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Environmental and economical sustainability of WEEE closed-loop supply chains with recycling: a system dynamics analysis

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Abstract Nowadays, the worldwide production of electrical and electronic equipment (EEE) is consequently increasing, reducing both resources and landfills. In this manuscript, we investigate the significance of the factors that comprise the environmental sustainability strategies (environmental legislation and green image) and the operational features of the closed-loop supply chain (CLSC) (chain's features, products' features and economic parameters), their interactions and the type of their impact on the environmental (availability of natural resources and landfill availability) and economical sustainability of a WEEE CLSC. We use an extension of a System Dynamics-based model of a CLSC with recycling activities introduced by Georgiadis and Besiou [J Clean Prod 16(15):1665–1678, 2008]. The developed model is validated using data from a real-world CLSC of EEE in Greece. Extended numerical investigation provides insights to the managers of the WEEE CLSC and the legislators with regard to the actions which can lead to sustainability.

Keywords Closed-loop supply chains · Electrical and electronic equipment · Sustainable development · System dynamics · Recycling

Abbreviations

CLSC	Closed-loop supply chain
DfE	Design for environment
EEE	Electrical and electronic equipment
EU	European Union
GIF	Green image factor
SD	System dynamics
US	United States
WEEE	Waste electrical and electronic equipment

1 Introduction

Recently, the technological progress, market expansion and the trend for electronic products of shortening lifecycles increased the worldwide production of electrical and electronic equipment (EEE), making electronic waste one of the major and fastest growing waste streams in the world [1–3]. Specifically, after transportation and food consumption, the EEE appears as the third biggest source of environmental footprint [4].

In Europe, the overall amount of electronic waste generated is estimated between 6.5 and 7.5 million tonnes per year, constituting around 4% (by mass) of the total municipal waste stream [5, 6]. It is also estimated that the amount of waste electrical and electronic equipment (WEEE) increases 16–28% every year, which means a growth rate three times as fast as average municipal waste [6, 7]. Nearly 40% of the lead disposed in landfills and 50% of the lead in incinerators comes from WEEE [8]. It is remarkable that the EEE is also responsible for 10–20% of the depletion of the amount of natural resources [4]. In the Netherlands, yearly about 130 million kilogrammes of EEE are discarded. In France, the total WEEE arisings are estimated at 1.7 million tonnes per year, whereas in Germany and in the UK at 950,000 t per year (http://www.actu-environnement.com/ae/news/1896.php4). Ylä-Mella et al., based on reference data, address that the

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amount of WEEE in Sweden and Norway is 100,000 t per year [6]. In Greece, about 185,000 t of WEEE have been discarded during 2003–2008, constituting around 3.8% of the total municipal domestic waste stream.

Due to the environmental problems involved in the management of WEEE and the pressures coming from the society (green image), many countries have already drafted national legislation to improve the take-back and recycling of such wastes in an effort to increase the usage rate of used products [1, 3, 9–11]. Recycling of WEEE has been identified by many authors as an important product reuse activity not only for waste treatment but also for the recovery of valuable materials [1, 3, 9]. The major benefits in material savings, when recycled materials are used, have also been identified by the US Environmental Protection Agency [1]. Another important factor affecting the recycling activities is the “green image” factor (GIF) which arose in the last years as a marketing element due to the environmental problems and the pressures coming from the society [12].

Over the last decades, the ecological problems have transferred the environmental actions from regional and national levels to international levels. The introduction of WEEE legislation along with the consumers' pressures (GIF) forced the firms to develop environmental sustainability strategies, such as design for environment (DfE) activities, the production of recyclable products and the usage of recycled materials for the production of new goods. These sustainability strategies affected the operational features of the closed-loop supply chains (CLSC) demanding changes. As the management of the WEEE CLSCs increases the effort in operating in a sustainable way, both the rate of product disposals in landfills and the usage rate of natural resources decrease.

In this paper, we develop a holistic approach to comprehend the WEEE CLSCs interactions with the environment. These interactions are easier to describe defining the ecological threats, the environmental sustainability strategies and the WEEE CLSCs with measurable characteristics. The ecological threats are defined by the availability of both natural resources and landfills, the environmental sustainability strategies by the WEEE environmental regulations and the GIF and the WEEE CLSCs by grouping the operational features in three categories: (a) supply chain features, (b) products' features and (c) economic parameters.

Many researchers have studied the interactions of the WEEE CLSCs with the environment. It is remarkable that most of them have concentrated their studies on specific characteristics, while ignoring others. The results of non-holistic studies may not respond accurately to the real-world system's behaviour since other important influences have been ignored. The study of the impact of the environmental legislation on the CLSC profitability ignoring the legislation's impact on the environmental aspect of sustainability or even the impact of the environmental sustainability on the CLSC profitability through the green image comprise such examples. Moreover, many authors focus their studies exclusively on the reverse channel of the supply chain ignoring the operations of the forward channel and their interactions [12–14].

Another important feature of CLSCs that many studies rule out is the dynamic process of the operations. Few exceptions are the dynamic CLSC models developed by Georgiadis et al. [15], Van Schaik and Reuter [16], and Spengler and Schroter [17]. An attempt in combining the dynamic feature of CLSCs with a holistic approach is made by Georgiadis and Besiou [18]. They investigate the impact of important ecological parameters, including the WEEE legislation, on the firms' environmental sustainability through the management of natural resources usage and landfill availability. The system dynamics (SD)-based model is restricted to the environmental dimension of sustainability, and it is used to evaluate the impact of environmental legislation, GIF and DfE on the long-term behaviour of a system encountered on a variety of real-world CLSCs with recycling activities. Specifically, they investigate how the different regulatory measures imposed by the European Union (EU) WEEE legislation (collection percentage and recycling percentage), the products' recyclability (percentage defining how recyclable a product is), the redesign time (time needed to redesign the product to comply with the legislation's requirements) and the GIF affect the environmental sustainability. The SD model includes an endogenous process for legislation modelling; the legislation depends on the “limits” issues that is the availability of natural resources and landfills. Moreover, the actual legislative percentages accomplished by the producer depend on the delay between the time of the imposition of WEEE legislation and the time of the firms' compliance. The authors used data from a real-world CLSC of EEE in Greece to build confidence in the model. This research is extended by Georgiadis and Besiou considering a WEEE CLSC that operates under the influence of EU legislation [19]. They also assume that the legislation imposes, besides collection percentage and recycling percentage, minimum limits for recyclability and recycled content (percentage of recycled materials found in 1 kg of finished product). The results of this study revealed that the imposition of the added two regulatory measures decrease the rates of natural resources' usage and used products' disposal promoting the environmental sustainability.

In this paper, the above analysis is proceeded one step further. Specifically, we provide a SD model which incorporates both the environmental and the economical dimensions of sustainability. A second improvement is that the modelling approach comprises a broader number of characteristics in describing the environmental sustainability strategies and the operational features of the CLSC (supply chain's features, products' features and economic parameters). More specifically, the review period of the environmental regulations, the minimum recycling activities performed by the firms even if there are no environmental regulations imposing them, the return rate of the used products by the consumers to the CLSC and the quality of the recycled materials constitute important factors that this research incorporates. Thus, the previous papers are significantly different from the present one in terms of objectives and model structure, but more importantly, they are much more limited in terms of scope and detail and, consequently, in terms of applicability and ability to provide useful managerial insights. We implemented the model to a real-world CLSC with recycling activities in the region of West Macedonia in Greece to test its validity. However, the SD model is applicable for other WEEE CLSCs with quite different global dimensions. For example, the model could also be applied in cases that the materials for the production of EEE are mined in Northern Europe; the supplier, the manufacturer and the market are in different countries in Central Europe and the recycler is in Balkans.

The contribution of this work is twofold; firstly, using the comprehensive dynamic model to assess not only the significance of characteristics that describe the environmental sustainability strategies and the operational features of the CLSC (supply chain's features, products' features and economic parameters) on the environmental (availability of natural resources and landfill availability) and economical sustainability of a WEEE CLSC, but also to specify the type of the impact and the magnitude of their interactions. The above analysis is performed by extended numerical investigation with parameter values in different levels in combination with analysis of variance (ANOVA). Secondly, based on the results obtained by the sensitivity analysis, we provide insights to the managers of the WEEE CLSC and the legislators regarding the actions which can lead to sustainability.

In the next section, we present a literature review of surveys and case studies and mathematical models that study WEEE CLSCs. A brief presentation of SD methodology follows. The presentation provides the strengths and weaknesses of SD approach in investigating environmental issues in CLSCs. Then, we briefly present the system under study; the presentation includes the modelling approach of the environmental legislation, GIF and economical sustainability and an empirical implementation in a real-world CLSC with recycling activities of EEE in Greece. The impact of sustainability on WEEE CLSCs is investigated through sensitivity analyses. Specifically, we examine the significance of the ecological threats, the environmental sustainability strategies and the operational features of the CLSC, their interactions and the type of their impact on the environmental and economical sustainability of the WEEE CLSC. Based on the observations obtained by the technical analysis, the section "Results and discussion" provides managerial insights with practical implications. The final section presents summary and possible extensions of our study.

2 Literature review

The tremendous interest in the proper recovery of WEEE resulted in the development of mathematical models and the conduction of several surveys and applications that study real-world take-back and recovery systems. For example, Stevels describes the effectiveness of the take-back WEEE system in the Netherlands based on its environmental gains and costs [20]. In addition to the Dutch recovery system [5, 20–23], the recovery systems of other countries have also been studied. For example, the German [23, 24], the Swedish [23], the Swiss [2], the Scottish [25], the Finnish [6, 26, 27], the Chinese [28, 29] and the Taiwanese [30] recovery systems have also been presented. Specifically, de Koster et al. [5], Nagel et al. [23] and Feszty et al. [25] present the current status of the WEEE take-back systems in the Netherlands, Germany, Sweden and Scotland. Hischier et al. [2] and Stoop and Lambert [22] assess the environmental footprint of the WEEE recovery systems in Switzerland and in Netherlands, respectively. Walther and Spengler develop a location-allocation mathematical model implemented to the German recovery system [24]. Karna and Heiskanen [26] and He et al. [28] assess the impact of the design process of EEE on the operations of the CLSC in Finland and in China, respectively. He et al. proceeded this study one step further by estimating the efficiency of the upcoming WEEE legislation in China [28]. Ylä-Mella et al. [6], Lehtinen and Poikela [27], and Lambert and Stoop [21] assess the efficiency of the EU WEEE legislation in Finland and in Netherlands. Yu et al. study the readiness of China for the implementation of WEEE legislation [29], while Chien and Shih use a survey to study whether the firms in Taiwan have adopted green manufacturing practices due to the EU WEEE legislation [30].

Besides studying the characteristics of the WEEE take-back and recovery systems, many surveys and mathematical models have concentrated on the characteristics of WEEE. Specifically, Moussiopoulos et al. assess the environmental burden, weight, quantity and ease of disassembly of WEEE [31]; Boks and Stevels [32] assess their energy, material, weight, packaging, potentially toxic substances and recyclability and Dowie [33] and Huisman

[34] assess their recyclability. Feszty et al. [25] assess the composition of WEEE in Scotland. Karagiannidis et al. [35, 36] aimed to contribute at the knowledge on the weight and lifecycle of WEEE for Greece, by presenting the results from a field survey on WEEE.

Other authors have concentrated their studies on end-of-life strategies. Specifically, Rose et al. 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 [37]. Neto et al. also examine different end-of-life recovery strategies by assessing their environmental gains concentrating on the waste reduction and on energy and virgin materials savings [4]. Cui and Forssberg deal exclusively with the mechanical recycling of WEEE [9], while White et al., using a case research from the computer and electronics industry, highlight the challenges that the firms' managers confront at each recycling stage regarding the location and collection of used products and the disassembling process [38].

The majority of the developed mathematical models on WEEE estimate the total cost or/and profit of the operations of the CLSCs [3, 17, 24, 39–42]. Other models define either the environmental costs of the recovery of WEEE [3, 21] or its environmental footprint [2, 22, 43, 44]. Characteristically, Stoop and Lambert show that recycling of refrigerators should be based on an integral approach, aiming at maximum elimination of chloro-flouro-carbon, high recovery of metals and low input of energy [22], whereas Umeda et al. 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 [44]. Hischier et al. confirm that WEEE recycling is clearly advantageous from an environmental perspective compared to the scenario where no WEEE is recycled [2]. Kleijn et al. estimate the environmental impact of the WEEE CLSC from the extraction of raw materials to the WEEE recovery [43]. The operations of WEEE CLSC are also studied using location and allocation problems [24, 40, 45].

The most common WEEE product categories which are studied are the refrigerators [21, 22, 40, 42, 44], electrical brooms [33], personal computers [38] and mobile phones [46].

The observations concentrating on the efficiency of WEEE legislation [6, 18, 19, 21, 27, 28, 47, 48], that derived from the research, lead to the requirements of a better integration of the emissions and the resources. Finally, the impact of WEEE legislation on the firms' sustainability is studied in many research papers [11, 18, 40–42, 46, 49, 50]. However, Stutz et al. [46] are the only that assess also the cost impact of WEEE legislation on the products' design concentrating their study on the firms' economical sustainability.

3 System dynamics methodology

Forrester introduced SD in the 1960s as a modelling and simulation methodology in dynamic management problems [51]. Since then, SD has been applied to various business policy, strategy [52] and environmental problems. However, few strategic management and environmental problems in CLSC have been analysed and are reported in the literature [53]. Specifically, Spengler and Schroter present a CLSC using SD [17]. Georgiadis et al. present the major influence loops of product reuse [15]. Van Schaik and Reuter present a SD model focused on cars showing that the realisation of the legislation targets imposed by EU depends on the product design [16].

The SD methodology is a powerful methodology for obtaining insights into problems of dynamic complexity. Sterman mentioned that “whenever the problem to be solved is one of choosing the best from among a well-defined set of alternatives, optimization should be considered. If the meaning of best is also well-defined and if the system to be optimised is relatively static and free of feedback, optimization may well be the best technique to use” [54]. The latter conditions are rarely satisfied for systems in Environmental Management [55] and in supply chains [56]. The system under study in this paper is dynamic and full of feedbacks promoting SD as an appropriate modelling and analysis tool.

4 The system under study

We assume that the only recovery activity that the CLSC develops is recycling. The purpose of recycling is to reuse materials from used products and components; these materials can be used for the production of original parts if the quality of materials is high [53, 57]. Figure 1 depicts a simplified version of the system under study that incorporates the following activities: procurement of natural resources, production, distribution, product use, collection of used products, recycling and disposal.

The forward supply chain comprises three echelons: the producers’ inventory of raw materials, the serviceable inventory and the distributor’s inventory. 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). The recycled materials can either be of good quality and used as raw materials for the production of new goods (supply rate) or be of poor quality and end up to secondary markets of raw materials. The customers' demand depends on the firm's green image (GIF). The reverse channel starts at the end of the products' usage period and comprises two echelons: collected products and recyclable

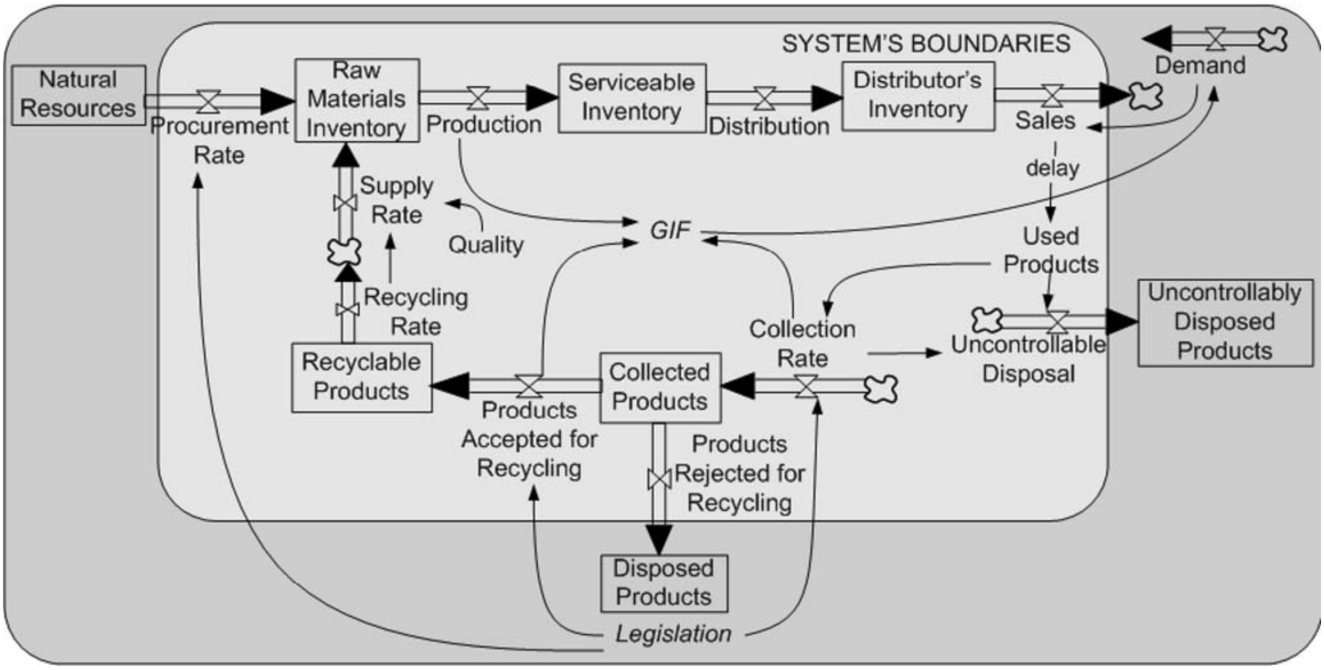


Fig. 1 Structure of the closed-loop supply chain

products. The collected products are inspected, and they are either accepted for recycling (recyclable products) or rejected for recycling (disposed products) and used as input for different recovery networks or B class product markets. The recyclable products turn into recycled materials after recycling.

The inventories in the system of Fig. 1 are managed by a "pull-push" policy. We adopt a "pull" policy in the forward channel to maintain better stock control [58], while we use a "push" policy in the reverse channel firstly to express, indirectly, the pressure of local governments on manufacturers to reduce the used product flows going into landfills [59] and secondly to achieve faster system response.

In Fig. 1, the material flows are the outcome of corresponding decision-making processes. In this research, the activities of collection, recycling and original raw materials (natural resources) procurement are determined by a decision-making process which is also influenced by the environmental legislation. We assume that the environmental legislation imposes minimum limits for collection percentage, recycling percentage, recyclability and recycled content. Specifically, the legislation urges (a) the increase of the collected products' amount, (b) the increase of the recycled materials' amount and (c) the production of goods using recycled materials with priority compared to the original raw materials. The firms develop collection activities to achieve the legislative collection percentage. However, to increase the amount of recycled materials, the firms should both develop recycling activities (legislative recycling percentage) and design recyclable products (legislative limit of recyclability). It is obvious that the firms can achieve the legislative limit of recycled content only if the volume of the recycled materials is sufficient for the production.

The influences of the environmental legislation and the GIF on the system's flows are presented in the following subsections.

4.1 The structure of *Legislation*

Figure 2 depicts the causal-loop diagram of the *Legislation*. Causal-loop diagrams in SD present the system's feedback structure [52]. 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). Moreover, variables expressing inventory levels are shown in capital letters, forecasts in small italics and all the other parameters in small plain letters. The causal links of the *Legislation* with the supply chain activities are analytically shown in Fig. 2.

Specifically, in this research, the *Legislation* modelling is an endemic process [60]. Georgiadis and Besiou [19] revealed that to promote the environmental sustainability, the environmental legislation should be introduced as an endemic process by taking into consideration the rates of natural resources' usage and used products' disposal. The sustainability threats (minimization of available landfills and natural resources) are the driving forces for the introduction of stringent *Legislation*.

For legislation modelling, we use the same approach that is analytically presented in Georgiadis and Besiou [19].

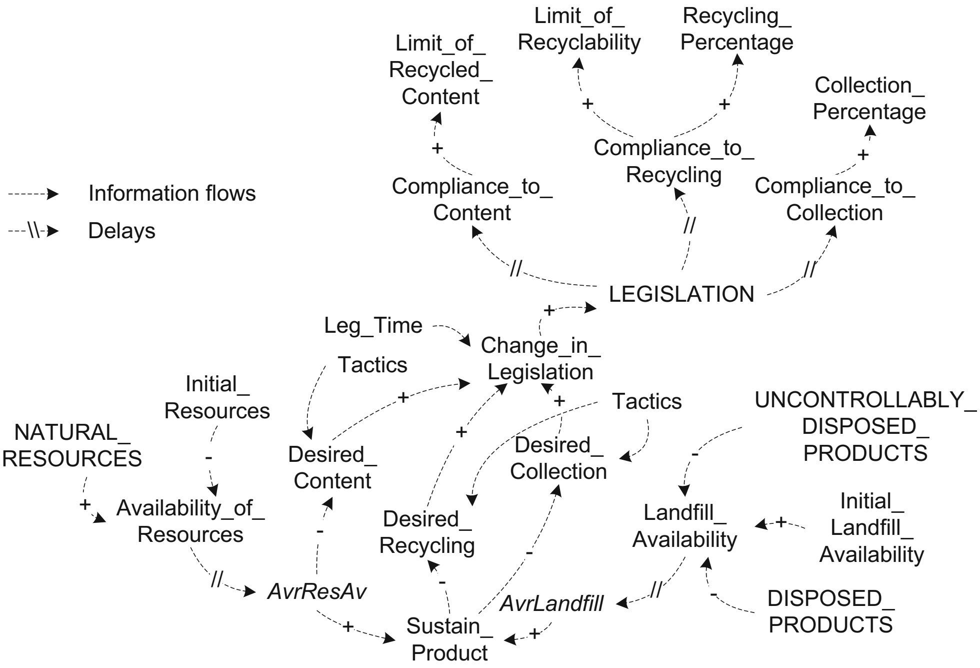


Fig. 2 Causal-loop diagram of *Legislation*

However, they did not incorporate in the developed SD model the time delay between imposition of regulations and firms' compliance with them [19]. In this paper, the dynamic model is extended, incorporating this delay. The need for this incorporation is also justified by the results of surveys in industrial firms in Northern Greece, suggesting a delay due to lack of human and financial resources essential for implementation [18]. Hence, the actual *Collection_Percentage*, *Recycling_Percentage*, *Limit_of_Recyclability* and *Limit_of_Recycled_Content* achieved by the firms vary according to the managers' compliance to *Legislation*. These percentages also depend on the minimum recycling activities performed by the firms even if there are no environmental regulations imposing them through the *Minimum_Collection_Percentage*, *Minimum_Recycling_Percentage*, *Minimum_Limit_of_Recyclability* and *Minimum_Limit_of_Recycled_Content*, respectively.

In summary, the sustainability threats are expressed by *AvrLandfill* (average landfill availability) and *AvrResAv* (average resources availability); the values of these two parameters are determined by smoothing and delaying past values of *Landfill_Availability* (reflects how much the available landfills have shrunk, in comparison with their initial value, *Initial_Landfill_Availability*) and *Availability_of_Resources* (reflects the decrease of *Natural_Resources* compared to their initial value, *Initial_Resources*), respectively. To decrease the shrinking of available landfills, more used products must be collected and reused through recycling activities. According to this approach, it arose that the *AvrLandfill* should affect the desired values of the collection (*Desired_Collection*) and the recycling activities (*Desired_Recycling*). Moreover, to reduce the usage of original raw materials, more recycled materials must arise from collection and recycling activities, and they must be used for the production of new goods. In a similar way, it arose that the *AvrResAv* should affect not only the collection (*Desired_Collection*) and the recycling activities (*Desired_Recycling*) but also the inventory of recycled materials used in production (*Desired_Content*). Since *AvrLandfill* and *AvrResAv* have a positive influence on *Desired_Collection*, we model the joint influence using the product of *AvrLandfill* and *AvrResAv* (*Sustain_Product*). The relationship between *Desired_Collection* and *Sustain_Product* depends on the political beliefs on environmental issues and the ecological influences coming from the society (*Tactics*). For the optimal study of this dependency, we incorporate in our model the four different tactics suggested by Georgiadis and Besiou (Fig. 3) [18].

The *Desired_Recycling* and the *Desired_Content* result from *Sustain_Product* and *AvrResAv*, respectively, in a similar way with *Desired_Collection*. The *Desired_Recycling* is used to formulate both the achieved *Recycling_Percentage* and the *Limit_of_Recyclability* since both of them affect the recycling activities. The new environmental policies are introduced (*Change_in_Legislation*) and reviewed in time periods according to the ecological pressures coming from the society (*Leg_Time*). In Table 1, we present the description of all variable and parameter nomenclature.

4.2 The structure of green image factor

Figure 4 depicts the causal-loop diagram for modelling of *GIF*. Georgiadis and Besiou study the structure of *GIF* for a CLSC with recycling activities [18]. They consider that the

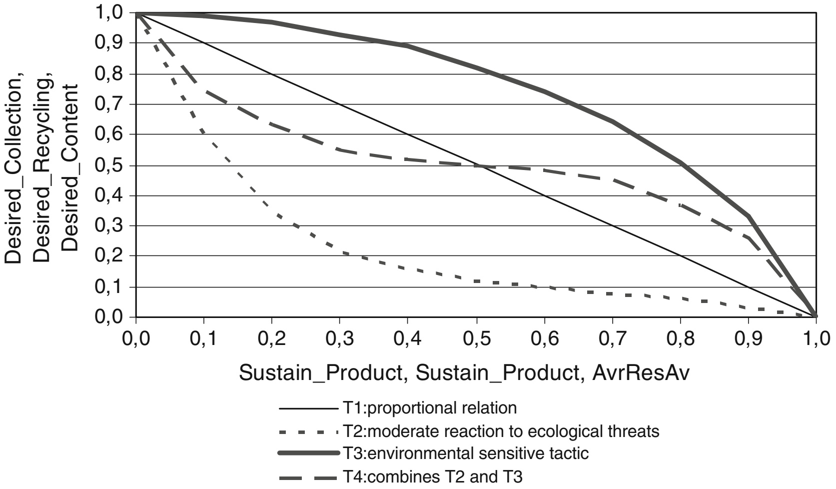


Fig. 3 Relationship between *Desired_Collection* (*Desired_Recycling* and *Desired_Content*) and *Sustain_Product* (*Sustain_Product* and *AvrResAv*) for various tactics

"green image" effect on customer demand depends exclusively on the firms' collection and recycling activities. However, they do not take into consideration that the *GIF* is also affected by the producers' willingness to use recycled materials rather than original raw materials for the production of new goods. In this research, the dynamic model is extended incorporating this effect. Specifically, *Collection_Ratio* is defined as the fraction of *Collected_Products* to *Used_Products*, *Recycling_Ratio* as the fraction of *Products_Accepted_for_Recycling* to *Collected_Products* and *Recycled_Content_Ratio* as the fraction of *Usage_Rate* of recycled materials to the aggregate *Production_Rate*. *Reuse_Ratio* is defined as the product of *Collection_Ratio*, *Recycling_Ratio* and *Recycled_Content_Ratio*. The values of *Reuse_Index* over time are determined by smoothing and delaying past values of the *Reuse_Ratio*. The relationship between *Reuse_Index* and *GIF* depends on the reaction of a specific market to the recycling activities (*Market_Behavior*). For the optimal study of this dependency, we incorporate in our model the four different market behaviours suggested by Georgiadis and Besiou (Fig. 5) [18].

4.3 The structure of profitability

The criterion we employed to evaluate the economical performance of the entire supply chain is the *Total_Supply_Chain_Profit* for the planning horizon. The total supply chain profit is the net present value of all the total revenues per period, which depend on products' price, minus the total costs per period, including the operational cost and the penalty cost. The penalty cost is the cost that arises when the CLSC does not comply with the regulations. The supply chain's operational cost includes the procurement cost of the original raw materials, the production cost, the collection cost, the consumer cost which is the fee supplied to the consumers who return their used EEE back to the reverse channel of the CLSC, the recycling cost, the holding costs, the transportation costs, the landfill cost of the disposed products and the products' redesign cost needed to comply with the environmental regulations.

4.4 WEEE case study in Greece

Due to the environmental problems that arise with the uncontrollable disposal of WEEE, EU regulations have been introduced forcing manufacturers to utilize natural resources rationally and to develop recovery activities. Such a representative example is the Directive 2002/96/EC on WEEE [10]. In Greece, the recognition of the importance of WEEE management has led to the introduction of a Law (no. 2939 in 2001) that aims at the harmonisation of national legislation with the current European Directives concerning packaging and other wastes [61]. This law also sets the framework for "other" wastes, including WEEE. In accordance with this law, the administrators (companies) that manufacture EEE have been called upon to participate in collective or individual alternative systems for the management of their end-of-life products, starting in August 2005. The manufacturers of EEE targeted to a collective goal, specifically to collect and process 30,000 t of WEEE by the end of 2005; this goal was not achieved due to lack of needed infrastructure. Moreover, according to the law, the first collection and treatment targets must be attained by December 2008 [10, 36].

To build confidence in the model, we had to check its validity and quality by assessing whether it behaves realistically under real-world conditions. Therefore, we used data from a real-world CLSC of EEE developed by a Greek municipality in Western Greece. The municipality has about 65,000 inhabitants and 10,000 households, and it is a pioneer municipality in recycling activities in Greece aiming also to innovative actions, characteristics that could be found in other small European towns. It was one of the few Greek municipalities dealing with WEEE collection even before

Table 1 Description of variables (in alphabetical order)

Variables	Description
Availability_of_Resources	Fraction of *Natural_Resources* to *Initial_Resources*
AvrLandfill	Forecast of *Landfill_Availability* obtained using exponential smoothing
AvrResAv	Forecast of *Availability_of_Resources* obtained using exponential smoothing
Change_in_Legislation	New and revised regulatory measures
Collected_Products	Used products collected by the firms' activities
Collection_Cost	Collection cost of the collected products
Collection_Percentage	Actual collection percentage achieved by the firms
Collection_Ratio	Fraction of *Collected_Products* to *Used_Products*
Compliance to *Legislation*	Time delay between imposition of regulations and firms' compliance with them
Compliance_to_Collection	Collection percentage according to managers' compliance to *Legislation*
Compliance_to_Content	Recycled content of the new products according to managers' compliance to *Legislation*
Compliance_to_Recycling	Recycling activities according to managers' compliance to *Legislation*
Consumer_Cost	Fee supplied to the consumers who return their used EEE back to the reverse channel of the CLSC
Demand	Products' demand
Desired_Collection	Desired value of the collection activities
Desired_Content	Desired value of the recycled content of the new products
Desired_Recycling	Desired value of the recycling activities
Disposed_Products	Accumulates the controllably disposed products
GIF	Influence of *Reuse_Index* on *Demand* according to the qualitative variable *Market_Behavior*
Initial_Landfill_Availability	The value of the landfill availability at the beginning of the simulation period
Initial_Resources	The value of *Natural_Resources* at the beginning of the simulation period
Landfill_Availability	Reflects how much the available landfills have shrunk concerning the *Initial_Landfill_Availability*
Landfill_Cost	The landfill cost of the disposed products
Leg_Time	Review period of the legislation
Legislation	Regulatory measures
Legislative_Collection_Percentage	Collection percentage imposed by the legislation
Legislative_Limit_of_Recyclability	Limit of recyclability imposed by the legislation
Legislative_Limit_of_Recycled_Content	Limit of recycled content imposed by the legislation
Legislative_Recycling_Percentage	Recycling percentage imposed by the legislation
Limit_of_Recyclability	Actual recyclability achieved by the firms
Limit_of_Recycled_Content	Actual recycled content of the new products achieved by the firms
Market_Behavior	Reaction of a specific market to the recycling activities
Minimum_Collection_Percentage	Minimum collection percentage performed by the firms even if there is no regulation imposing it
Minimum_Limit_of_Recyclability	Minimum recyclability performed by the firms even if there is no regulation imposing it
Minimum_Limit_of_Recycled_Content	Minimum recycled content of the new products performed by the firms even if there is no regulation imposing it
Minimum_Recycling_Percentage	Minimum recycling percentage performed by the firms even if there is no regulation imposing it
Natural_Resources	Inventory of the original raw materials
Penalty_Cost	Cost arising when the CLSC does not comply with the regulations
Price	Products' price
Procurement_Cost	Procurement cost of the original raw materials
Production_Rate	Production rate of the products
Products_Accepted_for_Recycling	Flow of *Used_Products* that can be recycled
Quality	Quality of recycled materials
Recycled_Content_Ratio	Fraction of *Usage_Rate* of recycled materials to the aggregate *Production_Rate*
Recycling_Cost	Recycling cost of the collected products
Recycling_Percentage	Actual recycling percentage achieved by the firms
Recycling_Ratio	Fraction of *Products_Accepted_for_Recycling* to *Collected_Products*
Redesign_Cost	Products' redesign cost needed to comply with the environmental regulations

Table 1 (continued)

Variables	Description
Redesign_Time	Time needed to redesign the product to comply with the legislation's requirements
Residence_Time	The time a product stays with the customer before its end of use
Return_Percentage	Return percentage of used products
Reuse_Index	Forecast of *Reuse_Ratio* obtained using exponential smoothing
Reuse_Ratio	Product of *Collection_Ratio*, *Recycling_Ratio* and *Recycled_Content_Ratio*
Sum_Disposal	Accumulates the *Disposed_Products* and the *Uncontrollably_Disposed_Products*
Sustain_Product	Product of *AvrLandfill* and *AvrResAv*
Tactics	The political beliefs on environmental issues and the ecological influences coming from the society
Total_Supply_Chain_Profit	Economical performance of the entire supply chain
Uncontrollably_Disposed_Products	Accumulates the uncontrollably disposed products
Usage_Rate	Usage rate of the inventory of raw materials
Used_Products	The products after their *Residence_Time*

the enforcement of the Directive 2002/96/EC. However, not all the manufacturers of EEE were aware of the municipality's collection activities causing a time delay between imposition of regulations and firms' compliance with them; in case of countries that had already developed voluntarily take-back schemes prior to legislation, this time delay does not exist.

The Directive 2002/96/EC and the Greek Law demand the collection of 4 kg of WEEE per inhabitant and per year. The collected WEEEs are transferred to the collection facilities. There, the dismantling activities also take place. For the recycling activities, the used products are carried to external contributors.

Data collected by the authors included (1) interviews with collection activities' managers, such as the collected WEEE amounts per month which were used only for the model's validation (next subsection) (2) archival data, such as population census. We focused our study on white goods and particularly on refrigerators. The collection of the related data started in 2003.

We also used data from Electrolux presentation in 2005 to estimate the *Residence_Time* (the time a product stays with the customer before its end of use [62]) of refrigerators [63]. Furthermore, using the results from a field survey on WEEE and the population [35], we estimated the refrigerators' annual demand. We conducted three surveys in 22 industrial firms of Northern Greece to estimate the time delay between imposition of regulations and firms' compliance with them (compliance to *Legislation*). In Georgiadis and Besiou, the reader can find detailed information about the case study [18].

4.5 Model testing

To build confidence in the developed model and to check its quality, we tested the model's dimensional consistency (every equation must be dimensionally consistent), we conducted extreme-condition tests (subject model to large shocks and extreme conditions) and behaviour reproduction tests (compare model output and historical behaviour) suggested by the SD literature [52, 64, 65]. Firstly, we tested the model's dimensional consistency. Then, we conducted extreme-condition tests checking whether the model behaves realistically even under extreme policies. For instance, we checked that if there is no *Demand* for new products, no *Used_Products* return back at the CLSC and, exclusively, *Natural_Resources* are used for the production of new goods.

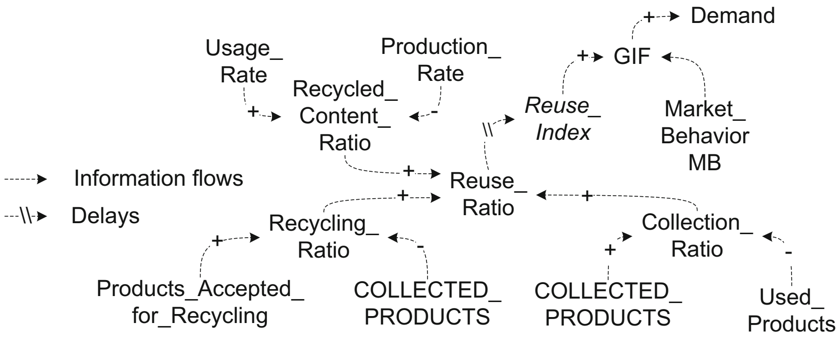
Finally, we simulated the model driven by the data series of the amount of *Collected_Products* to check if the model can replicate the historical behaviour. The results of the tests indicated that the errors are unsystematic meaning that the model can replicate the observed behaviour of the system under study.

5 The impact of sustainability on WEEE CLSCs

A complete numerical investigation of the model's behaviour requires the systematic study of problems with various levels of system parameters; such a detailed experimental design is practically impossible here due to the large number of model parameters. To choose the right mix of independent parameters, we firstly investigate the WEEE CLSCs interactions with the environment.

Specifically, we defined the ecological threats, the environmental sustainability strategies and the WEEE CLSCs with measurable characteristics. The environmental sustainability strategies are defined by the WEEE environmental regulations and the GIF. The WEEE legislation introduces measures for *Collection_Percentage*, *Recycling_Percentage*, *Limit_of_Recyclability* and *Limit_of_Recycled_Content*. Moreover, their introduction depends on the political beliefs and the ecological pressures on environ-

Fig. 4 Causal-loop diagram of *GIF*



mental issues (*Tactics*) and on their review period (*Leg_Time*). The WEEE CLSCs are defined grouping the operational features in supply chain features, products' features and economic parameters. The supply chain features consist of the return rate of used products, the minimum recycling activities performed by the firms and the compliance to *Legislation*. The only products' feature that appears in the developed mathematical model is the quality of recycled materials. Finally, the economic parameters are the product's *Price*, the products' *Collection_Cost*, the *Recycling_Cost*, the *Redesign_Cost*, the *Procurement_Cost* of the original raw materials, the *Consumer_Cost*, the *Landfill_Cost* and the *Penalty_Cost*.

Apart from their previous sorting, we have categorised the above measurable characteristics (in total 25) also in nine groups (A, B, C, D, E, F, G, H and I), according to the sector of the CLSC that they relate to. Group A includes all the variables that relate to the WEEE legislation. Specifically it includes the legislative percentages (*Legislative_Collection_Percentage*, *Legislative_Recycling_Percentage*, *Legislative_Limit_of_Recyclability* and *Legislative_Limit_of_Recycled_Content*), the legislators' behaviour (*Tactics*) and the review periods of the legislation (*Leg_Time*).

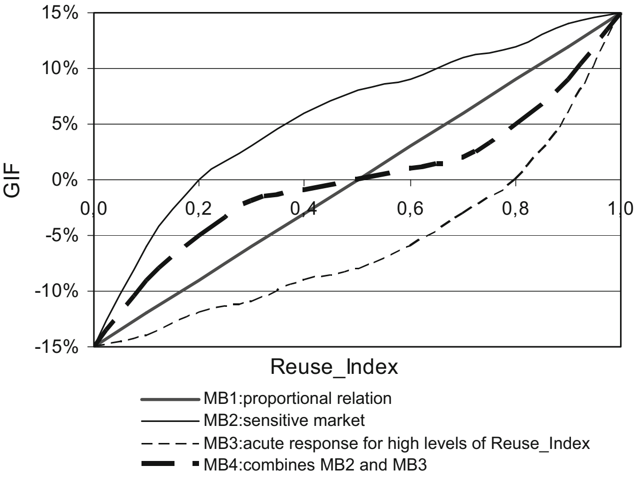


Fig. 5 Relationship between *GIF* and *Reuse_Index* for four market behaviours

Group B consists of the *Quality* of recycled materials. In group C, all the variables depend on the willingness of the management of CLSC to protect the environment, whereas group D expresses the consumers' willingness. Hence, group C includes the activities that the firm develops even if there are no environmental regulations imposing them (*Minimum_Collection_Percentage*, *Minimum_Recycling_Percentage*, *Minimum_Limit_of_Recyclability*, *Minimum_Limit_of_Recycled_Content*, *Redesign_Time* and compliance to *Legislation*). Group D contains the “green image” effect on customers' demand (*Market_Behavior*) and the return rate of used products (*Return_Percentage*).

The two ecological threats are expressed through the availability of natural resources and landfill availability. In this research, we study the impact of their initial values (group E, *Initial_Resources*) and (group F, *Initial_Landfill_Availability*) respectively on sustainability, checking also how sensitive is the model to the initial conditions. Groups G, H and I comprise exclusively of the economical parameters. Specifically, group G includes the *Price* of produced goods, group I the costs adjusted by the WEEE legislation (*Landfill_Cost* and *Penalty_Cost*) and group H all the remaining costs of the activities of CLSC (*Collection_Cost*, *Recycling_Cost, Redesign_Cost, Procurement_Cost and Consumer_Cost).*

6 Sensitivity analysis

In this section, we investigate the impact of sustainability on WEEE CLSCs through sensitivity analysis. The section provides a technical analysis of the impact of the ecological threats, the environmental sustainability strategies and the operational features of the CLSC on the environmental and economical sustainability of the WEEE CLSC leading to managerial insights with practical implications.

6.1 Experimental design

To assess the significance of the measurable characteristics and to specify the type of the impact and the magnitude of their interactions, we studied three experiments. At the first experiment, we use the ANOVA to understand the significance of the groups A, B, C, D, E, F, G, H and I on the availability of natural resources (*Natural_ Resources*), on landfill availability (*Sum_Disposal*) and on the profitability of CLSC (*Total_Supply_Chain_Profit*). *Sum_Disposal* equals with the sum of *Uncontrollably_ Disposed_ Products* and *Disposed_Products*; when *Sum_ Disposal* increases, the landfill availability decreases proportionally. We also specify the significance of their interactions and the type of their impact. For the ANOVA analysis, we used the commercial software package SPSS; ANOVA is a statistical technique for analysing data that tests for significant differences between means. To distinguish the significant parameters, we use *p*-value and partial eta squared. *p*-value reflects i.e. 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 to the error's significance.

Each of the nine groups of parameters is examined at three levels (Table 2). In the normal scenario, the values of all the groups' parameters are equal with those of the case study in Greece. In the pessimistic scenario, the values are 50% worse than those of the normal; such values could be observed at smaller European towns than the one taken under study. On the contrary, in the optimistic scenario, the values are 50% better than those of the normal scenario; such values are representative for bigger European towns. The number of all possible combinations of these nine groups of parameters is $3^9=19{,}683$; each combination was simulated twice to test for alternative generators of random numbers concerning the *Residence_Time* and *Demand*, leading to $2\times3^9=39{,}366$ simulations (first experiment).

At the second experiment we investigate which parameters or interactions generate the behaviour of the group that they belong to and we assess the type and the magnitude of their impact. Specifically, each of the parameters of a specific group is examined fixed at the same values with the three scenarios presented in Table 2 (pessimistic, normal and optimistic), while all the parameters' values of the remaining

Table 2 Levels of model parameters

Group	Parameters	Scenarios		
		Pessimistic	Normal	Optimistic
A	(a1): *Legislative_Collection_Percentage*	30%	60%	90%
	(a2): *Legislative_Recycling_Percentage*	30%	60%	90%
	(a3): *Legislative_Limit_of_Recyclability*	30%	60%	90%
	(a4): *Legislative_Limit_of_Recycled_Content*	30%	60%	90%
	(a5): *Tactics*	T2	T1	T3
	(a6): *Leg_Time* (weeks)	150	300	450
B	(b): *Quality*	30%	60%	90%
C	(c1): *Minimum_Collection_Percentage*	30%	60%	90%
	(c2): *Minimum_Recycling_Percentage*	30%	60%	90%
	(c3): *Minimum_Limit_of_Recyclability*	30%	60%	90%
	(c4): *Minimum_Limit_of_Recycled_Content*	30%	60%	90%
	(c5): *Redesign_Time* (weeks)	18	12	6
	(c6): Compliance to *Legislation* (weeks)	150	100	50
D	(d1): *Market_Behavior*	MB3	MB1	MB2
	(d2): *Return_Percentage*	30%	60%	90%
E	(e): *Initial_Resources* (items)	25,000	50,000	75,000
F	(f): *Initial_Landfill_Availability* (items)	900	1,800	2,700
G	(g): *Price* (€/item)	368	735	1,103
H	(h1): *Collection_Cost* (€/item)	13	26	39
	(h2): *Recycling_Cost* (€/item)	16.25	32.5	48.75
	(h3): *Redesign_Cost* (€/item)	2,400	4,800	7,200
	(h4): *Procurement_Cost* (€/item)	75	150	225
	(h5): *Consumer_Cost* (€/item)	2.5%	5%	7.5%
I	(i1): *Landfill_Cost* (€/item)	1	2	3
	(i2): *Penalty_Cost* (€/item)	1.6	3.2	4.8

groups change randomly between their values of the pessimistic and optimistic scenarios (again from Table 2).

At the third experiment, we concentrate on the influence of the significant interactions (that arose from the first experiment) of the significant groups' parameters (that arose from the second experiment). The significant parameters are examined fixed either at their values of the pessimistic scenario or at their values of the optimistic scenario, not considering the normal scenario due to the large number of the required simulations. The simulation horizon is 40 years and the integrating time step is 0.25 week.

6.2 Results and discussion

Table 3 contains the *p*-value and the partial eta squared for each of the significant influences concerning the first experiment. In our study, partial eta squared is very significant since it allows to determine not only which control factor affect the dependent parameter but also the magnitude of this effect. Thus, by changing the value of the control factor (independent parameter) with the highest partial eta squared value, it will be easier to adjust the dependent parameters to their desired values. For example, from the simulations' results, we have observed that the maximum value of *Total_Supply_Chain_Profit* is accomplished when all the parameters of the groups A, H and I are fixed at the values of the pessimistic scenario and all the parameters of the groups B, C, D, E and G at the values of the optimistic scenario, whereas it does not depend on the scenario of the parameter of group F. Concerning the groups G and B, they are both very significant (p-value=0) but the partial eta squared of the G group is about twice of the partial eta squared of the B group. Hence, if we keep the parameters of the groups A, B, C, D, E, H and I adjusted at such values in order the maximum *Total_Supply_Chain_Profit* to arise and at the same time, we change the value of the parameter consisting group G from the optimistic to the normal level, then there is a decrease in the value of the

Table 3 Results of analysis of variance tests (*p*-value/partial eta squared values) for the significant effects of groups A, B, C, D, E, F, G, H and I on *Natural_Resources*, *Sum_Disposal* and *Total_Supply_Chain_Profit* (first experiment)

Factor interaction	*Natural_Resources*	*Sum_Disposal*	*Total_Supply_Chain_Profit*
A	0.000*/0.122	0.000*/0.310	0.000*/0.042
B	0.000*/0.604	0.000*/0.031	0.000*/0.577
C	0.000*/0.235	0.000*/0.435	0.000*/0.290
D	0.000*/0.293	0.000*/0.627	0.000*/0.059
E	0.000*/0.999	0.000*/0.802	0.000*/0.974
G			0.000*/0.999
H			0.000*/0.976
I			0.000*/0.007
A*B	0.000*/0.038	0.000*/0.001	0.000*/0.035
A*C	0.000*/0.109	0.000*/0.250	0.000*/0.061
A*D	0.000*/0.018	0.000*/0.144	0.000*/0.060
A*E	0.000*/0.190	0.000*/0.032	0.000*/0.005
A*G			0.000*/0.081
A*H			0.000*/0.002
B*C	0.000*/0.097	0.000*/0.003	0.000*/0.101
B*D	0.000*/0.108	0.000*/0.006	0.000*/0.202
B*E	0.000*/0.709	0.000*/0.020	0.000*/0.039
B*G			0.000*/0.274
B*H			0.000*/0.012
C*D	0.000*/0.039	0.000*/0.207	0.000*/0.158
C*E	0.000*/0.300	0.000*/0.044	0.000*/0.010
C*G			0.000*/0.203
C*H			0.000*/0.002
D*E	0.000*/0.393	0.000*/0.082	0.000*/0.019
D*G			0.000*/0.277
D*H			0.000*/0.147
E*G			0.000*/0.979
E*H			0.000*/0.684
G*H			0.000*/0.058

*p-value ≤0.003

Total_Supply_Chain_Profit by 51.81%. However, if we change the values of all the parameters of group B from the optimistic to the normal level, there is a decrease in the value of the *Total_Supply_Chain_Profit* only by 3.83% by fixing parameters of the groups A, C, D, E, G, H and I at such values so as the maximum *Total_Supply_Chain_Profit* to arise.

ANOVA tests revealed that, concerning the main effects, the groups E, B, D, C and A have significant influence on the amount of *Natural_Resources*; the groups E, D, C, A and B have significant influence on *Sum_Disposal*; and the groups G, E, H, B, C, D, A and I have significant influence on *Total_Supply_Chain_Profit*. The groups are ordered according to their magnitude.

At the second experiment, the number of all possible combinations of the six parameters of group A is $3^6=729$; each combination was simulated three times to test for alternative generators of random numbers concerning the *Residence_Time* and *Demand*, leading to $3\times3^6=2{,}187$ simulations. In a similar way, we conducted 2,187 simulations to study the significance of the parameters of group C, 729 simulations for group H and 27 simulations for groups D and I. For the groups B, E and G that include only one parameter, we did not conduct any additional simulation runs since more simulation runs were executed at the first experiment increasing the results' reliability. Table 4 contains the *p*-value and the partial eta squared for each of the significant influences. Due to space reasons, the symbols used for the names' parameters are the same with those presented in Table 2.

The analysis of the impact of the economic parameters on the WEEE profitability of CLSC proceeded one step further to examine their significance if the profit (that is the difference between the products' price and the costs) is fixed very close to zero. The simulations' results confirm the significance of the *Procument_Cost* and the *Consumer_Cost* for the *Total_Supply_Chain_Profit* but also reveal the significance of the *Collection_Cost*, *Recycling_Cost* and the *Penalty_Cost*.

At the third experiment, we used the significant main effects and interactions of the groups that arose from the first experiment, and we concentrate on the influence of the significant interactions of the significant groups' parameters that arose from the second experiment; 14 significant parameters arose. The study of this impact on the *Total_Supply_Chain_Profit* would demand $3^{14}\times2=9{,}565{,}938$ simulations in case that each combination was simulated twice to test for alternative generators of random numbers concerning the *Residence_Time* and *Demand*. Due to this enormous number of simulations, each of the significant parameters is examined fixed at the values either of the pessimistic or of the optimistic scenario, not considering the normal scenario, leading to $2^{14}\times2=32{,}768$ simulations.

Table 5 contains the *p*-value and the partial eta squared for each of the significant influences of the third experiment. Due to space reasons, the symbols used for the names' parameters are the same with those presented in Table 2.

The analysis of the impact of the 14 significant main effects on the environmental and economical sustainability of the WEEE CLSCs proceeded one step further to reveal the exact type of the influence. The results of the ANOVA tests, shown in Table 6, lead to the following observations concerning the significant main effects on the available natural resources (*Natural_Resources*), the amount of

Table 4 Results of analysis of variance tests (*p*-value/partial eta squared values) for the significant effects of groups' parameters on *Natural_Resources*, *Sum_Disposal* and *Total_Supply_Chain_Profit* (second experiment)

Factor interaction	*Natural_Resources*	*Sum_Disposal*	*Total_Supply_Chain_Profit*
a1		0.000*/0.085	
a2	0.01*/0.006	0.000*/0.051	0.035**/0.004
a2*a3		0.006*/0.009	
a3*a4*a6		0.003*/0.015	
a1*a2*a3*a4*a5		0.008*/0.035	
c1		0.000*/0.100	
c2		0.000*/0.219	0.000*/0.018
c2*c3		0.002*/0.011	
c3*c5	0.003*/0.010		0.006*/0.010
c4*c5		0.005*/0.010	
d1	0.310/0.122		0.156/0.186
d2		0.000*/0.641	
h4			0.000*/0.770
h5			0.000*/0.045
i1			0.924/0.009

**p*-value ≤0.01

***p*-value ≤0.04

Table 5 Results of analysis of variance tests (*p*-value/partial eta squared values) for the significant effects of groups' parameters on *Natural_Resources*, *Sum_Disposal* and *Total_Supply_Chain_Profit* (third experiment)

Factor interaction	*Natural_Resources*	*Sum_Disposal*	*Total_Supply_Chain_Profit*
a1		0.000*/0.167	
a2	0.000*/0.140	0.000*/0.124	0.000*/0.014
a3		0.000*/0.012	
b	0.000*/0.916	0.000*/0.019	0.000*/0.385
c1		0.000*/0.188	
c2		0.000*/0.316	0.000*/0.087
c3		0.000*/0.019	0.000*/0.004
d1	0.000*/0.480		0.000*/0.023
d2		0.000*/0.654	
e	0.000*/0.999	0.000*/0.112	0.000*/0.836
g			0.000*/0.997
h4			0.000*/0.930
h5			0.000*/0.157
i1			0.002*/0.002
a1*a2		0.000*/0.003	
a1*c1		0.000*/0.165	
a1*c2		0.000*/0.009	
a1*d2		0.000*/0.167	
a2*a3		0.000*/0.014	
a2*b	0.007*/0.043		0.000*/0.013
a2*c1		0.000*/0.003	
a2*c2		0.000*/0.124	0.000*/0.024
a2*c3	0.000*/0.073	0.000*/0.018	
a2*d1			0.010*/0.001
a2*d2		0.000*/0.026	
a3*c2		0.000*/0.014	
a3*c3		0.000*/0.016	
a3*d2		0.000*/0.002	
b*c2			0.000*/0.035
b*d1	0.000*/0.159		0.000*/0.005
b*d2		0.000*/0.001	
c1*c2		0.000*/0.010	
c1*c3		0.006*/0.001	
c1*d2		0.000*/0.184	
c2*c3		0.000*/0.020	
c2*d1			0.000*/0.006
c2*d2		0.000*/0.084	
c3*d2		0.000*/0.004	
a2*e	0.000*/0.140	0.000*/0.001	0.000*/0.003
b*e	0.000*/0.916	0.000*/0.007	0.000*/0.033
c1*e		0.000*/0.001	
c2*e		0.000*/0.002	0.000*/0.004
d1*e	0.000*/0.480		0.000*/0.003
d2*e		0.000*/0.009	
a2*g			0.000*/0.009
b*g			0.000*/0.187
c2*g			0.000*/0.049
d1*g			0.000*/0.042

Table 5 (continued)

Factor interaction	*Natural_Resources*	*Sum_Disposal*	*Total_Supply_Chain_Profit*
e*g			0.000*/0.908
a2*h4			0.039**/0.001
b*h4			0.000*/0.014
c2*h4			0.001*/0.002
e*h4			0.000*/0.282
g*h5			0.000*/0.046
a2*a3*c2		0.000*/0.017	
a2*a3*c3		0.000*/0.014	
a2*a3*d2		0.000*/0.003	
a2*c2*c3		0.000*/0.019	
a3*c2*c3		0.000*/0.015	
c2*c3*d2		0.000*/0.004	
a2*c3*c5			0.000*/0.005
c3*c5*g			0.000*/0.003

*p-value ≤0.01

disposed products ending up to landfills (*Sum_Disposal*) and the total supply chain profit (*Total_Supply_Chain_Profit*):

1. The amount of disposed products ending up to landfills decreases (down arrow in the table) when stricter measures concerning the collection percentage (a1) and the limit of recyclability are imposed by the environmental legislation (a3), or the firms develop collection activities even if there are no environmental regulations imposing them (c1) or the consumers return more used products back to the reverse channel (d2).
2. The available natural resources and the total supply chain profit increase, whereas the amount of disposed products ending up to landfills decreases when stricter measures concerning the recycling percentage (a2) are imposed by the environmental legislation.
3. The available natural resources, the amount of disposed products ending up to landfills and the total supply chain profit increase when the firms produce (or procure from recyclers) recycled materials of high quality (b). Specifically, when recycled materials of better quality are produced through the recycling operations, less natural resources are procured, and the products' demand increases (due to the *GIF*) increasing the amount of disposed used products. Exactly the same behaviour is observed when the initial amount of available natural resources (e) increases since more goods are produced.

Table 6 Impact of the significant main effects of groups' parameters on *Natural_Resources*, *Sum_Disposal* and *Total_Supply_Chain_Profit* (third experiment)

		Natural_Resources	*Sum_Disposal*	*Total_Supply_Chain_Profit*
a1	a1↑		↓	
a2	a2↑	↑	↓	↑
a3	a3↑		↓	
b	b↑	↑	↑	↑
c1	c1↑		↓	
c2	c2↑		↓	↑
c3	c3↑		↓	↑
d2	d2↑	↓		↑
d1	d1↑		↓	
e	e↑	↑	↑	↑
g	g↑			↑
h4	h4↑			↓
h5	h5↑			↓
i1	i1↑			↓

4. The total supply chain profit increases, whereas the amount of disposed products ending up to landfills decreases when the firms develop recycling activities (c2) or redesign activities according to the DfE principles (c3) even if there are no environmental regulations imposing them (c3).
5. The total supply chain profit increases, whereas the available natural resources decrease in case of more environmental sensitive consumers (d1). Specifically, when the consumers are more environmental sensitive, the products' demand increases (due to the green image), increasing the total supply chain profit but decreasing the available natural resources since more products must be produced to satisfy demand.
6. The total supply chain profit increases not only increasing the products' price (g) but also decreasing the procurement cost of natural resources (h4), the fee supplied to the consumers who return their used EEE back to the reverse channel (h5) and the landfill cost of the disposed products (i1).

6.3 Practical implications

From Table 6 arise some observations, which, combined with the results of the first and the second experiments, reveal the following insights:

- *Legislators*: The legislators should enforce the recycling percentage in order to protect the availability of natural resources. Moreover, they should enforce the collection, recycling and recyclability percentages established in legislation in order to protect the availability of landfills.
- *Management of the firms*: The management of the firms should produce (or procure from recyclers) recycled materials of high quality as substitutes of natural resources for the production of new goods and to sustain the availability of natural resources. They should also invest in the collection and recycling activities and redesign their products according to the DfE principles to protect the availability of landfills. Moreover, they should produce (or procure from recyclers) recycled materials of high quality and invest in recycling activities and redesign their products according to the DfE principles to sustain their profitability. It is obvious that the profit of CLSC increases by increasing the price of the products and, at the same time, decreasing the procurement cost of original raw materials, the fee supplied to the consumers who return their used EEE back to the reverse channel of the CLSC and the landfill cost. To increase the products' price, the management of the firms should connect their green image to the price. To decrease the procurement cost of original raw materials, the recycling firms should produce recycled materials of high quality. Finally, to decrease the landfill cost, the firms should increase their collection activities.
- *Environmental conscious market*: The environmental sensitive consumers "reward" the firms that produce (or procure from recyclers) recycled materials of high quality or the firms that develop recycling operations by increasing the GIF. However, this decision increases the firm's sales demand and increases also the used products and the products that end up to landfills after their usage period decreasing the availability of landfills. Moreover, incentives should be given to the consumers in order to increase the returns of their used products and to decrease the used products ending up to landfills.
- *Environmental and economical sustainability*: The recycling percentage established in the legislation seems to be the only way to positively affect both the environmental and the economical sustainability; hence it does not affect the sustainability negatively as it is supported by the management of many firms [24]. Moreover, it is obvious that the management of the firms are not so stressed to develop recycling activities or to produce recycled materials of high quality when the available natural resources are abundant. However, nowadays this is not the case, and the firms should aim on sustaining the lifetime of natural resources because of its strong impact on the environmental and the economic aspects of sustainability. Finally, the production (or procurement from recyclers) of recycled materials of high quality improves the economical sustainability and the availability of natural resources. However, this decision increases the product sales and increases also the used products and the products that end up to landfills after their usage period deteriorating the availability of landfills. In such circumstances, the decision regarding investments on aspects of sustainability depends on the employed criterion. In cases that the employed criterion is economical sustainability, the firms should promote their green image to the consumers. However, if the employed criterion is availability of natural resources, the firms should not invest on such promotion. If the employed criteria are both economical sustainability and availability of natural resources, the firms must focus on producing (or procuring from recyclers) recycled materials of high quality.

7 Summary and future research

In this manuscript, we used an extension of the SD model of a CLSC with recycling activities introduced by Georgiadis and Besiou [18], including dynamically the economical dimension of the sustainability. The contribution of this work is using the dynamic model to assess not only the significance of the factors comprising the ecological threats, the environmental sustainability strategies and the operational features of the CLSC on the environmental (availability of natural resources and landfill availability) and economical sustainability of a WEEE CLSC but also to specify the type of the impact and the magnitude of their interactions. The extended numerical investigation provided insights according to the impact of various parameters, both internal and external to the WEEE operations of CLSC, on the environmental and economical sustainability.

The results presented in this paper certainly do not exhaust the possibilities of investigating all the influences on sustainability. A limitation of the SD model is the absence of the social aspect of sustainable development.

Another limitation is that it ignores that most of the natural resources needed for the production of EEE are not mined in Greece but are imported from other countries, and some of the EEE produced by Greek manufacturers are exported abroad since they leave the system's boundaries. However, these two actions could be incorporated in the model in case of available data. A third model limitation is that in most developed countries waste that can not be recycled is incinerated. Under these circumstances, in the model, the variable concerning the amount of products ending up to landfills could be used to calculate the amount of products that are incinerated and not recycled. In a similar way, the variable expressing the delay between imposition of regulation and firms' compliance to them could be omitted from the model in case of countries that had already volunteer take-back schemes prior to legislation.

The developed model can be extended from the narrow boundaries of a specific geographical state to that of a country or even to receive global dimensions depending on the availability of the necessary data. For example, the GIF considering both the effect of collection and recycling activities of WEEE or the environmental regulations could concern a specific country, whereas the producer willing to use recycled materials for the production of new EEE or the supplier of natural resources (or the mine) could be in a different country in another side of the world. Moreover, the company performing the recycling activities can develop recovery activities in other neighbour countries as well. For instance, besides the Greek WEEE manufacturer Pitsos, few global WEEE manufacturers serving also the Greek market are Bosch, Electrolux, General Electric, LG, Siemens and Whirpool. These manufacturers are known for their interest in sustainability. Specifically Bosch and Siemens constitute BSH (http://www.bsh-group.de/), which aims at the production of recyclable products, while Electrolux is a member of ErP (http://www.electrolux.com/node216.aspx) and GEODIS (http://www.geodis.com/); both of these two companies deal with recovery operations of WEEE. Therefore, this model could be used by a manufacturer e.g. Electrolux, whose headquarters is in the USA, selling its products to a market in a different country e.g. the German, while the recovery operations can be performed by a firm whose headquarters can be in a different country e.g. GEODIS with headquarters in the UK.

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