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Article

Environmental Strategies for Electrical and Electronic Equipment Supply Chains: Which to Choose?

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Abstract: Waste electrical and electronic equipment is one of the major world-wide waste streams triggering the emergence of environmental strategies. Environmental regulations, closed-loop supply chain (CLSC) activities and design-for-environment (DfE) practices are environmental friendly strategies being implemented by governments and industry. In this paper, we apply a System Dynamics model to a CLSC of electrical and electronic equipment in Greece. Extensive numerical investigation provides insights regarding the impact of different legislative measures, CLSC activities and DfE practices on the environmental (availability of natural resources and landfills) and economic sustainability.

Keywords: sustainability; closed-loop supply chains; design-for-environment; environmental legislation; electrical and electronic equipment; System Dynamics

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1. Introduction

Recently, waste electrical and electronic equipment (WEEE) has emerged as one of the major waste streams in the World due to the market expansion and the trend for electronic products of shortening lifecycles. Moreover, the electrical and electronic equipment (EEE) industry is recognized to be responsible for 10%–20% of the overall environmental impact with regard to the depletion of non-renewable resources [1].

It is estimated that in Europe the amount of WEEE generated ranges between 6.5 and 7.5 million tons per year at an annual increase of 16%–28% [2]. In Western Europe it is expected that by 2010 the amount of WEEE will be 12 million tons [3]. Specifically, the amount of WEEE in Sweden and

Norway is about 100,000 tons per year [2]. In Germany and in United Kingdom the total amount of WEEE is 950,000 tons per year, while in France the total amount of WEEE is even larger, since it amounts to 1.7 million tons per year. In Greece the total amount of WEEE is much smaller; about 185,000 tons of WEEE have been discarded during the period 2003–2008.

Under these circumstances the importance of implementing an environmental strategy had been demonstrated. Governments all around the World are imposing stringent environmental regulations, through increased collection and recycling percentages, and industries are developing environmentally friendly activities in order to decrease the pressures from the society. Under these circumstances, closed-loop supply chain (CLSC) activities and design-for-environment (DfE) practices are examples of common environmentally friendly activities developed by enterprises.

In this paper we examine the impact of different environmental strategies, regarding legislative measures, CLSC activities and DfE practices on the sustainability of CLSCs of electrical and electronic equipment. We use a System Dynamics (SD) based model applied to a real world closed-loop supply chain with recycling and design-for-environment activities of electrical and electronic equipment in Greece. The dynamic model includes the environmental and economic dimensions of sustainability. The SD model also comprises of a broader number of characteristics that describe environmental strategies. This research incorporates important factors such as the collection and recycling percentages imposed by the WEEE legislation and the delay between the time of the imposition of WEEE legislation and the time of the firms' compliance. This work examines the significance of the environmental strategies being studied on the environmental (availability of natural resources and landfill capacity) and economic sustainability of a WEEE CLSC, and also specifies the type of their impact. The results of numerical investigation obtained by simulation runs of the SD model illustrates the potential uses of the environmental strategies in order to achieve a sustainable future and also provides insights regarding their influence on the environmental and economic sustainability of the CLSC under study.

In Section 2 the environmental strategies under study affecting the sustainability of the WEEE CLSC are presented in detail. In Section 3 we briefly present the system under study; the presentation includes the modelling approach of the economic sustainability. The model is validated by using data from a real world CLSC of EEE in Greece. The impact of the three environmental strategies on the sustainability of the WEEE CLSC is investigated through sensitivity analyses in Section 4. Finally, in Section 5 we present the conclusions of our study.

2. Environmental Strategies

Nowadays, decreased landfill availability and serious raw material scarcity are recognized as realities of our modern age. The necessity for sustainability has led to the enforcement of more stringent environmental regulations regarding the take-back and recycling activities of such waste (subsection 2.1) and the development of CLSC activities (subsection 2.2) and DfE practices (subsection 2.3).

2.1. Legislative Measures

In the USA, the European Union (EU) and Japan environmental policies exist for the recovery of WEEE and to promote sustainability. Specifically, in the EU the Directive 2002/96/EC on WEEE introduces take-back obligations and recovery quotas for the used products through collection and recycling percentages. Moreover, the regulatory measures often impose stringent landfill costs to decrease the amount of used products that end up to landfills. Companies that do not comply with the regulations will face stiff fines.

Up to now the tremendous interest in the proper recovery of WEEE, pointed out also by the governments' policies, has resulted to the development of mathematical models and the conduction of surveys that study the impact of the legislative measures on sustainability. Ylä-Mella *et al.* [2], Lehtinen and Poikela [3] and Lambert and Stoop [4] have assessed the efficiency of the EU WEEE legislation in Finland and in Netherlands. He *et al.* [5] and Yu *et al.* [6] focused their studies on China. Specifically, He *et al.* [5] estimated the efficiency of the upcoming WEEE legislation in China, while Yu *et al.* [6] studied the readiness of China for the implementation of WEEE legislation.

Georgiadis and Besiou [7] investigated the impact of the Directive 2002/96/EC (imposed collection and recycling percentages) on the CLSC's environmental sustainability through the management of natural resources usage and landfill availability. This research was extended by Georgiadis and Besiou [8] assuming also that the EU legislation imposes, besides collection percentage and recycling percentage, minimum limits for recyclability. The results of this study revealed that the imposition of this added regulatory measure decreases the rates of natural resources' usage and used products' disposal promoting the environmental sustainability. Both of these studies ignore the economic aspects of sustainability.

2.2. Closed-Loop Supply Chain Activities

A "closed-loop supply chain" is a supply chain in which at the end of the usage period the products can be reused [9]. Direct reuse, remanufacturing and recycling are alternative reuse activities of a CLSC. Through remanufacturing, the companies aim to recover both the energy and the material content of the used products, whereas through recycling to recover only the material content. Nowadays, the cost of used products that end up to landfills without any revenue return becomes a more significant competitive issue, since the costs of raw materials have become a larger percentage of a product's total cost.

The scientific literature provides many research articles on the operations of CLSCs of electrical and electronic products. Rose *et al.* [10], Neto *et al.* [1] and Umeda *et al.* [11] have concentrated their studies on the end-of-life strategies in CLSCs. Specifically, Rose *et al.* [10] indicate that the number of materials used in production and the number of parts are important in determining the most suitable end-of-life strategy in the electronics industries, while Neto *et al.* [1] assess the environmental gains of different end-of-life recovery strategies concentrating on the waste reduction and on virgin material savings. Umeda *et al.* [11] suggest that the material and energy consumption of EEE can be reduced drastically without decreasing corporate profits by appropriately combining products' maintenance, reuse and recycling.

Many mathematical models developed for WEEE estimate the total cost and/or profit of CLSCs' operations [12-14]. Walther and Spengler [13] and Krikke *et al.* [14] proceed in their studies one step further by using also location and allocation problems.

2.3. Design-for-Environment Practices

DfE is an engineering challenge that focuses on different environmental options during the design stage. Fiksel [15] defines DfE as "a systematic consideration of design performance with respect to environmental, health and safety objectives over the full product and process life cycle". The products that are manufactured according to DfE principles are characterized by easy disassembly and are usually superior from an ecological perspective, since it is widely accepted that the cost of a product, the wastes generated and the resources harvested are determined in the design stage [16]. Moreover, DfE can lead to a competitive advantage, lighten regulatory measures and help the firms to reduce the time it takes to comply with the environmental regulations. The significance of the time delay between the time that regulations are imposed and the time that managers are ready to comply with such regulations to minimize the threat of environmental legislation is pointed out in a plethora of studies [17]. Also the achievement of the required product's recyclability requires time (redesign time) [8].

A number of studies have concentrated on DfE practices in EEE. Cui and Forssberg [18] deal exclusively with the mechanical recycling of WEEE. Karna and Heiskanen [19] and He *et al.* [5] assess the impact of the design process of EEE on the operations of the CLSCs in Finland and in China, respectively. Moussiopoulos *et al.* [20] and Boks and Stevels [21] study the characteristics of WEEE. Specifically, Moussiopoulos *et al.* assess the ease of disassembly of WEEE [20], while Boks and Stevels [21] assess their recyclability.

3. System Dynamics Model

In this section we present the structure of the SD model. Subsection 3.1 maps the causal-loop diagram of the CLSC and presents the formulation of the economic sustainability. The mathematical model was validated using data from a real world CLSC of WEEE in Greece (subsection 3.2).

3.1. Structure of the Closed-Loop Supply Chain under Study

Figure 1 depicts the causal-loop diagram of the CLSC under study that incorporates the forward and the reverse channels. The forward channel incorporates the following activities: procurement of natural resources, production, distribution and product use. The reverse channel consists of the collection of used products, recycling and disposal. Causal-loop diagrams in System Dynamics (SD) methodology present the system's feedback structure [22].

The structure of a system dynamics model contains level and rate variables. The level variables are the accumulations (i.e., the inventories) within the system, while the rate variables represent the flows in the system, which result from a decision making process. In Figure 1 the variables expressing inventory levels (levels) are shown in capital letters, while the rate variables are shown in small plain letters. The arrows in Figure 1 represent the relations between variables. The direction of the influence lines is the direction of the effect. The sign (+) or (−) at the upper end of the influence lines shows the sign of the effect. When the sign is (+), the variables change in the same direction; otherwise they change in the opposite direction. Variables not influenced by other variables denote the system parameters (constants), and are shown in small plain letters in Figure 1. Moreover, forecasts are shown in small italics. For the remaining paper variable names are shown in italics using terms with underscore, required by the employed SD commercial software package (Powersim®2.5c).

The forward channel starts from the upper left corner of Figure 1 and comprises of three echelons: *Raw_Materials_Inventory*, *Serviceable_Inventory* and *Distributor's_Inventory*. The flows and the stocks can be derived from the Figure 1 as follows.

- The producers demand for raw materials is satisfied with a mix of natural resources (*Procurement_Rate*), provided by external suppliers, and recycled materials deriving from recycling operations (*Recycling_Rate*).
- *Procurement_Rate* results from combining the *Expected_Producer's_Orders* and the *Expected_Recycling_Rate* with an adjustment that brings *Raw_Materials_Inventory* aligned to its desired value (stock management structure suggested by Sterman [23]). The same control rule is used for the rates of *Producer's_Orders* and *Distributor's_Orders*.
- *Usage_Rate* depletes *Raw_Materials_Inventory*.
- *Production_Rate* increases *Serviceable_Inventory*, which is depleted by *Shipments_to_Distributor*.
- *Shipments_to_Distributor* increase *Distributor's_Inventory*, which is depleted to satisfy *Demand*.
- All unsatisfied distributor's orders are backlogged (*Orders_Backlog*) and may be satisfied in a forthcoming time period. *Demand_Backlog* and *Production_Backlog* are also satisfied in a future period.
- *Sales* turn into *Used_Products* after *Residence_Time*.

The reverse channel starts at the end of the products' usage period and comprises of two echelons: *Collected_Products* and *Recyclable_Products*. Below we describe the stocks and flows of the reverse channel.

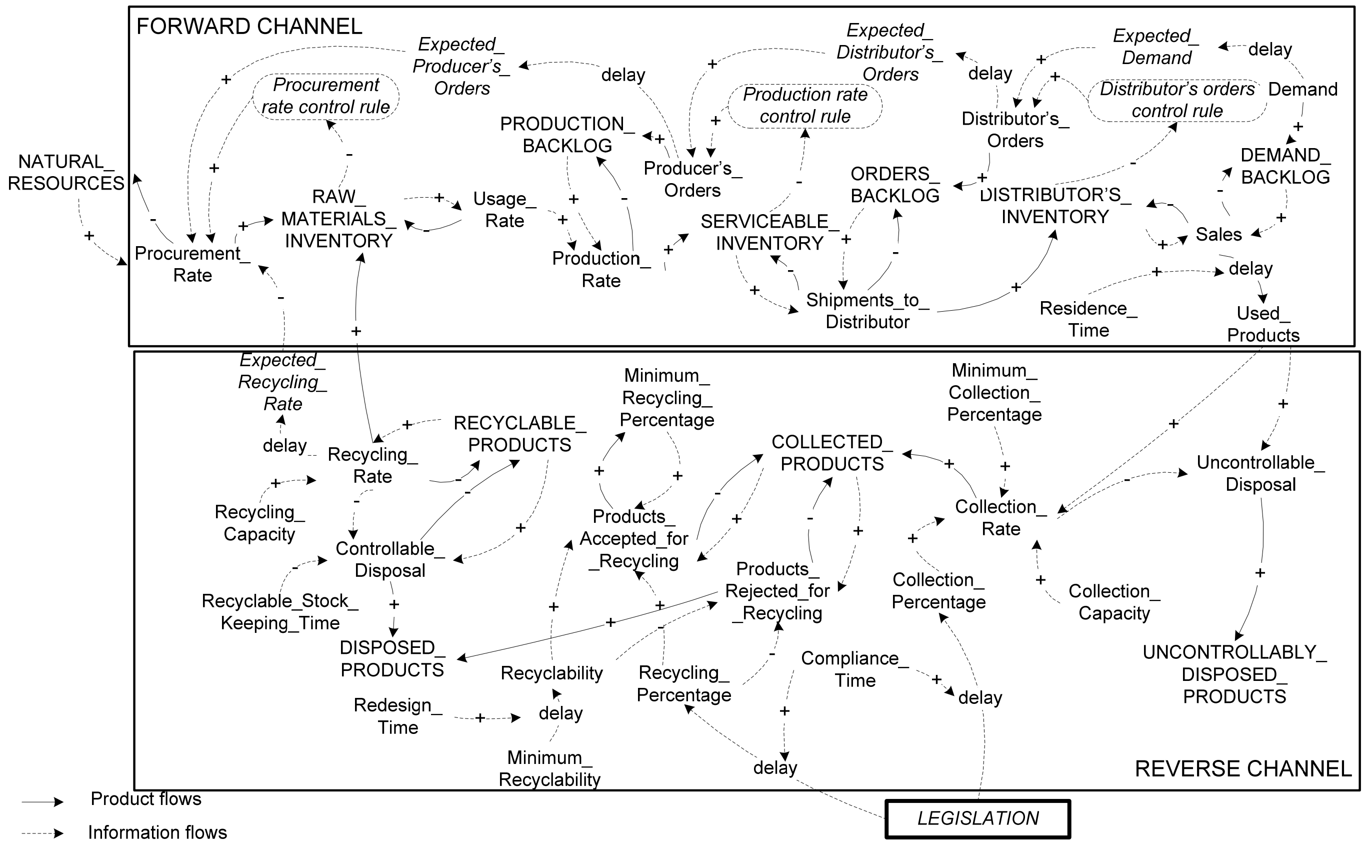
- *Used_Products* are either disposed (*Uncontrollable_Disposal*) or collected for recycling (*Collected_Products*).
- *Collected_Products* are increased by *Collection_Rate*, which depends also on *Collection_Capacity*, and are decreased by the number of products either accepted after inspection (*Products_Accepted_for_Recycling*) or rejected (*Products_Rejected_for_Recycling*).
- The stock of *Recyclable_Products* may be used for recycling if the *Recycling_Capacity*, which confines the *Recycling_Rate*, is adequate.
- To prevent an endless accumulation, *Controllable_Disposal* drains the *Recyclable_Products* if they remain unused for more than *Recyclable_Stock_Keeping_Time*.
- *Controllable_Disposal* and *Products_Rejected_for_Recycling* increase the *Disposed_Products*.

In Figure 1 all material flows are the outcome of the corresponding decision-making processes. Specifically, the activities of collection and recycling are determined by a decision-making process, also influenced by the environmental legislation. The environmental legislation imposes minimum limits for collection percentage and recycling percentage urging (a) the increase of the collected products' amount and (b) the increase of the recycled materials' amount. Hence *Legislation* affects the *Collection_Rate* and the *Products_Accepted_for_Recycling* through *Collection_Percentage* and *Recycling_Percentage*. The firm's collection and recycling activities depend also on the minimum recycling activities performed by themselves even if there are no environmental regulations imposing them through the *Minimum_Collection_Percentage* and *Minimum_Recycling_Percentage* respectively. Moreover, the products are designed with increased recyclability even if there is no legislative measure imposing it (*Minimum_Recyclability*). The achievement of the *Recyclability* requires *Redesign_Time* (time needed to redesign the product to increase its ease for recycling).

An innovative element of the SD model is the incorporation of the time delay between imposition of regulations and firms' compliance with them [17]. Hence the actual *Collection_Percentage* and *Recycling_Percentage* achieved by the firms vary according to managers' *Compliance_Time*.

The profitability of the CLSC under study is evaluated by using as a criterion the *Total_Supply_Chain_Profit*, which is the net present value of all the total revenues per period minus the total costs per period. The total cost per period includes the supply chain's operational cost and the penalty cost, which arises when the CLSC does not comply with the regulations. The operational cost comprises the procurement cost of the original raw materials, the production cost, the collection cost, the recycling cost, the holding costs, the transportation costs and the landfill cost of the disposed products.

Figure 1. Structure of the closed-loop supply chain.



3.2. Validation

To build confidence in the model we used data from a real world CLSC of electrical and electronic equipment developed by a Greek municipality; the case-study used in this paper was presented for the first time by Georgiadis and Besiou [7]. To check the model's validity, we conducted a variety of tests suggested by the SD literature [22]. Firstly, we tested the model's dimensional consistency. Then we conducted extreme-condition tests checking whether the model behaves realistically even under extreme policies. Finally, we simulated the model driven by the data series of the *Collected_Products* to check if the model can replicate the historical behavior. From the results of the tests arose low bias and variation components of the Thiel inequality statistics, which means that the model can replicate the observed behavior of the system under study.

4. Sensitivity Analysis of Environmental Strategies

To assess the impact of the legislative measures, the closed-loop supply chain activities and the DfE practices on sustainability, we conducted sensitivity analyses on the significance of the parameters that each environmental strategy affects. Specifically, the legislative measures affect the parameters of the introduced environmental regulations [the legislative collection percentage (s1) and the legislative recycling percentage (s2)], the penalty costs [the *Landfill_Tax* (s3) and the *Recycling_Tax* (s4)] and the *Landfill_Cost* (s5). The CLSC activities affect the *Minimum_Collection_Percentage* (s6) and the *Minimum_Recycling_Percentage* (s7), whereas the DfE practices affect the *Minimum_Recyclability* (s8), the *Redesign_Time* (s9) of the products and the *Compliance_Time* (s10).

The effects of the above 10 parameters (control factors) on the environmental and the economic sustainability are examined using Analysis of Variance. The environmental sustainability depends on the amount of *Natural_Resources* and on *Sum_Disposal* (*Sum_Disposal* equals with the sum of *Uncontrollably_Disposed_Products* and *Disposed_Products*), whereas the economic sustainability on the *Total_Supply_Chain_Profit*. Each of the 10 parameters is examined at the two levels given in Table 1. In low level (1) the values are 50% lower than those of the case-study in Greece. On the contrary, in the high level (2) the values are 50% higher than those of the case-study in Greece. The total number of all possible combinations is $2^{10} = 1024$; each combination was simulated twice to test for alternative generators of random numbers concerning the products' *Demand* and the *Residence_Time*, leading to $2 \times 2^{10} = 2048$ simulation runs. The simulation horizon is 40 years and the integrating time step is equal to ¼ week.

The results of ANOVA analysis are provided in Table 2. More specifically, Table 2 contains the P-values and the Partial Eta Squared for each of the significant influences. P-value reflects the lowest significance levels to reject the null hypothesis that the control factor does not affect the amount of *Natural_Resources* or *Sum_Disposal* or *Total_Supply_Chain_Profit*, while Partial Eta Squared reflects the significance of the control factor compared with the error's significance. Partial Eta Squared is crucial in our study in order to determine the control factors, which significantly affect the sustainability and also to measure the magnitude of the effect.

Table 1. Levels of model parameters studied with sensitivity analysis.

Parameters	**Levels**	
	(1)	(2)
s1	30%	90%
s2	30%	90%
s3 (€/item)	1.6	4.8
s4 (€/item)	1.6	4.8
s5 (€/item)	1	3
s6	30%	90%
s7	30%	90%
s8	30%	90%
s9 (weeks)	131	393
s10 (weeks)	50	150

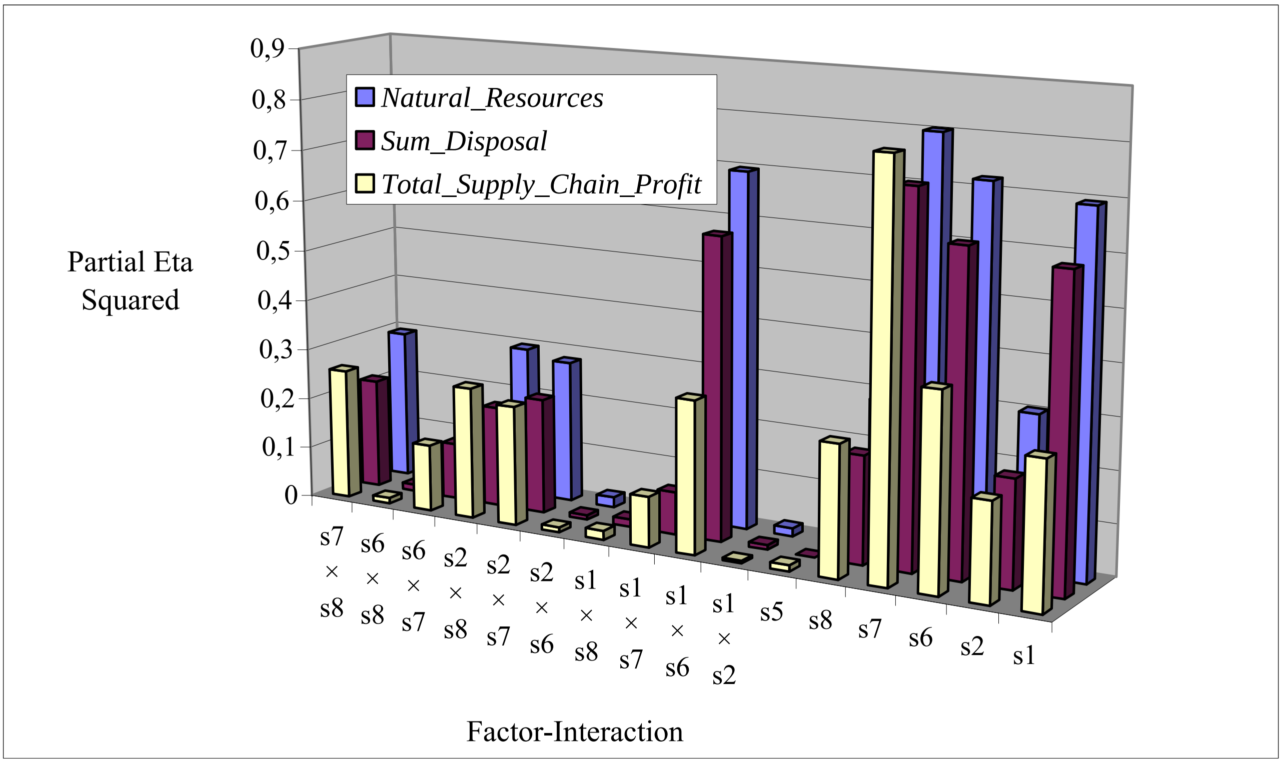
ANOVA tests revealed that, concerning the main effects, the parameters legislative collection percentage (s1), legislative recycling percentage (s2), *Minimum_Collection_Percentage* (s6), *Minimum_Recycling_Percentage* (s7) and *Minimum_Recyclability* (s8) have significant effect on *Natural_Resources*. The same parameters have significant effect on *Sum_Disposal* and on *Total_Supply_Chain_Profit*, but the *Total_Supply_Chain_Profit* is also affected by the *Landfill_Cost* (s5). These results arose using P-value equal to 0.002.

Table 2. P-values/Partial Eta Squared for the significant effects on sustainability.

Factor-Interaction	**Natural_Resources**	**Sum_Disposal**	**Total_Supply_Chain_Profit**
s1	0.000*/0.694	0.000*/0.598	0.000*/0.282
s2	0.000*/0.304	0.000*/0.208	0.000*/0.192
s5	0.974/0.000	0.693/0.000	0.000*/0.012
s6	0.000*/0.721	0.000*/0.620	0.000*/0.380
s7	0.000*/0.802	0.000*/0.718	0.000*/0.791
s8	0.000*/0.290	0.000*/0.210	0.000*/0.255
s1 × s2	0.000*/0.016	0.000*/0.009	0.002*/0.005
s1 × s6	0.000*/0.697	0.000*/0.590	0.000*/0.298
s1 × s7	0.000*/0.132	0.000*/0.083	0.000*/0.099
s1 × s8	0.000*/0.014	0.000*/0.015	0.000*/0.018
s2 × s6	0.000*/0.020	0.000*/0.009	0.000*/0.010
s2 × s7	0.000*/0.281	0.000*/0.227	0.000*/0.235
s2 × s8	0.000*/0.297	0.000*/0.198	0.000*/0.259
s6 × s7	0.000*/0.151	0.000*/0.111	0.000*/0.132
s6 × s8	0.000*/0.017	0.000*/0.013	0.000*/0.011
s7 × s8	0.000*/0.295	0.000*/0.216	0.000*/0.258

*P-value ≤ 0.002

Figure 2. Partial Eta Squared of the significant effects on *Natural_Resources*, *Sum_Disposal* and *Total_Supply_Chain_Profit*.



In a single figure (Figure 2) we present the Partial Eta Squared of the significant factors-interactions for the *Natural_Resources*, the *Sum_Disposal* and the *Total_Supply_Chain_Profit*, in order the significance of the effects to be comparable.

5. Concluding Discussions

The analysis of the impact of the 10 parameters on the environmental and economic sustainability of the WEEE CLSCs proceeded one step further to reveal the exact type of the effect. The results of the ANOVA tests show that when the value of the significant influence increases, the amount of *Natural_Resources* and *Total_Supply_Chain_Profit* increase whereas *Sum_Disposal* decreases. The only exception is the effect of the *Landfill_Cost* (s5) on the *Total_Supply_Chain_Profit*. In this case, when the value of the *Landfill_Cost* increases, the *Total_Supply_Chain_Profit* decreases.

The ANOVA results give the following interesting managerial insights:

(a) Legislative measures

The imposition of stringent legislative collection percentage (s1) or legislative recycling percentage (s2) by governments lead to:

(i) an increase in the amount of *Natural_Resources*.

(ii) a decrease in the amount of products disposed (*Sum_Disposal*).

(iii) an increase in the amount of *Total_Supply_Chain_Profit*.

From the above observations we can conclude that the legislative measures improve both the environmental and the economic sustainability. Moreover, the effect of penalty costs [*Landfill_Tax* (s3) and *Recycling_Tax* (s4)], incorporated in the legislative measures, appear to be almost negligible and show no impact on sustainability. Finally, the *Landfill_Tax* (s5) affects only negatively the economic sustainability without affecting the environmental sustainability.

(b) Closed-loop supply chain activities

The development of increased *Minimum_Collection_Percentage* (s6) or *Minimum_Recycling_ Percentage* (s7) by the firms leads to:

(i) an increase in the amount of *Natural_Resources*.

(ii) a decrease in the amount of products disposed (*Sum_Disposal*).

(iii) an increase in the amount of *Total_Supply_Chain_Profit*.

(c) Design-for-Environment practices

The production of products with increased *Minimum_Recyclability* (s8) by the firms leads to:

(i) an increase in the amount of *Natural_Resources*.

(ii) a decrease in the amount of products disposed (*Sum_Disposal*).

(iii) an increase in the amount of *Total_Supply_Chain_Profit*.

Although the effect of *Redesign_Time* (s9) of the products and *Compliance_Time* (s10) on sustainability is negligible, it may be higher if the environmental measures change during the simulation horizon.

The results presented in this paper certainly do not exhaust the possibilities of investigating all the influences on sustainability. A deeper understanding of the WEEE CLSC's behavior calls for further numerical investigations.

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