A Closed-Loop Sustainable Supply Chain Network Design with System Dynamics for Waste Electrical and Electronic Equipment

Gokhan Aldemir, Tugce Beldek and Dilay Celebi

Abstract Supply chain management covers the management of all activities starting from the supply of the raw material to the delivery of the final product to the end user. In the rapidly evolving and globalizing world, limited resources and increasing competitiveness are pushing both nations and organizations to make a difference in the context of supply chain management. The importance of the concept of the sustainability has become more widely recognized among nations and organizations recently. Recovery options are considered to be an economic gain by many companies. Moreover, pricing is no longer a unique competitive strategy since customers give today value and prefer environmentally friendly products. In other words, recovery options are considered by manufacturers due to customer demand, regulations, and economic return. This study puts forward a sustainable supply chain network design with a system dynamics model to minimize the waste of electric and electrical equipment, which is the one of the most crucial sectors in terms of waste management. This study contributes to filling the gap in the literature concerning the mathematical closed-loop reverse supply chain network design model from a system dynamics perspective rather than by using deterministic and static models proposed in the literature. The proposed model is visualized with the program AnyLogic. It constitutes a general framework with crucial variables of electrical and electric equipment supply chains. The results show the states of these variables by year, which can provide a decision-support system for policy making. The study ends by suggesting future directions and giving some helpful recommendations for other researchers on this topic.

Keywords Closed-loop supply chain · Network design · System dynamics

G. Aldemir (✉) · T. Beldek · D. Celebi
Management Engineering Department, Management Faculty, Istanbul Technical University, Istanbul, Turkey
e-mail: aldemirg@itu.edu.tr

T. Beldek
e-mail: beldek@itu.edu.tr

D. Celebi
e-mail: celebid@itu.edu.tr

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Introduction

Supply chain sustainability is the management of environmental, social, and economic impacts and the encouragement of good governance practices throughout the lifecycle of a good or service. The objective of supply chain sustainability is to create, protect, and increase long-term environmental, social, and economic value for all stakeholders involved in bringing products and services to a market (UN Global Compact Supply Chain Report 2008). Negative effects arise from many factors, such as solid waste, chemicals mixed with water, and gases produced by manufacturing facility activities that have been neglected for many years. By the end of the 1990s, protecting natural resources and the environment became a significant issue in both national and international arenas (Büyüközkan and Vardaloğlu 2008). Both technological improvements and a growing world population have sped up the rate of production and consumption of products as well as increasing the demand for raw materials as a result. For this reason, pollution levels have increased, which has led to resource scarcity and global warming. This has caused many enterprises and companies to worry about environmental and economical sustainability, so much so that many countries have developed new regulations related to green issues. That is why supply chain managers need to identify and use economic and environmental sustainability applications (Green et al. 2012). The supply chain and logistics management approach of companies is affected by the sustainable development concept and the traditional problem-solving approach is about to give way to the new sustainability-based approach.

Industries in developed countries have set up fully fledged systems to follow these regulations, implementing environmentally friendly strategies to reduce their waste (Xu et al. 2013). These systems are all about recovery options. In the past, companies thought that recovery options such as recycling would incur great costs. It was difficult to strike a balance between addressing environmental issues and production costs. Today however, recovery options are considered to represent an economic gain by many companies. Moreover, pricing is no longer a unique competitive strategy since customers give today value and prefer environmentally friendly products. In other words, recovery options are considered by manufacturers due to customer demand, regulations, and economic return.

The Aim of the Study

The aim of this study is to put forward a dynamic and sustainable supply chain network design to minimize waste electric and electrical equipment (WEEE), which is the one of the most crucial sectors in terms of waste management. The study is based on the multi-period, multi-product reverse logistics concept. There are many studies in the literature on closed-loop supply chain network design, but only a few take into account the dynamic perspective with regard to the important variables of the supply chain. Therefore, this study contributes to filling the gap in the literature on the mathematical closed-loop reverse supply chain network design model from a system dynamics (SD) perspective rather being based on the deterministic and static models proposed in the literature and to create a general dynamic framework for that chain.

The Scope of the Study

This study includes six parts: the introduction, literature review, analysis of WEEE management in Turkey and other countries, the SD model and its application with illustrative data, the results, and the conclusion together with recommendations for future study. In the literature review, supply chain management (SCM), the concept of sustainability, dimensions of sustainability, and sustainable supply chain management (SSCM) will be defined first, and then quantitative studies related to the sustainability concept will be discussed. In addition, sustainability will be examined and compared across different sectors. The definitions of closed-loop supply chain and reverse logistics will be included. Then, studies that provide examples of closed-loop supply chain and reverse logistics network design models with multi-product, multi-period, and/or multi-echelon concepts will be explained.

In the analyses of WEEE management, information from Turkey's waste management directive will be presented to set specific parameter values that are used in the model of WEEE management. Moreover, the targets for collection and recovery by year will be investigated in this section.

In the section on the dynamic model, the parameters, costs, and decision variables will be defined first. Then, the general framework of the model will be explained. The aim of study will be to minimize and visualize the total investment with the first costs of new collection centers and new recovery centers, costs of collection and recovery of products, and the cost of acquisition of raw material from suppliers and third parties by year. After that, the data will be explained for the application of the model.

The results of the illustrative data and its comment will be analyzed in the results and discussion section.

Finally, the conclusion and recommendations section will contain some critical points to offer helpful information for further studies.

Literature Review

SSCM is defined as the management of material, information, and capital flows as well as cooperation among companies along the supply chain while taking into account goals from all three dimensions of sustainable development, that is, economic, environmental, and social ones, which are derived from customer and stakeholder requirements. In sustainable supply chains, environmental and social criteria need to be fulfilled by the members to remain within the supply chain, while it is expected that competiveness will be maintained through meeting customer needs and related economic criteria. This definition is rather broad and joins together those given for sustainability and SCM. It is also able to integrate green or environmental SCM as one part of the wider field (Seuring and Müller 2008).

Sustainability, the consideration of environmental factors and social aspects, in SCM has become a significant topic for researchers and practitioners. The application of operations research methods and related models, that is, formal modeling for closed-loop SCM and reverse logistics, has been thoroughly examined in previously published research (Brandenburg et al. 2014).

Combining environmental and social perspectives with financial aspects, known as the triple-bottom-line (TBL) dimensions of organizational sustainability, has continually gained relevance generally for managerial decision making and specifically for SCM and operations management (Carter and Rogers 2008).

It can be seen from the literature that reverse-oriented CLSCM models are widely accepted but a significant number of forward SCM models focusing on sustainability also exist (Min and Kim 2012).

By using reverse logistics, used materials are converted into new products and materials that have market value through reuse, remanufacture, refurbishment, and recycling. Therefore, a typical supply chain becomes a closed loop under favor of reverse logistics (Hervani et al. 2005). Therefore, closed-loop SCM consists of both forward and reverse flows. Forward supply chains start with the raw material that ends up at the customer, while reverse supply chains define the collection of the end-of-life products from customers followed by their recovery, recycling, or reuse in dependence on their quality; if they do not reach the required quality level, they will be disposed of (Guide et al. 2003).

Jindal et al. (2015) propose a network design for a multi-product, multi-time, multi-echelon closed-loop supply chain framework in an uncertain environment. The proposed CLSC network is represented by a fuzzy mixed integer linear programming (MILP) model to decide on the optimal location and allocation of parts at the facility, inventory level of the parts, number of products to be remanufactured, and number of parts to be purchased from external suppliers in order to maximize the profit of the organization.

Easwaran and Üster (2010) consider a multi-product closed-loop logistics network design problem with hybrid manufacturing/remanufacturing facilities and finite capacity hybrid distribution/collection centers to serve a set of retail locations. In their model, hybrid production plants, hybrid collection centers, hybrid distribution centers, and hybrid remanufacturing centers are opposed to separate plants. They determine the locations of facilities in both forward and reverse channel networks and incorporate processing and storage capacity restrictions.

Qiang et al. (2014) propose a two-period CLSC network model with manufacturers that compete with one another to serve the consumers of various demand markets. Manufacturers decide on the production quantity and remanufacturability level in the first period. They assume that those manufacturers who are proactive in the product remanufacturability design will incur a higher production cost for the new product but will reap the benefit by having a lower production cost for the remanufactured product in the second period. Consumers are assumed to be conscious of the price and quality of the product and therefore discount their willingness to pay for the remanufactured product. In spite of being proactive in product remanufacturability design, the market share of the new product decreases for competitors who are reactive in choosing the design, and the former product is more profitable due to the capture of additional market share by the refurbished product. Also, they find that if all customers have a higher willingness to pay for the refurbished product, being proactive is less promising.

Garg et al. (2015) investigate a multi-criteria optimization approach to manage environmental issues in CLSC-ND. They formulate a bi-objective non-linear programming problem, and in order to solve it they propose an interactive multi-objective programming approach algorithm. Their model determines the optimal flow of parts and products in the CLSC network and the optimum number of trucks hired by facilities in the forward chain of the network. They carry out numerical experimentation with the proposed model to validate its applicability with the help of data from a real-life case study. The case presented in the paper is based on a geyser manufacturer, and the application of the model to this case provides them with the underlying tradeoffs between the two objectives. The model also results in the very interesting fact that with the implication of the extended supply chain, a firm can create a green image for its product, which eventually results in an increase in demand while significantly reducing the use of transportation in both directions.

He et al. (2006) review the implementation of strategies for WEEE treatment and the technologies for recovery of WEEE. It presents the current status of WEEE and corresponding responses adopted so far in China. The concept and implementation of scientific development are critical to the electronics sector as one of the important industrial sectors in China's economy. To achieve this objective, it is significant to recycle WEEE sufficiently to comply with the regulations regarding WEEE management and to implement green design and cleaner production concepts within the electronics industry in line with the upcoming EU and Chinese legislation in a proactive manner.

Yang et al. (2008) also study WEEE flow and mitigating measures in China. They identify the sources and generation of WEEE in China and calculate WEEE volumes. The results show that recycling capacity must increase if the rising quantity of domestic WEEE is to be handled properly. Simultaneously, suitable WEEE treatment will generate large volumes of secondary resources. They describe the existing WEEE flow at the national level and future challenges and strategies for WEEE management in China.

Walther and Spengler (2005) analyze the impact of the WEEE directive on reverse logistics in Germany. They think that essential changes in the field of treatment of electronic products in Germany are expected due to the new regal requirements owned. On the other hand, the consequences in terms of changes of organization and material flows of the German treatment system are currently unknown. Their contribution is to predict relevant changes in this context. That sets the framework for a deduction of recommendations for political decision makers and actors in the treatment system.

Forrester (1961) introduced SD in the 1960s as a modeling and simulation methodology for dynamic management problems. Since then, SD has been applied to various business policies, strategies, and environmental problems (Sterman 2000). However, according to Dekker et al. (2004), only a few strategic management and environmental problems in CLSC have been analyzed and reported in the literature. Specifically, Spengler and Schröter (2003) present a CLSC using SD. Georgiadis et al. (2004) present the loops of product reuse with a major influence. Van Schaik and Reuter (2004) present an SD model focused on cars showing that the realization of the legislation targets imposed by the EU depends on the product design. SD is a powerful methodology for obtaining insights into the 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 optimized is relatively static and free of feedback, optimization may well be the best technique to use”. Bloemhof-Ruwaard et al. (1995) state that the latter conditions are rarely satisfied for environmental management and supply chain systems (Georgiadis et al. 2005). The system under study in this paper is dynamic and full of feedbacks, promoting SD as an appropriate modeling and analysis tool.

Analysis of WEEE Management in Turkey

The first study of WEEE in Turkey was done by the Ministry of Environment and Urban Planning with a regulation for the limitation of some certain hazardous substances in 2009. The regulation was published in the *Official Gazette* on May 30, 2009 and entered into force in 2009. The purpose of this regulation was to establish guidelines for the restriction of the use of certain hazardous substances found in electric and electronical goods, determination of the applications to be exempted from this limitation, and recovery or disposal of WEEE in order to protect the environment and human health (Ministry of Environment and Urban Planning 2008).

The Waste of Electric and Electrical Controlling Regulations were enacted by the Ministry of Environment and Urban Planning with the post in the *Official Gazette* on May 22, 2012 (Ministry of Environment and Urban Planning 2012). The purpose of the regulations was the same as that of the regulation published in 2009. Companies that had letters of conformity collected 4000 tons of WEEE in 2009, while they collected only 1818 tons of WEEE in 2006. The household WEEE collection targets are shown in Table 1.

Table 2 shows the recycling targets and Table 3 shows the recovery targets according to the categories of types of equipment.

Table 1 Household WEEE collection targets

	EEE category	Waste collection target by year (kg/capita-year)				
		2013	2014	2015	2016	2018
1	Refrigerators/cooling/air-conditioning appliances	0.05	0.09	0.17	0.34	0.68
2	Large white appliances (with the exception of refrigerators/cooling/ air-conditioning appliances)	0.1	0.15	0.32	0.64	1.3
3	Televisions and monitors,	0.06	0.10	0.22	0.44	0.86
4	IT and telecommunications equipment, and consumer equipment (with the exception of televisions and monitors)	0.05	0.08	0.16	0.32	0.64
5	Lighting equipment	0.01	0.02	0.02	0.04	0.08
6	Small household appliances, electrical and electronic tools, toys, sports and leisure equipment, monitoring and control tools	0.03	0.06	0.11	0.22	0.44
Total household WEEE (kg/capita-year)		0.3	0.5	1	2	4

Table 2 Recycling targets

	Year	
	2013	2018
Electrical and electronic equipment category		(%) by weight
Large household appliances (%)	65	75
Small household appliances (%)	40	50
IT and telecommunications equipment (%)	50	65
Consumer equipment (%)	50	65
Lighting devices and equipment (%)	20	50
Gas discharge lamps	55	80
Electrical and electronic tools (%)	40	50
Toys, leisure, and sports tools (%)	40	50
Medical devices (%)	–	–
Monitoring and control devices and tools (%)	40	50
Automatic dispensers (%)	65	75

Model Structure

In this study, a sustainable supply chain model for refrigerators is designed with AnyLogic (Fig. 1). SD is a way to understand the entire behavior of actors in the long term.

At a random moment, a decrease means the total amount of goods divided by their lifespan. This means that it is e-waste after a few years. Refrigerators will become e-waste after an average lifespan of five years. It is assumed that the

Table 3 Recovery targets

	Year	
	2013	2018
Electrical and electronic equipment category		(%) by weight
Large household appliances (%)	75	80
Small household appliances (%)	55	70
IT and telecommunications equipment (%)	60	75
Consumer equipment (%)	60	75
Lighting devices and equipment (%)	50	70
Gas discharge lamps	70	80
Electrical and electronic tools (%)	50	70
Toys, leisure, and sports tools (%)	50	70
Medical devices (%)	–	–
Monitoring and control devices and tools (%)	50	70
Automatic dispensers (%)	70	80

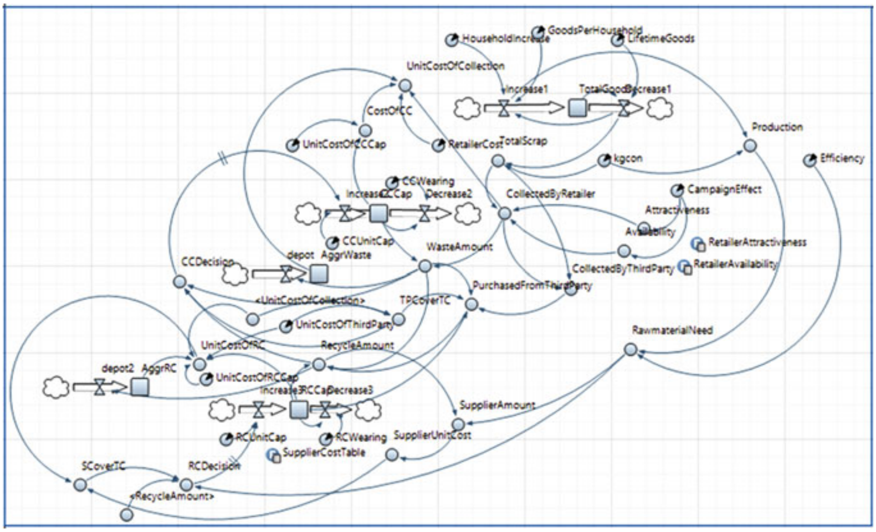

Fig. 1 System dynamics model conducted using AnyLogic

household amount will increase every year and as a result they will buy refrigerators for each. When production increases due to demand, the total amount of scrap will also increase year by year. For the production facility, regulation requirement is a must so that a specific amount (in kilograms) of e-waste has to be collected. The producer can collect end-of-life products via its retailers or from third-party firms.

If the producer wants to collect WEEE from its retailers, it has to carry out a campaign to make customers bring their end-of-life products to buy a new one, maybe at a lower price. For this reason, retail attractiveness is defined, which comes with the campaign rate. By the time the retailer collects the WEEE, it will reach its capacity, so another parameter, namely retailer availability, is used. To calculate the total amount of WEEE collected from the retailer, we can multiply the total scrap, attractiveness, and availability. Also 50% of the rest, which is coming from the difference between total scrap and "collected by the retailer", will be collected by third parties.

When we consider the capacity of the collection center, the amount of waste must be the minimum out of the collected amount and the capacity. By using this formula, if more capacity is needed, the results will show that a capacity increase is essential and a new collection center may need to be opened. The capacity of the collection center has a wearing ratio that will decrease year by year as 0.0001. There is unit cost for the collection center, which is fixed as 80 TL/ton. From the beginning, the model shows that 1000 WEEE is collected.

There is also a unit cost of the collection center, which is defined by dividing the total of cost of the collection center and multiplication of the retailer cost and collected by retailer to aggregate waste amount. The decision of the collection center (CCDecision) can be calculated by multiplying the waste amount and the third party cost and dividing it to amount recycled. The amount recycled must be at least 50% for the recycling center to be efficient. Also, it is important to define a "delay" after the decision of the collection center is given because of the time needed to build it up.

If the third party cost changes over time, the producer can change the amount of waste it collects from the retailer. The most important thing is for the company to provide the required amount, which is already certain due to the WEEE regulation.

The same loop is designed with the same parameters for the recycling center. At this time, we have to consider both recycling and collection costs together.

There is a table defining the supplier cost that gives data about quantity discounts. With this cost table, the producer will decide to purchase raw material from suppliers or to recycle its scrap for use as a raw material. It will compare costs to enable it to make a decision about this purchasing action.

To represent a pull system, if there is demand, production will be carried out. Production requires raw material, so the material needed will be bought or recycled.

Simulation Results

The simulation was run without any errors in AnyLogic software. Sample data were used to test the model and the data information of parameters is given in the section on the model structure. Graphs are taken as a result to make comments on the capacity of the recycling center and collection center (Fig. 2).

In this model, the decision to open a new collection or recycling center is made due to capacity. The model shows crucial conclusions regarding two big dilemmas. First it selects its own collection system rather than working with a third-party

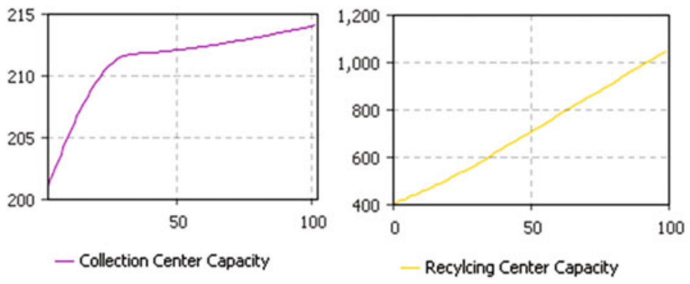

Fig. 2 Time plots for collection and recycling centers

logistics firm. Secondly, it suggests opening recycling centers to obtain raw materials rather than purchasing them from suppliers. These preferences result in a decrease in the unit costs of collection centers and recycling centers year by year, which can be seen from Fig. 3.

When increasing the capacity of collection and recycling centers, decreasing unit cost is a big benefit for the producer.

Conclusions and Future Study

Nowadays, firms are choosing strategies that increase their economic performance as well as increasing their competitiveness in the field of social responsibility. Interest in the effective reuse of resources and/or manufactured products continues to increase in all companies as a result of global climatic changes, population increase, rapid urbanization, and the reduction in the availability of natural resources. Due to customer demand, governmental regulations, and economic returns, manufacturers consider recovery options.

SD is a method that allows a whole system to be controlled over time to see whether or not it is sustainable. This model shows a WEEE collection system for a white appliances manufacturer. This study will give an idea for collection and recycling of e-waste, making it possible to obtain benefits such as reaching

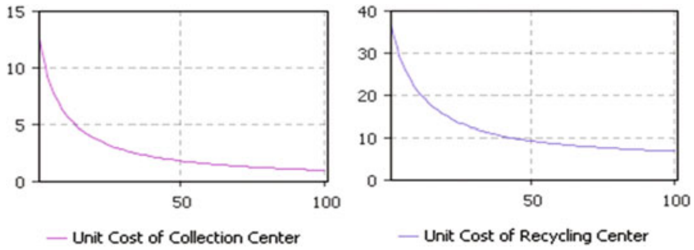

Fig. 3 Time plots for the unit cost of collection and recycling centers

governmental targets, reducing cost by using recycled material as a raw material, and having an environmentally friendly image.

If the investment cost is implemented in this model as a fixed cost of collection and recycling centers, opening a new facility can be considered instead of increasing the capacity. This model is specified for refrigerators but with a change in the life cycle parameter it can be generalized for many kinds of electrical and electronic equipment. Also, it can be extended to more areas and facilities for different producers in different countries according to their own regulations. This model is a basis framework for a closed-loop sustainable supply chain network design.

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