Official Recycling and Scavengers: Symbiotic or Conflicting?
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Maria Besiou*

Patroklos Georgiadis**

Luk N. Van Wassenhove***

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* PhD, Research Fellow at INSEAD Social Innovation Centre, Boulevard de Constance, 77300 Fontainebleau, France, E-mail: maria.besiou@insead.edu

** Aristotle University of Thessaloniki, Department of Mechanical Engineering, P.O. Box 461, 54124 Thessaloniki, Greece, Email: geopat@auth.gr

*** Professor of Operations Management, The Henry Ford Chaired Professor of Manufacturing, INSEAD Social Innovation Centre at INSEAD Boulevard de Constance, 77300 Fontainebleau, France, Email: luk.van-wassenhove@insead.edu

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Abstract

For decades, if not for centuries, collection of end-of-use products was performed by scavengers, especially if these products could be reused or if there was value to be recovered. Nowadays, most societies in their effort to increase availability of natural resources and avoid landfills have displaced scavengers by formal waste collection systems. However, scavenging still exists, mainly in case of collection capacity shortages or low standard of living. While the participation of scavengers in waste collection systems has a social dimension, economical and environmental dimensions are also important. Informal recycling of waste electrical and electronic equipment by scavengers not only constrains profits of the formal system. In their effort to recover the value of used products scavengers also pollute the environment. In this paper we develop a system dynamics model to study the impact of scavenging on the operations of the formal recovery system of waste electrical and electronic equipment. We consider three different regulatory measures; a legislation that ignores scavengers though they participate, a legislation setting barriers to the participation of scavengers and a legislation that incorporates them into the formal waste management system. We use data from a real world closed-loop supply chain that operates in Greece. Extended numerical experimentation investigates the impact of the three different regulatory measures on economical, environmental and social sustainability. The results show that a legislation that incorporates scavengers into the formal waste management system is beneficial for all aspects of sustainability.

Keywords: Supply Chain Management; Scavengers; WEEE; Sustainable Development; System Dynamics
1. Introduction

Recently, mass consumption and the tendency of shortening lifecycles of consumer products have increased worldwide production of goods and led to indiscriminate disposal habits. The usage rate of raw materials is increasing and available landfills are filling up, while new ones cannot be easily located due to residents’ reactions (González-Torre et al., 2004). One of the major and fastest growing waste streams in the world is from waste electrical and electronic equipment (WEEE) (Hischier et al., 2005), which also appears as one of the biggest sources of environmental footprint (Neto et al., 2007). WEEE contains toxic substances such as lead, cadmium and mercury. While these toxins are embedded inside the appliance and separated from the user during operation, concerns have been raised regarding the environmental risk associated with toxic substances leaching when WEEE is disposed of in landfills (Williams et al., 2008). Nearly 40% of the lead disposed in landfills and 50% of the lead in incinerators comes from WEEE (Toffel, 2003). According to estimations the amount of WEEE in Europe increases 16%-28% every year, three times faster than the average municipal waste (Ylä-Mella et al., 2004). It is estimated that by the end of 2010 the amount of WEEE will be 3.9 kilograms - 4.3 kilograms per resident leading to a total of 12 million tons (Widmer et al., 2005).

Under these circumstances governments all around the world impose stringent environmental regulations, through increased collection and recycling percentages and restricting the usage of certain hazardous substances (Directive 2002/96/EC; Directive 2002/95/EC). However, informal waste recycling activities are still carried out by specific social groups. The informal recycling sector (also known as “grey” recycling) refers to the waste recycling activities of scavengers and waste pickers (Medina, 2000; Wilson et al., 2006) and corresponds to a significant part of the total recycling sector both in developed [for example in Germany by handicapped people (Tobias, 2009)] and developing countries [for example in Mexico by Catroneros and Buscabotes (Wilson et al., 2006)].

Scavenging is a widespread phenomenon with environmental, economical and social dimensions. Scavengers are usually people with limited employment potential who make their living by collecting all kinds of materials for reuse or recycling and by directly extracting recyclable and reusable materials from waste. However, the participation of scavengers often creates a barrier to formal solid waste collection operations. For example according to estimations about 90% of WEEE in Greece in the time period 2003 - 2006 was processed by “grey” recycling (Aravossis et al., 2007; Antonopoulos and Karagiannidis, 2007).

Many researchers have studied the operations of reverse supply chains and official waste streams, but most ignored scavenging. Scavenging has implications not only for the societies where they operate but also for the firms that develop reverse logistics activities. The absence of scavenging in reverse logistics studies raises the question of practical relevance; especially for developing and developed countries where informal recycling is still substantial. Noticeable exceptions are the studies of Medina (2000) and Wilson et al. (2006).
The attitude of the formal waste management system to scavengers is often negative, regarding scavenging as potentially harmful to health and generally incompatible with a modern waste management system (Wilson et al., 2006). Some regulatory measures declare scavenging as illegal and scavengers get punished, while others simply ignore informal recycling hoping it will disappear in the foreseeable future (Medina, 2000). However, considering the economical crisis and the living conditions of scavengers throughout the world, this hope could be considered idle.

Studies on scavenging concentrate on problem identification, driving forces, cause-effect and social impact, but from a qualitative point of view. In this paper we develop a holistic approach to comprehend the interactions of scavenging with formal waste management systems and to study the impact of scavenging on environmental, economical and social aspects of sustainability. We develop a comprehensive dynamic closed-loop supply chain (CLSC) model which enables the joint examination of formal and grey recycling operations. In particular, we consider a WEEE recovery system imposed by environmental legislation and study the impact of the regulatory measures, the scavengers’ activities and the formal waste recovery system activities. The used methodological tool is System Dynamics (SD). To estimate parameters we apply the model to recycling activities in Central Macedonia in Greece.

The innovative elements of our work are twofold. Firstly, we study the impact of scavenging on the operations of a WEEE recovery system through the environmental dimension (pollution due to the scavengers’ uncontrollable disposal, natural resources and landfills availability), the economical dimension (CLSC profitability) and the social dimension of sustainability (number of unemployed scavengers). Secondly, we assess the efficiency of different regulatory measures in limiting the inherent risk of informal recycling on the economical, environmental and social aspects of sustainability. We study the efficiency of three different regulatory measures; the current “real” system in which the environmental legislation ignores scavenging, the “ideal” system where the informal recycling sector has disappeared as a result of the legislation, and the “symbiotic” system where the legislation supports scavenging as symbiotic to the formal system. The above analysis is performed by extended numerical investigation with parameter values at different levels in combination with Analysis of Variance (ANOVA) to analyse the sensitivity of the system.

In the next section we present a literature review of studies describing the impact of scavenging on societies. We also provide a brief presentation of System Dynamics methodology. In Section 3 we present the structures of the “real”, the “ideal” and the “symbiotic” system. In Section 4 we implement the model in a real-world CLSC with recycling activities of EEE in Greece, while in Section 5 we conduct sensitivity analyses to study the impact of alternative regulatory measures on the sustainability of the system under study. The final section presents a summary of the results.
2. Literature Review

There are many studies that present the dimensions of scavenging and the cause-effects at a city level. According to Medina and Dows (2000), only 50% - 80% of the waste generated in cities within developing countries is usually collected, with open dumping as the only available disposal method. The World Bank has estimated that in developing countries about 1% of the population makes a living by scavenging (Medina, 2007). In most of such cities, scavenger settlements are located near landfills in order to respond to scarcity and use the discarded materials in their households, to have easy access and to reduce transportation costs (Brunner and Fellner, 2007). In Dhaka city waste recovery and recycling are performed by more than 100,000 scavengers, in Calcutta by 20,000, in Manila by 12,000 and in Mexico City by 15,000. Informal recyclers often belong to marginalised social groups or minorities, such as the Pepenadores, Catroneros and Buscabotes in Mexico, Basuriegos, Cartoneros, Traperos and Chatarreros in Colombia, Harijans in India, Chambers in Ecuador, Buzos in Costa Rica and Cirujas in Argentina (Medina and Dows, 2000; Berthier, 2003), Roma people in Europe (Karagiannidis et al., 2008) and Zabbaleen in Egypt who belong to a Christian minority.

In Third World cities that lack municipal waste collection, scavengers play the role of official collection systems. For example, in the Mexico City suburbs of Ciudad Nezahualcoyotl, Chalco and Iztapaluca, scavengers using different transport means, such as pick-up trucks, tricycles, push carts and horse carts provide service in areas not served by the municipal collection system (Figure 1). In Santa Cruz (Bolivia) scavengers serve about 37% of the population, in Dhaka city (Bangladesh) serve more than 50%, while in Damascus City (Syria) thousands of scavengers serve about 10% of the population. In some Indian communities, informal collectors charge a fee to residents for picking up their garbage and for cleaning the street in front of their houses (Phatak, 1993).

*Figure 1 about here*

Usually, informal recycling is carried out by poor and marginalised social groups who resort to scavenging to generate income for everyday survival. These people are often poorly educated. Economical conditions and limited employment opportunities drive them to informal recycling. Scavenging is also amplified by insufficient collection, uncontrolled street collection points and improper disposal in open landfills that allow disposed products to be readily available for informal waste recycling. Brunner and Fellner (2007) investigated whether the waste management systems applied in developed countries are appropriate solutions for waste management in less developed regions. Specifically, they studied how variations in economic conditions determine waste management strategies, concepts and measures. They consider three distinctly different regions in terms of economic conditions (Vienna, Damascus, and Dhaka) and conclude that the less developed countries do not have the same economic capacity for the collection and treatment of their waste. The hygienic risk for inhabitants having direct contact with waste can only be reduced by the introduction
of a complete and formally structured collection service. However, the income of thousands of scavengers would be cut by this measure.

Scavenging has environmental, social and economical dimensions. In developing countries informal recycling of electrical and electronic equipment causes serious environmental problems and has come under increasing public scrutiny (Williams et al., 2008). The improper disposal of waste constitutes a source of land, air and water pollution, and poses risks to human health. Half the collected waste is dumped illegally in vacant lots or openly burned in residential areas, which is associated with major health hazards for people living in these neighborhoods (e.g. hygiene problems, spreading of diseases, smoke emissions, etc.) (Brunner and Fellner, 2007). For example, wires are burned in open piles to remove casings and recover copper after they are pulled from computers. Circuit boards are treated to recover precious metals using acid, sometimes next to rivers.

The health and safety risks for the scavengers are even more acute given that they usually live on or next to landfills. According to Medina (2000), Mexico City scavengers have a life expectancy of 35 years, while the general population's is 67 years. Another social dimension is that scavengers, due to their way of life, are often marginalised as their activities are considered unhygienic (Medina and Dows, 2000) and they constitute a subject of harassment by the authorities and police (Eerd, 1996).

The informal sector is largely unregulated and unregistered (Wilson et al., 2006). Therefore, scavengers or informal sector enterprises do not pay taxes, have no trading license and are not included in social welfare or government insurance schemes (Haan et al., 1998). The informal system also constitutes a very efficient and hard competitor of legal collection and recovery systems.

However, scavenging can render significant social and economical benefits. Firstly, if addressed properly, it can be “symbiotically” incorporated into the formal waste management system. This incorporation a) will improve the efficiency of the formal system, b) will help the implementation of environmental regulations (such as the WEEE Directive), c) will save energy and water while generating less pollution than the procurement of virgin materials (especially in developing countries where the formal system has limited capacity), d) will reduce the required collection and disassembling capacity, and their costs, e) will create jobs for unskilled individuals, and f) could bring some control over the scavengers’ operations, aiming to stop illegal dumping by keeping them accountable for their actions and creating incentives to bring the collected end-of-use products to specific places. Secondly, in case the informal sector is further marginalised or declared illegal, unemployment and crime will increase (Medina, 2000) and scavengers may get exploited by corrupt government officials (such as in Mexico City).

It is an open question whether scavenging should be incorporated in the formal waste management system, confronted as illegal and punished (such as in several Colombian, Indian, and Philippine cities) or ignored (such as in several African cities). Although scavenging is an issue that appears both in developing and developed countries, affecting operations and in some cases even viability of formal
waste management systems, rarely a comparison of costs and benefits of the incorporation of scavengers by the formal system is performed (Medina, 2000). In this paper we develop a mathematical model to comprehend the interactions of scavenging with the formal waste management system and to investigate the impact of different regulatory measures on the system’s sustainability. The System Dynamics (SD) methodology we use is a modeling and simulation tool for obtaining insights into problems of dynamic complexity. It is used when a system is full of feedbacks, there are stochastic variables and the behaviour of the system is dynamic (Sterman, 1991). The model can have both quantitative and qualitative variables. These conditions are satisfied for supply chain systems (Georgiadis et al., 2005) and for environmental systems (Bloemhof-Ruwaard et al., 1995). In this paper the dynamic system under study is full of feedbacks, hence SD is an appropriate analysis tool. Forrester introduced system dynamics methodology in 1960 for dynamic management problems (Forrester, 1961). The publications “World Dynamics” (Forrester, 1971) and “Limits to Growth” (Meadows et al., 1972) increased the interest for environmental issues. Since then SD has been applied to various environmental problems, business policy and strategy (Sterman, 2000). However, few strategic sustainability problems in CLSC are reported in the literature. Specifically, Van Schaik and Reuter (2004) present a model for vehicle recovery incorporating EU legislation targets. Georgiadis and Besiou (2010) study economical and environmental sustainability of a CLSC of electrical and electronic equipment.

3. The System under Study

We present three different structures of the system under study. In subsection 3.1 we introduce the current system (“real” system) where the informal recycling sector constrains the activities of the formal waste management system. In subsection 3.2 the “ideal” system is presented, where the informal recycling sector has disappeared, while in subsection 3.3 we outline the structure of an alternative system where the scavengers are symbiotic to the formal system.

3.1. The Structure of the “real” system

In Figure 2 we present a simplified version of the system under study. The forward channel of the CLSC consists of three actors: producers, distributors and the market, and it incorporates the activities of procurement of natural resources, production, distribution and product use. The reverse channel consists of the formal waste management system. It incorporates the following activities: collection of end-of-use products, recycling and disposal. We assume that the only recovery activity the CLSC develops is recycling, required by environmental legislation. For the recovery of the end-of-use products, besides the formal waste management system, there are scavengers who collect used products the formal system fails to collect.

Figure 2 about here

The producers consist of two echelons: the inventory of raw materials and the serviceable inventory of end products. Their demand for raw materials is satisfied by a mix of natural resources (procurement
rate), and recycled materials (recycling rate). End products are transported to distributors and end up in the market according to demand. The formal waste management system starts at the end of the product usage period. The collection and recycling activities of the formal waste management system are the outcome of decision-making processes which are also influenced by environmental legislation through minimum levels for collection and recycling percentages. However, there is a time delay between the imposition of regulations and firm compliance with them due to lack of human and financial resources essential for implementation (Georgiadis and Besiou, 2010).

Used products not collected by the formal system end up with scavengers, if their capacity is sufficient, or in landfills. Scavengers recover any possible value from collected products, usually by applying practices with negative impact to the environment, thus creating pollution. If the collection capacity of the formal system or the legal collection percentage is low, the collection rate of scavengers increases which leads to an increase in environmental pollution. On the other hand, in case of high collection capacity of the formal system or high legal collection percentage, the amount of used products scavengers manage to collect decreases, causing their unemployment, which may lead to criminal actions. The inventories in the system of Figure 2 are managed by a “pull-push” policy. We adopt a “pull” policy in the forward channel to maintain better stock control (Van der Laan et al., 1999), while we use a “push” policy in the reverse channels to achieve faster system response.

Figure 3 depicts the simplified causal-loop diagram for the definition of the rates in the reverse channel of the system under study (Recycling Rate, Collection Rate from Recovery System, Collection Rate from Scavengers, Uncontrollable Disposal). In SD, causal-loop diagrams are used to describe the system’s feedbacks (Sterman, 2000). The arrows in Figure 3 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 opposite direction. In the remainder of the paper variable names are shown in italics.

*Figure 3 about here*

The diagram consists of four balancing feedback loops. In Loop1 an increase in Uncontrollable Disposal decreases Landfills Availability, forcing governments to impose stringent Environmental Legislation through increased Legislative Collection Percentage of used products. The formal system, due to the time delay, achieves a Collection Percentage that increases the Collection Rate from Recovery System leading to a decrease in Uncontrollable Disposal.

In Loop2 a decrease in Natural Resources Availability forces government to impose stringent Environmental Legislation through Legislative Recycling Percentage of collected products. The formal system, again due to the time delay, achieves a Recycling Percentage that increases the Recycling Rate leading to an increase in Natural Resources Availability. The formal waste management system pays
fines according to the deviation of the *Collection Rate from Recovery System* and *Recycling Rate* from the *Legislative Collection Percentage* and *Legislative Recycling Percentage*, respectively.

In Loop3 an introduction of a stringent *Legislative Collection Percentage* through the *Environmental Legislation* increases the *Collection Percentage* and the *Collection Rate from Recovery System*. Hence, the number of collected products increases, increasing the *Recycling Rate* and the *Natural Resources Availability* allowing the governments to impose not so strict *Environmental Legislation*.

Finally, in Loop4 an increase in *Uncontrollable Disposal* decreases *Landfills Availability*. Stringent *Environmental Legislation* is imposed through the *Legislative Collection Percentage* increasing the *Collection Percentage* and the *Collection Rate from Recovery System*. Therefore, there are not many used products for scavengers to collect and the *Collection Rate from Scavengers* decreases, decreasing the *Uncontrollable Disposal*. The *Collection Rate from Scavengers* increases *Pollution* but decreases *Unemployment*.

In Figure 4 we present the generic stock and flow diagram of the system. In system dynamics methodology, stock and flow diagrams are used as graphical representations of the mathematical formulation. The mathematical equations are divided in two main categories: the level equations, which define the accumulations (level variables) within the system through the time integrals of the net flow rates (flow variables), and the rate equations, which define the flows among the levels as functions of time (Sterman, 2000). Level variables are represented by rectangles and flow variables are represented by valves. Forecasts are shown in small italics, levels in capital letters, and other parameters in small plain letters.

*Procurement Rate* is determined by employing the stock management structure suggested by Sterman (1989). Specifically, the *Procurement Rate* results from combining the *Expected Producer’s Orders* with an adjustment that brings *Raw Materials Inventory* in line with its desired value [stock management structure suggested by Sterman (1989)]. The same control rule is used for the rates of *Producer’s Orders* and *Distributor’s Orders*. *Controllable Disposal* drains the *Recyclable Products* if they remain unused for more than *Recyclable Stock Keeping Time* to prevent endless accumulation.

*Figure 4 about here*

The profitability of the CLSC under study is evaluated by calculating the net present value of total revenues per period minus total costs per period. Total cost per period includes the supply chain’s operational cost and fines, which arise when the CLSC does not comply with the regulations and due to the pollution produced by the scavengers’ activities since the formal waste management system is responsible for the end-of-use products. The operational cost comprises the procurement cost of original raw materials, production cost, collection cost, recycling cost, holding costs, transportation costs and landfill cost. *Switch1* and *Switch2* are variables indicating a switch from the “real” system (*Switch1 = 1, Switch2 = 0*) to the “ideal” system (*Switch1 = 0, Switch2 = 0*) or to the “symbiotic” system (*Switch1 = 1, Switch2 = 1*).
3.2. The Structure of the “ideal” system
Figure 5 depicts the causal-loop diagram for defining the rates in the reverse channel of the “ideal” system, where collection and recycling activities are developed only by the formal waste management system. The diagram consists of only three balancing feedback loops (Loop1, Loop2 and Loop3), which are identical to Figure 3. The profitability of the system is similar to the profitability of the “real” system in Figure 4 but now there is no fine for the pollution produced by the scavengers.

3.3. The Structure of the “symbiotic” system
The causal-loop diagram for the definition of the rates in the reverse channel of the “symbiotic” system is presented in Figure 6. In the “symbiotic” system scavenging is incorporated into the formal waste management system. The diagram consists of four balancing feedback loops (Loop1, Loop2, Loop3 and Loop4). Loop1, Loop2 and Loop3 are identical to Figure 3. In Loop4 the only difference with Figure 3 is that now the Legislative Collection Percentage increases also the Collection Rate from Scavengers, since they act in a symbiotic way with the formal system and the fines are depleted (it is easier now for the formal system to comply with the regulatory measures). The profitability of the “symbiotic” system is similar to that of the “real” system but now there is no fine for the pollution produced by the scavengers and the operational cost is increased due to the scavengers’ collection cost.

4. Empirical Study
To study the dynamic behaviour of our model, we used data from Greece. In 2001, Greece introduced a law to harmonise the national legislation with the current European Directives concerning packaging and other wastes, including WEEE. This law allowed harmonisation with the Directive 2002/96/EC, according to which the first collection and treatment targets should be attained by December 2008. One of the difficulties the Greek formal waste management system (Appliances Recycling S.A) had to face was grey recycling, which is still carried out mainly by Roma people (Karagiannidis et al., 2008). In Europe the Roma population is estimated between 7,000,000 and 8,500,000 (Liegeois and Gheorghe, 1995), while the Greek Roma people are estimated at around 200,000. Roma people mainly earn their living through trading obsolete electrical and electronic appliances, which have generally non-negligible and often significant economic value due to their high content of ferrous metals (Taylor, 1999). Illiteracy in the adult Roma population is about 90%, which is the main reason forcing them to be self-employed in the “traditional” profession of scavenging. The introduction of barriers for the scavengers will result in significant unemployment in Roma people, with social side effects. A crucial question that arises is whether these people should be incorporated into the formal system. In 2005 the formal system collected only 107 tonnes of WEEE. In 2007 the collected amount increased sharply to 30,000 tonnes of WEEE, and in 2008 Greece achieved the collection target of 44,000 tonnes. However, since the maximum recycling capacity of the formal system for WEEE is estimated
at 100,000 tonnes/year more used electrical and electronic products could be recycled to provide a secondary supply of raw materials for the local manufacturing industry, substituting more expensive imported ones. The scavengers could contribute to the system by collecting and transporting WEEE to legal collection points. Furthermore, the system’s collection capacity would not have to be increased to satisfy the legislation’s requirements and valuable landfill space will be preserved. It is remarkable that in Greece there is already a municipality where Roma people have formed an enterprise and are dealing with collection and disassembly of WEEE (Karagiannidis et al., 2008).

To estimate the values of the model’s variables we used data from different stakeholders in the region of Central Macedonia: a producer of electrical and electronic equipment, one firm that deals with collection and recovery of refrigerators and a few smaller firms trading recycled materials, procured from scavengers. The region of Central Macedonia represents about 20% of the total population of Greece. The largest city in this region is Thessaloniki, the second city in Greece.

The current system operates in a way similar to that of Figure 4. The producer’s demand for raw materials is satisfied with a mix of natural resources and recycled materials. The serviceable inventory ends up in the market and at the end of its usage period it is collected either from scavengers or from the formal waste recovery system, which has been developed due to the environmental legislation on WEEE. The scavengers use their collected products to recover any possible value, creating pollution, and they sell the recovered materials to traders. The WEEE collected by the formal system is transferred to the collection facilities, where dismantling and sorting activities take place. We focus our study on white goods, particularly on refrigerators.

4.1. Numerical Investigation

Data collected by the authors included a) interviews with production, collection and recycling activity managers and, b) census data. To estimate Demand and Residence Time (the time a product stays with the customer before its end of use), we used the results from a field survey on WEEE conducted in the area of Central Macedonia (Karagiannidis et al., 2003). To estimate time delay between imposition of regulations and firm compliance, we used data for WEEE collected in Greece from the case study of Georgiadis and Besiou (2008). In Appendix we present the values of the model parameters.

We checked the model’s validity by conducting tests suggested by the SD literature (Sterman, 2000; Barlas, 1996). 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 example, we checked that if no Used Products are collected, then only Natural Resources are used for production or if there is no Demand, production ceases. Finally, integration error tests were subsequently conducted. In our model we used the Euler numeric method since the integration method Runge-Kutta should be avoided in models with random disturbances such as this one (Demand is not constant). We chose a simulation horizon of 40 years to be able to analyse strategic decisions and an integrating time step equal to ¼ week, since the shortest time constant in the model is one week.
In Table 1 we present the values of Natural Resources, Sum Disposal (Sum Disposal equals the sum of Uncontrollably Disposed Products and Disposed Products; when Sum Disposal increases, the landfill availability decreases proportionally), Pollution, Total Supply Chain Profit (the CLSC’s profitability) and Unemployed Scavengers at the end of the simulation period for the three different systems (“real”, “ideal”, “symbiotic”). As can be seen, the behaviour of the “symbiotic” system is better than the other two. Specifically, in the “symbiotic” system the amount of available natural resources is bigger than the corresponding amount in the “real” system, and the number of disposed products in the “symbiotic” system (Sum Disposal plus Pollution) is less than the corresponding amount in the “real” and “ideal” systems. Even the system’s profitability is improved since it is easier for the formal system to comply with the legislation’s requirements.

Table 1 about here

Figure 7 illustrates the dynamic behaviour of the Total Supply Chain Profit for the three different systems for a period of 40 years. The interesting observation is that the Net Present Value (NPV) of the formal system in the “real” case increases for a time horizon of 19 years, but turns to negative values for a time horizon of 9 years. The joint examination of the results presented in Table 1 and the dynamics shown in Figure 7 reveals that the “real” system in a strategic horizon of 31 years will not be able to comply with environmental legislation and will be unprofitable.

Figure 7 about here

5. Results of Sensitivity Analysis

In this section we investigate the impact of regulatory measures, scavengers’ activities and formal waste recovery system activities on sustainability of the three systems. More specifically, regulatory measures refer to Legislative Collection Percentage and Legislative Recycling Percentage, scavengers’ activities to Initial Scavengers, Scavengers Capacity and Scavengers Collection Cost, formal waste recovery system activities to formal system’s collection capacity (System Collection Capacity), its Recycling Capacity and the Collection Cost. We examined the effects of the above 8 parameters (control factors) on sustainability using Analysis of Variance. Sustainability is described by its dimensions; the environmental dimension which depends on the amount of Natural Resources, the Sum Disposal and Pollution, the economical dimension which depends on Total Supply Chain Profit and the social dimension which depends on number of Unemployed Scavengers. Each of the 8 control factors is examined at three levels given in Table 2. In medium level (2) the values are equal to those presented in Appendix. In low level (1) the values are 50% lower than those of the medium level while in high level (3) the values are 50% higher than those of the medium level. The total number of all possible combinations is $3^8 = 6,561$; each combination was simulated twice to test for alternative generators of random numbers concerning the products’ Demand, leading to $2 \times 3^8 = 13,122$ simulation runs. The simulation horizon is 40 years and the integrating time step is equal to $\frac{1}{4}$ week. All
parameters that are not explicitly handled by the experimental design are set equal to the values given in Appendix.

Table 2 about here

Table 3 contains the results of ANOVA analysis and specifically, 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 sustainability, while Partial Eta Squared reflects the significance of the control factor compared to the error’s significance. In our study, Partial Eta Squared is very important because it determines the control factors that affect significantly sustainability and it also measures the magnitude of the effect.

Table 3 about here

The results in Table 3 and detailed simulation runs (experiments) not shown for brevity, lead to the following observations about the impact of control factors on the system’s sustainability:

- The parameters that affect more significantly the system’s sustainability are System Collection Capacity, Legislative Collection Percentage and Legislative Recycling Percentage, while Scavengers Collection Cost and Collection Cost affect the system least significantly.
- Regulatory measures improve the economical sustainability of the system since collection and recycling activities are actually profitable for the system.
- System Collection Capacity affects positively Total Supply Chain Profit of the closed-loop supply chain since by increasing it, the CLSC manages to collect and recycle more products and it is easier both to comply with the legislation’s requirements and to increase profits by selling the recycled materials. This result is quite contradictory with the usual practice of many manufacturers of electrical and electronic equipment who support that they develop CLSC activities due to the legislation’s requirements and not because of their profitability.

To further understand the influence of System Collection Capacity, Legislative Collection Percentage and Legislative Recycling Percentage on Total Supply Chain Profit and specifically on the operational cost of the reverse channel (Reverse Channel Cost), we conducted more experimental runs. Figure 8 depicts the long-term effect (after 40 years) of System Collection Capacity and Legislative Collection Percentage on economical sustainability of the “symbiotic” system. The graph depicts also iso-curves, which provide equivalent combinations of System Collection Capacity and Legislative Collection Percentage policies. We observe that Legislative Collection Percentage affects Reverse Channel Cost more significantly than System Collection Capacity. Hence, based also on other simulation results, in countries where the collection percentage is stringent, it is even more profitable for the waste management system to incorporate scavengers in its activities. From the environmental and social point of view, if policy-makers/regulators are interested in sustaining the operations of the formal waste management system, it will be more efficient to provide incentives to incorporate scavengers into the formal system than to provide economical incentives to increase the established collection.
capacity. Thus, we can generalise the conclusion that the “symbiotic” system contributes to economical, environmental and social dimensions of sustainability.

*Figure 8 about here*

In Figure 9 we present the long-term effect (after 40 years) of *Legislative Collection Percentage* and *Legislative Recycling Percentage* on economical sustainability of the “symbiotic” system through the operational cost of the reverse channel. The graph also depicts iso-curves. It is obvious that *Legislative Collection Percentage* affects *Reverse Channel Cost* much more than *Legislative Recycling Percentage*. In fact, if *Legislative Collection Percentage* increases from 15% to 20% (a change of 5%), *Reverse Channel Cost* increases from 2,600 to 2,800. The same increase in *Reverse Channel Cost* occurs if *Legislative Recycling Percentage* increases from 2% to 27% (a change of 25%). Hence, it is more profitable for firms that develop collection and recycling operations to invest in their collection activities than in recycling activities.

*Figure 9 about here*

One of the paper’s contributions is to help regulators and managers of formal waste recovery systems to make a decision regarding the participation of scavengers in the system’s activities. First of all, as Medina (2000) states, the “ideal” system is unrealistic, so even if the formal system ignores scavengers they will still collect used materials and produce pollution and the system will react like the “real” system. This statement calls for a comparative study of the observations obtained for the cases of the “real” and the “symbiotic” systems. The comparative study of simulation results obtained by the numerical investigation reveals the following:

- The “symbiotic” system is more sustainable than the “real” because of reduced pollution and since it offers employment to the scavengers.
- Total Supply Chain Profit of the closed-loop supply chain when scavengers contribute, is higher than when scavengers react as competitors of the formal system.
- In the “symbiotic” system availability of natural resources is higher than in the “real” system.
- Availability of landfills expressed through Pollution and Sum Disposal is higher in the “symbiotic” system than in the “real” system.

6. **Summary of Results**

In this manuscript we developed a SD model to study the impact of scavenging on operations of a closed-loop supply chain with collection and recycling activities. Although most studies until now develop mathematical models assuming scavenging does not exist, in most developing and in many developed countries informal recycling is still carried out affecting the operations of a closed-loop supply chain. Using our model we have shown that research should consider scavenging in order to correspond accurately to the real-world system, and that “scavenging” is a way to move towards and not to diverge from sustainability as many regulators and firms fear.
Even current environmental regulations on WEEE tend to ignore the scavengers’ role in collection and recycling activities. This behaviour not only promotes their marginalisation and pollution of the environment but also creates additional costs to manufacturing companies who, in their effort to comply with legislation, have to invest more in recovery operations and to compete with smaller and more flexible informal sector enterprises. However, if manufacturers manage to cooperate with these systems, they will reduce required collection capacity, comply easier with legislation’s requirements and use cheaper indigenous recycled materials instead of more expensive natural resources. The simulation results strengthen the advantages of this cooperation since we have also shown that collection activities are more crucial for economical sustainability of the closed-loop supply chain than recycling activities.

Governments and regulators may also consider assisting manufacturers and formal waste management systems to incorporate scavengers in their activities by the implementation of a legislation that includes informal systems in social welfare and government insurance schemes. In this way unemployment of specific social groups will be reduced and more natural resources and landfills will be available for future generations.

The model could be also helpful as a Decision Support System to conduct extensive what-if analyses, both for legislators (to study how environmental and social aspects of sustainability would be affected through changes in legislation or incentives), and for managers of CLSCs (to assess how different decisions concerning capacity would affect profitability). Furthermore, depending on available data, the model can be extended from the narrow boundaries of a specific geographical state to that of a country or even to global dimensions. The results presented in this paper certainly do not exhaust the possibilities of investigating all influences of different parameters on sustainability. With proper modifications the SD model could take into consideration the amount of WEEE that can be transferred to developing or to neighbour countries.


Appendix Parameter values for numerical examples (in alphabetical order)

Collection Cost = 9.841 [Euro/item]: Collection cost of the formal system
CP Transportation Cost = 11.355 [Euro/item]: Transportation cost of the collected products
Delivery Time = 2 [Weeks]: Time needed to transfer products from distributor to end users
DI Holding Cost = 0.725 [Euro/item/week]: The holding cost of distributor's inventory
Discount Factor = 0.001 [1/week]
Holding Cost = 0.725 [Euro/item/week]: The holding cost of the Recyclable Products
Initial Resources = 7,500,000 [Items]: The value of Natural Resources at the beginning of the simulation period
Initial Scavengers = 50 [Scavengers]: The value of Scavengers at the beginning of the simulation period
Inspection Time = 1 [Weeks]: Time needed for the inspection process
Landfill Cost = 2 [Euro/item]: The landfill cost of disposed products
Landfill Tax = 20 [Euro/item]: The legislative tax in case the firm does not comply with the Legislative Collection Percentage
Legislative Collection Percentage = 60%: Collection percentage imposed by the legislation
Legislative Recycling Percentage = 60%: Recycling percentage imposed by the legislation
Price = 1004 [Euro/item]: The price of the selling products
Price of Recycled Materials = 34.65 [Euro/item]: The price of selling recycled materials
Procurement Cost = 538.07 [Euro/item]: The procurement cost of natural resources
Procurement Time = 2 [Weeks]: Time for the natural resources to arrive to the producer
Production Capacity = 1000 [Items/week]: Capacity of the producer's facilities
Production Cost = 66.72 [Euro/item]: The production cost of new products
Recyclable Stock Keeping Time = 2 [Weeks]: The maximum time that the Recyclable Products remain unused in the recycling facilities
Recycling Capacity = 100 [Items/week]: Capacity of the recycling facilities
Recycling Cost = 3.028 [Euro/item]: The recycling cost of recyclable products
Recycling Tax = 20 [Euro/item]: The legislative tax if the firm does not comply with the Legislative Recycling Percentage
Residence Time = 12 [Years]: Residence time of refrigerators
Reverse Investment Cost = 140,000 [Euros]: Investment cost in CLSC activities
RM Holding Cost = 0.725 [Euro/item/week]: The holding cost of raw materials inventory
Scavengers Capacity = 18 [Items/week/scavenger]: The collection capacity of a scavenger
Scavengers Collection Cost = 6 [Euro/item]: The collection cost of scavengers
Shipment Time = 2 [Weeks]: Time needed to transfer products from producer to distributor
SI Holding Cost = 11.63 [Euro/item/week]: The holding cost of serviceable inventory
$SI\ \text{Transportation Cost} = 11.355\ [\text{Euro/item}]$: The transportation cost of serviceable inventory

$Switch1 = 1$

$Switch2 = 1$

$System\ Collection\ Capacity = 50\ [\text{Items/week/scavenger}]$: Capacity of the collection system
Figure captions

Figure 1 A scavenger with a horse cart
Figure 2 Structure of the current system
Figure 3 Causal-loop diagram of the reverse channel of the “real” system
Figure 4 Stock and flow diagram of the system
Figure 5 Causal-loop diagram of the reverse channel of the “ideal” system
Figure 6 Causal-loop diagram of the reverse channel of the “symbiotic” system
Figure 7 Dynamic of Total Supply Chain Profit for the three systems
Figure 8 Behaviour of Reverse Channel Cost as a function of Legislative Collection Percentage and System Collection Capacity
Figure 9 Behaviour of Reverse Channel Cost as a function of Legislative Collection Percentage and Legislative Recycling Percentage

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Figure 9 Behaviour of **Reverse Channel Cost** as a function of **Legislative Collection Percentage** and **Legislative Recycling Percentage**
Table 1 Behaviour of the three systems

<table>
<thead>
<tr>
<th>Variables</th>
<th>Systems (Values)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real</td>
</tr>
<tr>
<td>Natural Resources (items)</td>
<td>6,377,296</td>
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<tr>
<td>Sum Disposal (items)</td>
<td>24,370</td>
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<tr>
<td>Pollution (items)</td>
<td>321,103</td>
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<tr>
<td>Total Supply Chain Profit (euros)</td>
<td>-14,338,796</td>
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<tr>
<td>Unemployed Scavengers (people)</td>
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</tbody>
</table>

Table 2 Levels of model parameters related to collection and recycling

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Levels</th>
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<tbody>
<tr>
<td></td>
<td>(1)</td>
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<tr>
<td>Legislative Collection Percentage</td>
<td>30%</td>
</tr>
<tr>
<td>Legislative Recycling Percentage</td>
<td>30%</td>
</tr>
<tr>
<td>Initial Scavengers</td>
<td>25</td>
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<tr>
<td>Scavengers Capacity</td>
<td>9</td>
</tr>
<tr>
<td>Scavengers Collection Cost</td>
<td>3</td>
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<tr>
<td>System Collection Capacity</td>
<td>25</td>
</tr>
<tr>
<td>Recycling Capacity</td>
<td>50</td>
</tr>
<tr>
<td>Collection Cost</td>
<td>4.9205</td>
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</table>
Table 3 Results of ANOVA tests (P-values/Partial Eta Squared values) for the significant main effects of the regulatory measures, the scavengers’ activities and the formal system’s activities on sustainability for the “real” (r), “ideal” (i) and “symbiotic” (s) systems

<table>
<thead>
<tr>
<th>Factor-Interaction</th>
<th>Natural Resources</th>
<th>Sum Disposal</th>
<th>Pollution</th>
<th>Total Supply Chain Profit</th>
<th>Unemployed Scavengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legislative Collection Percentage</td>
<td>0/0.977 (r)</td>
<td>0/0.979 (r)</td>
<td>0/0.979 (r)</td>
<td>0/0.820 (r)</td>
<td>0/0.041 (s)</td>
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<tr>
<td></td>
<td>0/0.041 (i)</td>
<td>0/0.109 (i)</td>
<td>0/0.996 (s)</td>
<td>0/0.008 (i)</td>
<td>0/0.041 (s)</td>
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<tr>
<td></td>
<td>0/0.630 (s)</td>
<td>0/0.799 (s)</td>
<td>0/0.979 (r)</td>
<td>0/0.041 (s)</td>
<td>0/0.041 (s)</td>
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<tr>
<td>Legislative Recycling Percentage</td>
<td>0/0.004 (r)</td>
<td>0/0.705 (r)</td>
<td>0/0.705 (r)</td>
<td>0/0.042 (r)</td>
<td>0/0.232 (r)</td>
</tr>
<tr>
<td></td>
<td>0/0.398 (i)</td>
<td>0/0.645 (i)</td>
<td>0/0.645 (i)</td>
<td>0/0.042 (r)</td>
<td>0/0.232 (s)</td>
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<tr>
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<td>0/0.962 (s)</td>
<td>0/0.999 (s)</td>
<td>0/0.999 (s)</td>
<td>0/0.232 (s)</td>
<td>0/0.232 (s)</td>
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<tr>
<td>Initial Scavengers</td>
<td>0/0.893 (r)</td>
<td>0/0.998 (r)</td>
<td>0/0.968 (r)</td>
<td>0/0.042 (r)</td>
<td>0/0.232 (s)</td>
</tr>
<tr>
<td>Scavengers Capacity</td>
<td>0/0.999 (r)</td>
<td>0/0.997 (s)</td>
<td>0/0.997 (s)</td>
<td>0/0.232 (s)</td>
<td>0/0.232 (s)</td>
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<tr>
<td>Scavengers Collection Cost</td>
<td>0/0.999 (r)</td>
<td>0/0.985 (r)</td>
<td>0/0.999 (r)</td>
<td>0/0.005 (s)</td>
<td>0/0.232 (s)</td>
</tr>
<tr>
<td>System Collection Capacity</td>
<td>0/0.999 (r)</td>
<td>0/0.725 (i)</td>
<td>0/0.725 (i)</td>
<td>0/0.970 (r)</td>
<td>0/0.962 (r)</td>
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<tr>
<td></td>
<td>0/0.975 (s)</td>
<td>0/1.000 (s)</td>
<td>0/1.000 (s)</td>
<td>0/0.219 (i)</td>
<td>0/0.962 (s)</td>
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<tr>
<td>Recycling Capacity</td>
<td>0.002/0.003 (i)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*P-value<0.05
Europe Campus
Boulevard de Constance
77305 Fontainebleau Cedex, France
Tel: +33 (0)1 60 72 40 00
Fax: +33 (0)1 60 74 55 00/01

Asia Campus
1 Ayer Rajah Avenue, Singapore 138676
Tel: +65 67 99 53 88
Fax: +65 67 99 53 99

Abu Dhabi Campus
Muroor Road - Street No 4
P.O. Box 48049
Abu Dhabi, United Arab Emirates
Tel: +971 2 651 5200
Fax: +971 2 443 9461

www.insead.edu