electronic equipment (WEEE) is a constantly increasing component of the total volume of municipal solid waste. E-waste streams are expected to continue escalating in the near future. The underlining paradox lies in the fact that end-of-life electrical and electronic equipment constitute a critical waste stream owing to the contained hazardous and toxic elements, but they also present an important source of valuable raw materials. Therefore, identification of alternative scenarios for integrated WEEE management is imperative. To that end, this research develops a methodological approach that focuses on determining the optimal WEEE management scheme, among available alternatives, applicable to the specific case of Greece. In particular, a binary linear programming model is formulated that maximizes the performance of 9 alternative WEEE management scenarios. The mathematical model considers 12 performance assessment criteria identified across financial, technical, social, and environmental dimensions. Priority levels are assigned to each criterion based on the input of 19 involved experts. A range of "what-if" analyses indicate that mechanical recycling of WEEE, in tandem with exporting of residues, is the most efficient e-waste management strategy in the case of Greece. The research findings indicate that the joint cooperation of all stakeholders, together with political will and effectiveness, is required for the integrated WEEE management at a national level.

**Keywords:** waste electrical and electronic equipment; e-waste management; decision support model; mathematical programming; Greece

## 1. Introduction

Manufacturing of electrical and electronic equipment has emerged as one of the fastest growing industrial sectors during the last decades [1,2], mainly because of the transition towards digitalization and the 'appetite' of consumers for technology-driven applications. This trend has resulted in a rapid increase in the amount of waste of electrical and electronic equipment (WEEE) generated internationally, hence raising environmental concerns relating to both the production and use phase of products [3–6]. Indicatively, the global amount of WEEE generated in 2016 was about 44.7 million tons, or 6.1 kg per inhabitant, while projections foresee that WEEE volumes will amount to 52.2 million tons by 2021, corresponding to 6.8 kg per inhabitant [7]. From an economic point of view, the value of raw materials

present in WEEE was evaluated at approximately €55 billion in 2016 [7]. However, only 20% (about 8.9 million tons) of the generated WEEE is collected and properly managed [7].

In this light, the environmental management of e-waste streams is of the upmost importance because WEEE: (i) presents a constantly increasing component of the total volume of municipal solid waste [8,9]; and (ii) is composed of valuable, scarce, and hazardous materials [10–15]. In order to reduce the related waste management cost, in the European Union the Original Equipment Manufacturers established Producer Responsibility Organizations (PROs) which are nonprofit organizations with the responsibility to manage electrical and electronic equipment at the end of their useful life [16].

Integrated management of WEEE streams is feasible, despite the underlining technical complexity. Efficient management of such particular wasted material assumes the consideration of a number of financial, environmental, technical, and social criteria; the cooperation of all involved stakeholders, along with political will and effectiveness, is also imperative [17]. To that end, alternative regulations and practices for sustainable e-waste management exist, from reuse and recycling to the recovery of valuable and scarce materials [18], rather than landfilling and exporting to developing countries [19].

Selection of an optimal scenario for WEEE management, under specific constraints, involves a critical decision-making process for ensuring optimal efficiency. The principles of reuse, recycling, and recovery need to be incorporated into any efficient WEEE management scheme to decrease environmental impact and avoid depletion of natural resources. In addition, WEEE schemes need to ensure that recycling fees for electrical and electronic equipment entering the market remain at affordable rates for the consumers. In this context, several mutually conflicting criteria (e.g., financial, technical, social, and environmental) need to be assessed in order to identify the best available compromise. In this regard, leveraging the technical expertise and knowledge of key stakeholders is crucial to inform the decision-making process over WEEE management, particularly in specific national or regional settings.

In particular, Greece, a country with a gross domestic product severely affected by the financial crisis in 2008, presented a drastically reduced WEEE generation rate over the post-crisis era [20]. The Greek law adopted the EU Directive 2002/96/EC for WEEE management, as outlined by the Presidential Decree 117/2004: "Alternative Management of the Waste of Electrical and Electronic Equipment". This Directive aims to: (i) prevent the generation of WEEE; (ii) reduce the generated e-waste volumes by encouraging reuse; (iii) reduce the resulting WEEE volumes through introducing quotas for collection, recovery, and recycling; and (iv) reduce the amount of hazardous substances present in WEEE. However, only 41.4% of the generated WEEE was collected, based on statistics available for 2016; the country can be regarded as a low performer in terms of WEEE collection rate considering that the corresponding average rate in Europe was 45% [21].

In this research we develop a methodological approach that focuses on the determination of the optimal WEEE management scheme among alternative options, namely: (i) recycling; (ii) reuse; (iii) disposal; and (iv) export. The analysis is based on the quantification of a number of mutually conflicting performance assessment criteria (across financial, technical, social, and environmental dimensions) and the selection of the optimal WEEE management scenario with the use of mathematical programming. The proposed mathematical model considers a priority level assigned to each performance criterion, based on the input of interviewed experts. The developed methodology is demonstrated through its application to the case of Greece with the aim to address the following research questions:

- Research Question 1—What is the mathematical formulation of a decision support model for the assessment of alternative WEEE management scenarios under specific criteria?
- Research Question 2—What are recommended performance criteria for the assessment of alternative WEEE management schemes?
- Research Question 3—Which could be a viable WEEE management strategy for the case of Greece?

To respond to Research Question 1, we identified 9 potential scenarios for the management of WEEE across the alternative options of recycling, reuse, disposal, and exporting. Thereafter, a binary linear programming model was developed to optimize the performance of the identified scenarios. In response to Research Question 2, the developed mathematical program was optimized in terms of 12 selected criteria, under functional constraints. The assessment criteria are identified at the financial, technical, social, and environmental domains. Furthermore, to address Research Question 3, we contacted 19 experts in the field of WEEE management in Greece, and we performed "what-if" sensitivity analyses through 18 different cases; the latter cases emanated from alternative combinations of performance coefficients, as described in Section 4.

This research contributes to the Operations Research field by providing a binary linear programming model for the assessment of alternative WEEE management scenarios via capturing a range of assessment criteria. In addition, each performance criterion is assigned a priority level based on input from key informants. The extant literature over WEEE management documents that studies elaborating mathematical programming are rather myopic in scope, hence providing opportunities for further and more inclusive research [22]. Additionally, performance assessment of alternative WEEE management scenarios for the case of Greece, through mathematical programming capturing diverse evaluation criteria, poses an original research contribution. Existing studies for the case of Greece are either empirical [23] or focus only on retrieving an optimal solution with regard to: (i) location of waste treatment plants [1]; (ii) transportation cost [17,24]; and (iii) management cost that captures operational perspectives [25].

The rest of this paper is organized as follows. Section 2 presents the materials and methods relevant to this research. In particular, the parameters and variables of the proposed decision support mathematical model are detailed, while 9 examined WEEE management scenarios capturing 12 performance assessment criteria are exemplified. Section 3 presents the performance evaluation of alternative WEEE management scenarios in terms of the selected criteria. Section 4 explores "what-if" sensitivity analyses of the optimal solution and briefly discusses the insights of this research. Conclusions, implications for practice, limitations, and future research perspectives are discoursed in the final Section 5.

## 2. Materials and Methods

The methodological framework along with the decision support model, application scenarios, and assessment criteria pertinent to this research are exemplified in the subsections that follow. The methodological approach underpinning this research provides an easy-to-use decision support tool for policymakers, institutional actors, and relevant stakeholders regarding the assessment of alternative WEEE management policies. The developed mathematical model can be adapted to capture the specific WEEE management characteristics relevant to the specific requirements and prioritization of performance assessment criteria in selected regional settings.

### *2.1. Methodological Framework*

The development of WEEE management systems has not been homogeneous but varies depending on every country's special characteristics, particular requirements, and existing infrastructure [26–31]. In addition, a constantly increasing number of developing countries are prohibiting imports of WEEE within the context of the Basel Convention [19], a typical strategy explored by developed economies thus far, hence motivating the establishment of robust national and/or local WEEE management systems [32]. In this setting, a structured conceptual framework for the identification of the optimal WEEE management scheme among available alternatives is herein presented. The approach was based on the quantification of a number of mutually conflicting parameters and the hierarchical ranking of a number of different WEEE management scenarios based on the characteristics of the area under study with the use of a decision support model. The adopted conceptual framework for the evaluation of alternative WEEE management scenarios is illustrated in Figure 1.

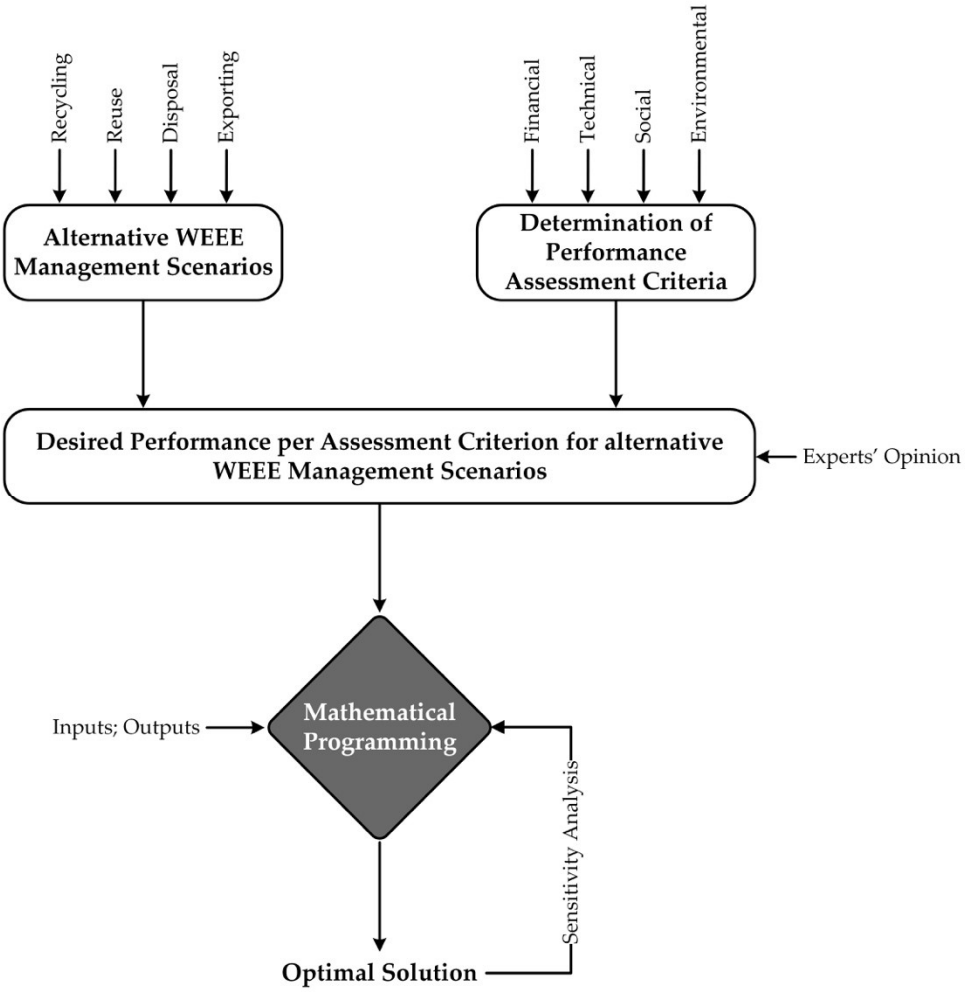


**Figure 1.** Methodological framework for the evaluation of alternative waste of electrical and electronic equipment (WEEE) management scenarios.

At the first step, alternative WEEE management scenarios were identified with reference to recycling, reusing, disposing, and exporting [18]. In fact, 9 application scenarios were identified based on the concepts of WEEE management (as detailed in Section 2.3), namely: (i) recycling ($Rec_1$–$Rec_3$, three scenarios); (ii) reuse ($Reu_1$–$Reu_2$, two scenarios); (iii) disposal ($Disp_1$–$Disp_2$, two scenarios); and exporting ($Exp_1$–$Exp_2$, two scenarios). The alternative scenarios were then evaluated on a range of multiple criteria to enable robust a decision-making process [33]. Typically, such criteria cover financial [34,35], technical [1,36], social [1,35], and environmental [34,35] constituents. In this research, we identified 4 financial criteria, 3 technical criteria, 2 social criteria, and 3 environmental criteria that were captured in the proposed mathematical program to support the operationalization of the results. These assessment criteria were determined at the initial stage of the methodological process. Other common methodology used in the hierarchical evaluation of WEEE management schemes refers to data envelopment analysis (DEA) [33]; however, the use of DEA was out of the scope of this research. In addition, in DEA methodology the results are sensitive to the selection of inputs and outputs.

Thereafter, the quantification of the criteria for the performance evaluation of the selected scenarios is realized either quantitatively, by statistical analyses, or qualitatively, through interviewing experts in the field. Owing to the lack of quantitative information for the assessment of the 9 identified scenarios (i.e., $Rec_1$, $Rec_2$, ... , $Exp_2$) for the 12 different criteria, we performed a qualitative assessment. Towards this direction, in order to assess the different criteria for the selected scenarios, 19 experts were interviewed in 2 rounds following a Delphi approach. The informants, who represented expertise on the waste management field from academia, industry, and the public sector, qualitatively assessed

the proposed scenarios on a scale from 1 to 10. Moreover, the involved experts critically evaluated the priority of each criterion (i.e., assigning priority levels from 1 to 3) for the overall effectiveness of the scenarios.

Following, a mathematical model was formulated, which was further solved based on the aforementioned performance assessment criteria in order to identify the optimal WEEE management scenario. The robustness of the elaborated decision-making process was further supported by a sensitivity analysis over the alternative WEEE management scenarios.

### 2.2. Decision Support Model

In this subsection, we present the proposed decision support model that addressed the optimal selection of WEEE management scenarios under specific criteria. The objective function of the proposed mathematical program aims to maximize the performance of the system by selecting the most appropriate WEEE management scenario. To this effect, multiple groups of constraints are considered, while assessment criteria are identified and divided into input and output variables; the assessment criteria are further categorized into 3 priority levels (high priority level—level 1; medium priority level—level 2; and low priority level—level 3). Below, we provide the related nomenclature of the mathematical model:

$$i = 1, \ldots, I\text{: alternative solutions}$$

and

$$j = 1, \ldots, J\text{: priority levels.}$$

In Tables 1 and 2 we provide the nomenclature for the decision variables and the parameters of the model, respectively.

**Table 1.** Nomenclature for the decision variables.

| Variable | Definition |
|---|---|
| $Y_i$ | Binary decision variable that determines the selection or not of solution $i$:<br>$Yi = 0$ the solution $i$ is not recommended<br>$Yi = 1$ the solution $i$ is proposed |

**Table 2.** Nomenclature for the parameters of the model.

| Parameter | Definition |
|---|---|
| $G_j^{in^+}$ | Desired value for input criteria with positive effect ($in^+$) in priority level $j$ |
| $G_j^{in^-}$ | Desired value for input criteria with negative effect ($in^-$) in priority level $j$ |
| $G_j^{out^+}$ | Desired value for output criteria with positive effect ($out^+$) in priority level $j$ |
| $G_j^{out^-}$ | Desired value for output criteria with negative effect ($out^-$) in priority level $j$ |
| $P_{ij}^{in^+}$ | Performance of solution $i$ in input criteria with positive effect ($in^+$) in priority level $j$ |
| $P_{ij}^{in^-}$ | Performance of solution $i$ in input criteria with negative effect ($in^-$) in priority level $j$ |
| $P_{ij}^{out^+}$ | Performance of solution $i$ in output criteria with positive effect ($out^+$) in priority level $j$ |
| $P_{ij}^{out^-}$ | Performance of solution $i$ in output criteria with negative effect ($out^-$) in priority level $j$ |
| $M$ | A very large number (compared to the other parameters of the model) |
| $e_j$ | Coefficient with a domain 0 to 1 |

Consequently, the following binary linear programming model is formulated:
Maximize:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Y_i \cdot \left(1 - \frac{P_{ij}^{in-}}{G_j^{in-}}\right) + \sum_{i=1}^{I}\sum_{j=1}^{J} Y_i \cdot \left(\frac{P_{ij}^{in^+}}{G_j^{in^+}} - 1\right) \sum_{i=1}^{I}\sum_{j=1}^{J} Y_i \cdot \left(1 - \frac{P_{ij}^{out^-}}{G_j^{out^-}}\right) + \sum_{i=1}^{I}\sum_{j=1}^{J} Y_i \cdot \left(\frac{P_{ij}^{out^+}}{G_j^{out^+}} - 1\right)$$

Subject to:

$$\sum_{i=1}^{I} Y_i = 1; \quad (1)$$

$$P_{i1}^{in^-} \cdot Y_i \le G_1^{in^-}, \ \forall i \text{ in priority level } 1; \quad (2)$$

$$P_{i1}^{out^-} \cdot Y_i \le G_1^{out^-}, \ \forall i \text{ in priority level } 1; \quad (3)$$

$$(1 - Y_i) \cdot M + P_{i1}^{in^+} \ge G_1^{in^+}, \ \forall i \text{ in prioritey level } 1; \quad (4)$$

$$(1 - Y_i) \cdot M + P_{i1}^{out^+} \ge G_1^{out^+}, \ \forall i \text{ in priority level } 1; \quad (5)$$

$$e_j \cdot P_{ij}^{in^-} \cdot Y_i \le G_j^{in^-}, \ \forall i \text{ in priority level } j = 2, \ldots, J; \quad (6)$$

$$e_j \cdot P_{ij}^{out^-} \cdot Y_i \le G_j^{out^-}, \ \forall i \text{ in priority level } j = 2, \ldots, J; \quad (7)$$

$$(1 - Y_i) \cdot M + P_{ij}^{in^+} \ge G_j^{in^+}, \forall i \text{ in priority level } j = 2, \ldots, J; \quad (8)$$

$$(1 - Y_i) \cdot M + P_{ij}^{out^+} \ge G_j^{out^+}, \forall i \text{ in priority level } j = 2, \ldots, J; \quad (9)$$

$$Y_i \in \langle 0 , 1 \rangle. \quad (10)$$

More specifically, constraint (1) ensures that only one scenario is selected. The group of constraints (2)–(5) dealt with high priority level criteria. In particular, inequality (2) dictates that the performance of the selected solution $i$ in input criteria with negative effect ($in^-$) in priority level 1 is less than the desired value for the specific criteria. Inequality (3) ensures that the performance of the selected solution $i$ in output criteria with negative effect ($out^-$) in priority level 1 is less than the desired value for the specific criteria. Inequality (4) dictates that the performance of the selected solution $i$ in input criteria with positive effect ($in^+$) in priority level 1 is greater than the desired value for the specific criteria, while inequality (5) ensures that the performance of the selected solution $i$ in output criteria with positive effect ($out^+$) in priority level 1 is greater than the desired value for the specific criteria.

Furthermore, the group of constraints (6)–(9) consider low priority level criteria. Especially, inequality (6) dictates that the performance of the selected solution $i$ in input criteria with negative effect ($in^-$) in low priority levels multiplied by a predefined coefficient is less than the desired value for the specific criteria. Furthermore, inequality (7) ensures that the performance of the selected solution $i$ in output criteria with negative effect ($out^-$) in low priority levels multiplied by a predefined coefficient is less than the desired value for the specific criteria. Inequality (8) dictates that the performance of the selected solution $i$ in input criteria with positive effect ($in^+$) in low priority levels is greater than the desired value for the specific criteria multiplied by a predefined coefficient. In addition, inequality (9) ensures that the performance of the selected solution $i$ in output criteria with positive effect ($out^+$) low priority levels is greater than the desired value for the specific criteria multiplied by a predefined coefficient. Finally, (10) is the binary constraint.

### *2.3. Application Scenarios*

The presented methodological framework and the developed mathematical model were implemented for the case of Greece. Alternative WEEE management scenarios are briefly described in Table 3. In total, 9 scenarios were assessed. The scenarios were characterized by 4 discrete basic concepts regarding the management of WEEE, namely:

- Recycling (Scenarios $Rec_1$–$Rec_3$)
- Reuse (Scenarios $Reu_1$–$Reu_2$)
- Disposal (Scenarios $Disp_1$–$Disp_2$)
- Exporting (Scenarios $Exp_1$–$Exp_2$).

**Table 3.** Alternative WEEE management scenarios.

| E-Waste Management Concept | Scenario | Description—Process Flow |
|---|---|---|
| Recycling | $Rec_1$ | Collection of e-waste → Recycling and recovery of useful and precious quantities → Disposal of residues in landfills |
| | $Rec_2$ | Collection of e-waste → Recycling and recovery of useful and precious quantities → Incineration of residues |
| | $Rec_3$ | Collection of e-waste → Recycling and recovery of useful and precious quantities → Export of hazardous waste and residues |
| Reuse | $Reu_1$ | Collection of e-waste → Control of reusability → Recovery of devices or components → Disposal of residues in landfills or incineration |
| | $Reu_2$ | Collection of e-waste → Control of reusability → Recovery of devices or components → Recycling-disposal of residues in landfill or incineration |
| Disposal | $Disp_1$ | Collection of e-waste → Disposal in landfills |
| | $Disp_2$ | Collection of e-waste → Incineration |
| Exporting | $Exp_1$ | Collection of e-waste → Export of collected quantities for further processing |
| | $Exp_2$ | Collection of e-waste → Recovery of reusable materials and components → Export of non-reusable material |

### 2.4. Assessment Criteria

In order to compare the 9 alternative WEEE management scenarios on their efficiency, 12 criteria were selected. The criteria were categorized into 4 basic thematic areas, namely financial, technical, social, and environmental. The criteria selected are depicted in Table 4. As discussed in Section 2.2, the assessment criteria were divided into input and output variables and were further categorized into 3 priority levels. To that end, in the case under study, criteria $F_1$–$F_3$ and $T_1$–$T_2$ were considered as inputs to the decision support model, while criteria $F_4$, $T_3$, $S_1$–$S_2$, and $E_1$–$E_3$ were outputs. The priority levels provided in Table 4 were an outcome of the engagement with 19 interviewed experts. In order to allocate a priority level to each criterion, the mode values of the 19 responses were taken into account.

**Table 4.** Selected assessment criteria.

| Thematic Area | Criterion | Description of Criterion | Type | Priority Level |
|---|---|---|---|---|
| Financial | $F_1$ | Investment cost | Input (−) | 1st |
| | $F_2$ | Operational cost | Input (−) | 2nd |
| | $F_3$ | Collection cost | Input (−) | 2nd |
| | $F_4$ | Profit from reused products | Output (+) | 2nd |
| Technical | $T_1$ | Existence of infrastructure | Input (+) | 3rd |
| | $T_2$ | Reliability and experience | Input (+) | 3rd |
| | $T_3$ | Flexibility | Output (+) | 3rd |
| Social | $S_1$ | Social acceptance | Output (+) | 1st |
| | $S_2$ | Employment opportunities | Output (+) | 3rd |
| Environmental | $E_1$ | Air, water and solid waste pollution | Output (−) | 2nd |
| | $E_2$ | Noise and aesthetics pollution | Output (−) | 3rd |
| | $E_3$ | Energy and material recovery | Output (−) | 3rd |

## 3. Results

Following the conceptual approach depicted in Figure 1, the performances of 9 alternative WEEE management scenarios were quantified for the 12 identified criteria. Moreover, for each criterion, the desired value of performance was defined. For the study needs, the views and opinions of 19 experts for the optimal WEEE management scenario for the case of Greece were assessed. Those experts, representing academia, business, collective systems, and public authorities, were asked to indicate a desired value of performance over the 12 criteria. In order to allocate a priority level to each assessment criterion the mode values of the 19 retrieved responses were taken into account to reduce bias.

The resulting optimization model consists of 9 binary variables and 22 non-negativity constraints. The mathematical model was solved on a computer with 3.6 GHz CPU and 16 GB RAM with the

use of Microsoft Solver. The computational time was a few seconds for a variety of generated problem instances, and, thus, the solution performance of the proposed model was deemed satisfactory. The resulting average performances are illustrated in Table 5. The performance assessments and the desired values for each scenario (for the selected criteria) resulted from the qualitative answers of the experts provided on a scale of 1 to 10. For example, for the criterion $F_1$ (i.e., investment cost) scenario $Rec_2$ (i.e., "Collection of e-waste → Recycling and recovery of useful and precious quantities → Incineration of residues") scored 6.7, which indicates the requirement for high capital expenditure to develop the necessary infrastructure. On the contrary, scenario $Disp_1$ (i.e., "Collection of e-waste → Disposal in landfills"), which was associated with WEEE landfilling, had an $F_1$ score of 1.2, as the required investment is not deemed substantial.

**Table 5.** Performance assessment matrix.

| Scenario | Assessment Criterion | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **$F_1$** | **$F_2$** | **$F_3$** | **$F_4$** | **$T_1$** | **$T_2$** | **$T_3$** | **$S_1$** | **$S_2$** | **$E_1$** | **$E_2$** | **$E_3$** |
| $Rec_1$ | 4.8 | 4.2 | 5.0 | 1.0 | 6.3 | 3.6 | 3.1 | 4.1 | 5.2 | 4.0 | 3.7 | 2.2 |
| $Rec_2$ | 6.7 | 5.8 | 5.1 | 1.0 | 2.1 | 1.5 | 2.8 | 2.2 | 5.4 | 2.7 | 3.1 | 4.8 |
| $Rec_3$ | 1.9 | 1.3 | 4.2 | 1.0 | 6.3 | 2.7 | 3.0 | 2.6 | 2.8 | 1.3 | 1.2 | 1.2 |
| $Reu_1$ | 2.8 | 2.2 | 6.1 | 5.3 | 1.6 | 2.3 | 3.1 | 6.7 | 6.4 | 4.2 | 3.6 | 5.4 |
| $Reu_2$ | 5.7 | 5.9 | 6.1 | 5.3 | 1.6 | 2.3 | 3.1 | 6.7 | 6.4 | 3.6 | 3.4 | 6.2 |
| $Disp_1$ | 1.2 | 1.3 | 1.0 | 1.0 | 6.8 | 3.4 | 3.5 | 1.9 | 1.2 | 7.0 | 5.2 | 1.0 |
| $Disp_2$ | 5.8 | 2.5 | 1.0 | 1.0 | 1.7 | 2.6 | 2.6 | 1.4 | 1.4 | 6.4 | 4.9 | 2.2 |
| $Exp_1$ | 3.1 | 2.0 | 5.2 | 1.0 | 6.1 | 3.1 | 3.3 | 2.4 | 1.1 | 2.2 | 2.4 | 1.0 |
| $Exp_2$ | 3.6 | 5.1 | 6.1 | 5.3 | 1.6 | 2.3 | 3.1 | 6.4 | 6.2 | 4.0 | 3.2 | 5.8 |
| Desired value | 5.2 | 4.0 | 4.0 | 1.05 | 2.0 | 2.3 | 3.0 | 2.5 | 1.6 | 4.4 | 4.3 | 4.4 |

## 4. Discussion

Scenarios involving the co-incineration of WEEE (i.e., $Rec_2$, $Disp_2$) require a considerably high investment cost which is attributed to the lack of relevant national infrastructure. Moreover, collection cost is highly polarized between the recycling/reuse/export-based scenarios and the disposal-based ones considering that in the later scenarios e-waste could be collected in bulk, thus significantly reducing the relevant cost. Similarly, reuse-based scenarios (i.e., $Reu_1$ and $Reu_2$) as well as scenario $Exp_2$, which promote the reuse of components/equipment before exporting the majority of WEEE quantities to other countries for further processing, present high values in terms of profit from reused products (criterion $F_4$). These scenarios also demonstrate good performance in regard to their social acceptance and employment opportunities. The lack of companies and bodies operating in the second-hand electronics market (i.e., reuse of components and/or equipment) in Greece, as well as the lack of previous experience in WEEE co-incineration, decrease the corresponding technical criteria values for scenarios $Reu_1$, $Reu_2$, $Disp_2$, and $Exp_2$.

An interesting "what-if" analysis involves exploring the sensitivity of the optimal solution on the values of coefficient $e$ in the second and third priority levels. More specifically, 18 different problem cases were examined by considering alternative values and combinations for:

- coefficient $e_2$ (second priority level) ranging from 0.10 to 0.95 with an increment step of 0.05;
- coefficient $e_3$ (third priority level) ranging from 0.05 to 0.90 with an increment step of 0.05.

The optimal value of the objective function along with the recommended scenario for each case are inserted in Table 6. The 'Objective Function Value' represents the outcome of the objective function, taking into account the corresponding assessments for the criteria of the evaluated scenarios. No physical interpretation can be attributed to the objective function value, but the value is calculated as a comparative indicator for the effectiveness of the different scenarios. In Table 6, only the objective function value for the optimal (most effective) WEEE management scenario is provided.

**Table 6.** 'What-if' analysis matrix.

| Case | Values for $e_2$, $e_3$ | Recommended Scenario | Objective Function Value |
|---|---|---|---|
| 1 | $e_2 = 0.10$<br>$e_3 = 0.05$ | $Reu_1$ | 8.93 |
| 2 | $e_2 = 0.15$<br>$e_3 = 0.10$ | $Reu_1$ | 8.93 |
| 3 | $e_2 = 0.20$<br>$e_3 = 0.15$ | $Reu_1$ | 8.93 |
| 4 | $e_2 = 0.25$<br>$e_3 = 0.20$ | $Reu_1$ | 8.93 |
| 5 | $e_2 = 0.30$<br>$e_3 = 0.25$ | $Reu_1$ | 8.93 |
| 6 | $e_2 = 0.35$<br>$e_3 = 0.30$ | $Reu_1$ | 8.93 |
| 7 | $e_2 = 0.40$<br>$e_3 = 0.35$ | $Reu_1$ | 8.93 |
| 8 | $e_2 = 0.45$<br>$e_3 = 0.40$ | $Reu_1$ | 8.93 |
| 9 | $e_2 = 0.50$<br>$e_3 = 0.45$ | $Reu_1$ | 8.93 |
| 10 | $e_2 = 0.55$<br>$e_3 = 0.50$ | $Reu_1$ | 8.93 |
| 11 | $e_2 = 0.60$<br>$e_3 = 0.55$ | $Reu_1$ | 8.93 |
| 12 | $e_2 = 0.65$<br>$e_3 = 0.60$ | $Reu_1$ | 8.93 |
| 13 | $e_2 = 0.70$<br>$e_3 = 0.65$ | $Rec_3$ | 6.48 |
| 14 | $e_2 = 0.75$<br>$e_3 = 0.70$ | $Rec_3$ | 6.48 |
| 15 | $e_2 = 0.80$<br>$e_3 = 0.75$ | $Rec_3$ | 6.48 |
| 16 | $e_2 = 0.85$<br>$e_3 = 0.80$ | $Rec_3$ | 6.48 |
| 17 | $e_2 = 0.90$<br>$e_3 = 0.85$ | $Rec_3$ | 6.48 |
| 18 | $e_2 = 0.95$<br>$e_3 = 0.90$ | $Rec_3$ | 6.48 |

A noteworthy insight obtained from the conducted numerical analysis is the following: for higher values of $e_2$ and $e_3$, the recommended scenario is $Rec_3$ (i.e., collection of e-waste, recycling and recovery of useful and precious quantities, and export of hazardous waste and residues), while for lower values of $e_2$ and $e_3$, the selected scenario is $Reu_1$ (i.e., collection of e-waste, control of reusability, recovery of devices or components, and disposal of residues in landfills or incinerators).

## 5. Conclusions

WEEE management is a sufficiently studied issue in the extant scientific literature; existing works approach the issue from a plethora of methodological angles depending on the research objective and the nature of the study. Indicatively, Kumar and Dixit [37] identified 7 primary barriers towards WEEE management in India and applied the decision-making trial and evaluation laboratory (commonly known as DEMATEL) method to prioritize these barriers and further unveil any underlining interdependencies. In this vein, Casey et al. [38] applied a quasi-ethnographic approach to examine the behavior of Irish consumers towards the disposal of small WEEE. Furthermore, Ismail and Hanafiah [39] reviewed a significant number of studies considering WEEE management from a life cycle assessment viewpoint.

Mathematical programming has been applied in the WEEE management field, but the scope of the extant studies varies. Indicatively, Polat et al. [40] analyzed data from recycling companies in Turkey and Germany; the authors developed a linear programming model for maximizing the profit of a multiperiod WEEE recycling operations plan under uncertainty. Moreover, Messmann et al. [41] developed a mixed integer, linear programming model that captured a European reverse network for WEEE with the objective of maximizing economic (i.e., profit generated) and environmental (i.e., raw materials used) performances. From a different standpoint, the present study contributes to the Operations Research field by proposing a binary mathematical programming model that maximizes the performance of alternative WEEE management schemes, particularly applicable to the case of Greece, while further incorporating insights of experts in the field across a range of performance criteria.

In order to support the assessment of alternative WEEE management scenarios for the case of Greece, this research grounded 3 research questions and applied alternative methodologies in an attempt to answer them. In particular, to tackle Research Question 1, a binary linear programming model is formulated that maximizes the performance of alternative WEEE management scenarios. Furthermore, in response to Research Question 2, 12 criteria are identified across 4 basic thematic areas, namely: financial, technical, social, and environmental. More specifically, the performance assessment criteria are: (i) financial—investment cost, operational cost, collection cost, and profit from reused products; (ii) technical—existence of infrastructure, reliability and experience, and flexibility; (iii) social—acceptance and employment opportunities; and (iv) environmental—air, water and solid waste pollution, noise and aesthetics pollution, and energy and material recovery. The assessment criteria are divided into input and output variables and are further categorized into 3 priority levels. Moreover, to address Research Question 3, the research findings indicate that for the case of Greece, mechanical recycling of WEEE, while contemporarily exporting of residues, is the most efficient e-waste management strategy.

### *5.1. Practical Implications*

The methodological approach proposed in this research presents an easy-to-use tool for decision-makers towards the selection of the most efficient WEEE management strategy, based on the special requirements and the already developed infrastructure in an area under study. For the case of Greece, mechanical recycling of WEEE, along with contemporarily exporting of residues, is identified as the most efficient e-waste management strategy. The selection of this scenario is mostly based on the grounds that such infrastructure (i.e., mechanical recycling of WEEE) is already in place [1] at a national level, whereas Greece lacks adequate infrastructure for managing the residues resulting from the mechanical recycling of WEEE. In this light, this particular alternative presents very good performances in terms of financial criteria (both investment and operational costs). Reduced costs would further result in proportional reduced recycling fees where customers would have to pay for purchased goods, and this would, thus, create a more competitive electrical and electronic equipment market at a national level.

The decision support model that is proposed through the presented framework takes into account financial, technical, and environmental issues as well as social concerns. Towards this direction, mechanical recycling is highly rated for its technical merits, further supported by the existence of relevant infrastructure, the reliability and experience of the relevant PROs in Greece, and the inherent flexibility of mechanical recycling to adapt to different technologies.

### *5.2. Limitations and Future Research Perspectives*

The presented decision support system is successfully implemented for the case of Greece. However, the procedure could be easily adopted—with slight modifications and adjustments to the special requirements of the problem under consideration—in order to solve similar problems in other countries. The methodological approach applied in this research is not limited to the specific field of WEEE; it can be also used in order to assist environmental managers and decision-makers

in their judgements towards the determination of optimal strategies for other waste streams (e.g., construction and demolition waste) based on their efficiency. However, such a decision-making process, notwithstanding the fact that they would not require significant changes to the proposed conceptual framework, are not included in the present paper and constitute future research topics for the authors.

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