Discussion Paper Series

RIEB

Kobe University

DP2017-30

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Qinxin GUO
Enci WANG
Yongyou NIE
Junyi SHEN

November 8, 2017

Research Institute for Economics and Business Administration
Kobe University
2-1 Rokkodai, Nada, Kobe 657-8501 JAPAN

Profit or Environment? A System Dynamic Model Analysis of Waste Electrical and Electronic Equipment Management System in China

Qinxin Guo[a,*], **Enci Wang**[b], **Yongyou Nie**[b], **Junyi Shen**[b,c]

[a] Graduate School of Economics, Kobe University, Kobe University, 2-1 Rokkodai, Nada, Kobe 657-8501, Japan.

[b] School of Economics, Shanghai University, 99 Shangda Road, Baoshan 200444, Shanghai, China.

[c] Research Institute for Economics and Business Administration, Kobe University, 2-1 Rokkodai, Nada, Kobe 657-8501, Japan.

[*] Corresponding author. Email: 151e701e@stu.kobe-u.ac.jp

Abstract

In the past decade, sales of electrical and electronic equipment have undergone explosive growth worldwide, while at the same time, the life cycles of electrical and electronic equipment have been getting shorter. This has resulted in large numbers of waste electrical and electronic equipment (WEEE) being generated, which causes serious environmental problems that each country has to face. In this paper, we use the system dynamic method to analyze how China's "WEEE processing fund" policy, wherein levies or subsidies are set on appropriate targets, influences the economic and environmental conditions of participants in the WEEE management system. The simulations results suggest that the "WEEE processing fund" policy could improve the economic status of those receiving subsidies without losing the economic revenue from levies and improve the entire system's ability to recover and process waste equipment.

Keywords: Waste electrical and electronic equipment management; Waste electrical and electronic equipment processing fund; System dynamic model; Economic and environmental effects; China

1. Introduction

Waste electrical and electronic equipment (WEEE), commonly called "e-waste", refers to discarded electrical or electronic devices generally used in household appliances such as refrigerators, air conditioners, washing machines, televisions, computers, and mobile phones. In recent decades, with the reduction the life cycle of electrical and electronic products, the worldwide output of these products has increased dramatically. This has resulted in large amounts of WEEE being generated.

Dealing with WEEE's potential to threaten the environment in every country has become a critical issue. The ideal means to solve the WEEE problem is the creation of a circular economy (Pearce and Turner, 1990). Stepping toward that goal, WEEE recycling and processing systems include producers, formal WEEE processors, informal WEEE recycling peddlers, and consumers. The WEEE recycling process starts with consumers. Formal WEEE processors and informal WEEE recycling peddlers purchase WEEE from consumers to produce recycled materials. This can reduce the threat to the environment posed by consumers' disposal of WEEE. This procedure can also increase resource recycling, extraction, and reuse of electronic waste, and decrease consumption of natural resources. However, because WEEE recycling, treatment, and reuse require large amounts of capital costs, companies that are financially weak might face bankruptcy. In addition, lower thresholds in recycling lead to the possibility that informal recycling peddlers could harm the interests of formal enterprises or even crowd them out of the market.

On the basis of the "Law on Solid Waste Pollution Prevention" and the "Cleaner Production Promotion Law" approved by the Standing Committee of the National People's Congress (NPC) of the People's Republic of China, the Chinese government promulgated a series of policies and regulations to explicitly set forth the responsibilities and obligations of producers, recyclers, and processors. The laws also introduced government supervision and management of the e-waste recycling process. The "Old for New" scheme, which was launched in June 2009, allows consumers to hand over their old appliances to a formal collection point or retailer and receive a discount of up to 10% on an equivalent new device (Wang et al., 2013). Another project called the "waste electrical and electronic products processing fund" was implemented in 2012. Under the electrical products processing fund scheme, levies are imposed on the basis of units produced or imported. Some levies are as follows: TVs 13 RMB/unit, refrigerators 12 RMB/unit, washing machines 7 RMB/unit, air conditioners 7 RMB/unit, and computers 10 RMB/unit. The total of the funds raised by the levies is earmarked for dismantling subsidies for qualified companies. The subsidy on television sets is 85 RMB/unit, washing machines and air conditioners receive 35 RMB/unit, and refrigerators and computers receive 80 RMB/unit (Yu et al., 2014). Both the levies and the subsidies aim at encouraging participation in electronic waste recycling and maximizing the environmental and economic benefits of recycling. However, there are inevitable contradictions between the environmental and economic benefits, so the two policies have encountered a number of difficulties in implementation, which leads us to search for an efficient measure for finding an optimum balance.

Scholars have tried to analyze the problems of realizing efficient recycling and processing of WEEE from the points of view of participants in WEEE recycling and processing systems. For producers, a common approach for regulating producers' behavior in the WEEE management process is the extended producer responsibility (EPR) concept. EPR is an environmental protection strategy that makes product manufacturers responsible for the entire life cycle of the product, especially for its take-back, recycling, and final disposal (Khetriwal et al., 2009). Manomaivibool et al. (2014) described three electronic waste recycling systems implemented in South Korea over 2 decades and tracked their evolution. The three were a producer-based deposit refund system, an extended producer responsibility system, and an eco-assurance system. Magalini and Huisman (2006) analyzed the European Electronic Waste Equipment Directive using four cost models, concluding that e-waste management requires not only producers to be held responsible but also the cooperation of every stakeholder in the industrial chain to optimize the entire system. Most electrical companies in China are relatively small and there is serious competition among them. They cannot afford the cost of recycling activities like large foreign companies can do. Therefore, to solve the e-waste problem in China, we should not only focus on EPR, but also consider governmental capabilities and consumer behavior (Nnorom et al., 2009).

As WEEE generators, consumers play a significant role in WEEE management. Some studies have discussed consumer-related problems in WEEE recycling. Nixon and Saphores (2007) investigated California residents and found that age, income, trust in government and companies, degree of closeness to recycling facilities, density of community population, education, and environmental attitudes were vital factors affecting residents' payment of advanced recycling fees (ARFs). Saphores et al. (2012) showed that the most important variables affecting U.S. residents' willingness to recycle are internal variables such as ethical standards, recycling convenience, knowledge of the potential toxic materials in electronic waste, recycling experience, gender, and marital status. In China, consumers tend to sell their used electrical appliances to the collectors who offer them the best price, regardless of their actual technical and environmental performance. This behavior strongly influences the financial model of the formal collection system, which must compete with the informal sector (Wang, 2013). For instance, the willingness of Beijing residents to participate in WEEE recycling seems lower than in western developed countries. Furthermore, recycling habits play the most significant role in Beijing residents' e-waste recycling behavior (Wang et al., 2011).

Participants in the recycling process include formal and informal recyclers, a factor that relates directly to whether the correct electronic wastes are efficiently transported to the formal processing enterprises. Formal recovery networks have been built to prevent illegal WEEE dumping and dismantling, especially in the EU and Japan (Gu et al., 2016). However, unlike in developed countries, despite legislative and market progress, the collection of household WEEEs in China is still dominated by informal individual collectors – a type of specialized waste buyers who purchase multifarious waste materials from households, selling them later to the bidder who offers them the best price (Chi et al., 2011). Because of the relatively low costs they incur, the price of recycling (i.e., the price that informal individual collectors pay to consumers) is often higher than what a formal recycler can offer, thus having the potential to crowd formal enterprises out of the market. For instance, a used TV set is sold at 50-100 RMB to a peddler, while Dongtai (a private registered e-wastes treatment company) can only offer about 15 RMB (Qu et al., 2013). Informal WEEE recycling generally involves non-professional treatment, including informal dismantling and selling to second-hand markets, both of which have potential environmental pollution problems. Thus, regulating informal recycle participants is significant for the entire system.

System Dynamics (SD) is a powerful methodology for obtaining insights into problems of dynamic complexity and policy resistance. Forrester (1961) introduced SD as a modeling and simulation methodology for dynamic management problems. Several researchers have considered WEEE problems through the system dynamics approach, which have provided insight on the rules of WEEE management systems. Georgiadis and Besiou (2008) examined the impact of ecological motivation and technological innovations on the long-term behavior of a closed-loop supply chain with recycling activities and developed an SD model of supply chain of electrical equipment in Greece which indicated that legislation enforcement, reuse of non-renewable resources, and landfill preservation are important factors. Some others like Poles (2013) have focused on the production and inventory processes of remanufacturing activities using an SD simulation approach. The results claimed that efficiency in the remanufacturing process and higher remanufacturing capacity occur if the quantity of remanufactured returns and remanufacturing lead time are increased and decreased, respectively. Besiou et al. (2012) tried to figure out whether formal recovery system and scavengers in WEEE management system could be symbiotic or whether they inherently conflict. Their SD model results implied that incorporating scavengers into formal waste recovery system is beneficial for economic, environmental, and social sustainability. Wang et al. (2014) applied the SD model to analyze the impact of subsidy policies on the development of the auto parts recycling and remanufacturing industry China. Their results showed that recycling subsidies play a significant role in overcoming the bottleneck problem termed the “lack of cores” and that mixed-subsidy policies have better positive effects on remanufacturing promotion than do single subsidy policies, but that they involve higher costs.

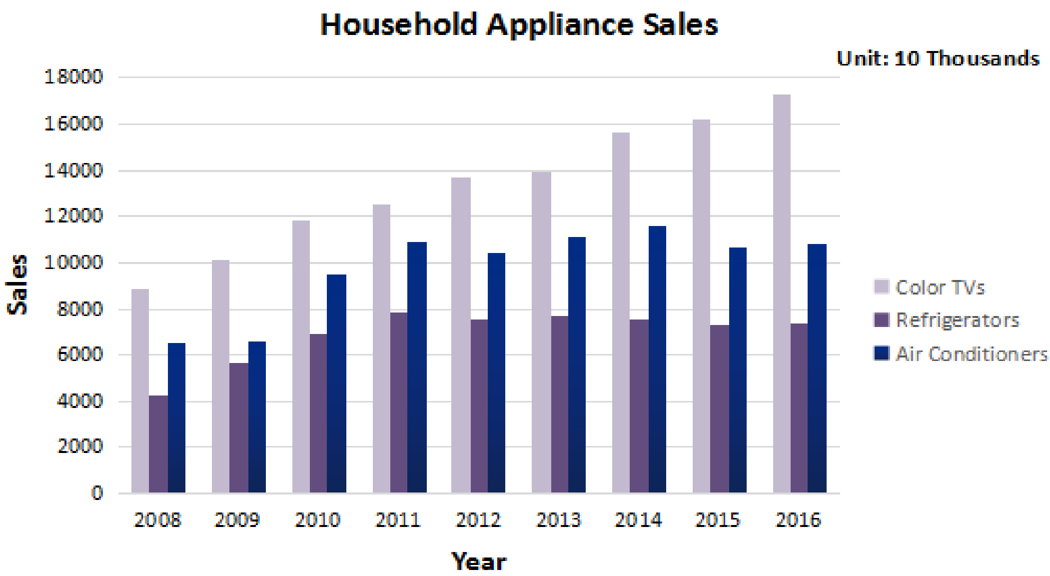
In this paper, we consider both economic and environmental effects on participants in China’s WEEE recycling system under specific policy settings related to the “WEEE processing fund” and use the SD model to construct a system for evaluating policy efficiency. Our study has two contributions. First, while most of the previous literature focused on the environmental effects of policies, our SD model is the first to analyze both the economic and environmental effects of the “WEEE processing fund” in the recycling system. Second, we try to consider consumers’ obligations during WEEE recycling. The simulation results provide significant policy implications for improving the efficacy of the WEEE recycling system.

The remainder of the paper is organized as follows: The next section describes the status and policies of WEEE recycling. Section 3 presents the model structure and methodological issues. Simulation results are presented and discussed in Section 4. Section 5 and section 6 offer discussions and conclusions.

2. Status and policies of WEEE recycling

2.1 WEEE recycling status in China

The amount of global e-waste (discarded electrical and electronic equipment) reached 41.8 million tons in 2014. Just the US and China discarded nearly one-third of the world's total e-waste in 2014 and the amount is still increasing (Baldé et al., 2015). As China's standard of living has risen in recent years, sales of household appliances have increased rapidly (Figure 1), causing a concomitant increase in WEEE. China has entered a peak period for scrapped electrical and electronic products. During 2014–2015, the scrapping rate reached 18.8% (China Ministry of Commerce, 2016) and domestic WEEE generation in China has risen continuously, eventually reaching approximately 5.4 million tons in 2015 (Chi et al., 2011).



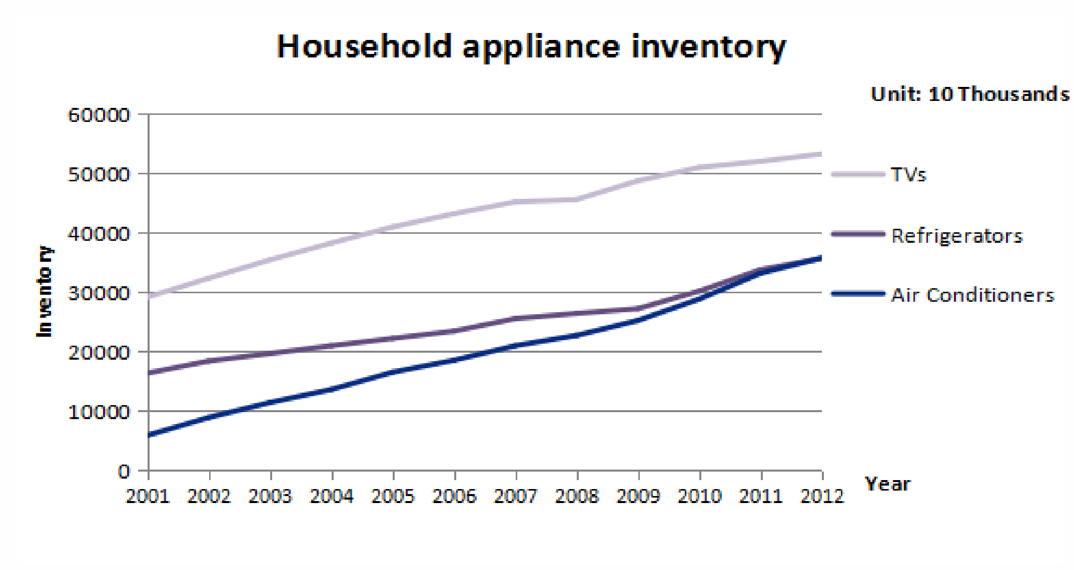


Figure 1. Sales and inventory of household appliance

Data source: Wind data base and White paper on WEEE recycling industry in China 2013

WEEE scrapping is related to household appliance inventory. It is obvious that the inventory of TV sets is the largest among the five main household appliances in China, which means that it has the highest number of scrapped units. However, although the inventory of computers is low compared to other household appliances, due to their short product lifespan, the scrapping speed of computers is much higher than other household appliances.

2.2 WEEE recycling policy in China

2.2.1 Experience from other countries

The WEEE problem has been of concern worldwide. Developed countries were the first to try to address the increasingly severe environmental problems caused by discarded WEEE and informal WEEE processing by enacting laws and regulations.

EU: The European WEEE Directive was implemented in 2003, and was promoted for all member states by 2007. In the WEEE Directive, all types of electrical products (classified into 10 categories) have standards for collection, recovery, and recycling. Moreover, the well-known free take-back of used products and establishment of collection points play a critical role in the EU in dealing with WEEE issues (EU, 2003). Another directive, the Restriction of Hazardous Substances (ROHS), aimed at setting weight percentage limitations on six specific metals and polybrominated diphenyl ethers (PBDE) (flame retardants) to reduce the environmental impact of EEE at the end of its lifespan (Ongondo et al., 2011).

US: As the largest WEEE producer, the US did not limit the international movement of electronic waste, so that most of its e-waste flowed into China, India, and Pakistan before the Basel Convention (Schmidt, 2006). In 2010, the Responsible Electronic Recycling Act (HR2284) began to control the shipment of WEEE containing hazardous materials to developing countries. In the US, Apple, Sony, Sharp, Mitsubishi, Samsung, Hewlett-Packard, Dell, LG, Lenovo, Panasonic, and Toshiba have free collection points or mail-in take-back programs for their products. HR2284 also funds initiatives researching the recovery of rare earth materials.

Japan: In order to decrease the environmental impact of WEEE, Japan introduced a home appliance recycling law (HARL) and began enforcing it in April 2001 (Zhang and Kimura, 2006). The law was enacted to tackle the four largest sources of consumer WEEE in Japan, namely refrigerators, washing machines, TVs, and air conditioning units. These four large items represent a significant percentage by volume and weight of the total WEEE produced by consumers (Bains et al., 2006).

The most notable distinction of WEEE recycling in Japan is that consumers need to pay a recycling fee at the time of disposal and manufacturers are directly obliged to recycle and have a physical rather than a financial responsibility (Aizawa et al., 2008).

2.2.2 Policies in China

Since recognizing the impact of e-waste on the environment and health, China has enacted and implemented a series of policies and legislation over the past two decades. Considering policies for the electronic equipment industry as well as the impact on the recovery stage of the domestic economy, the Chinese government adopted a very cautious approach, opting to regulate e-waste in a stepwise manner (see Table 1).

Table 1. China's national WEEE management regulations

Regulations	Major Content	Effective Date
Measures for the Administration of Prevention and Treatment of Pollution by Electronic Information Products (China RoHS)	Restrictions on the use of six toxic and hazardous substances; 'green' product design; mandatory labeling and provision of information on components, hazardous substances and recycling	Enacted February 28, 2006; Effective from March 1, 2007
Technical Policies for Controlling Pollution of WEEE	Promotes eco-design; defines requirements on the collection, transport, storage, reuse, and treatment of e-waste	Effective from September 27, 2006
Administrative Measures for the Prevention and Control of Environmental Pollution by WEEE	The Ministry of Environmental Protection (MEP) is designated as responsible for supervising and administering the prevention and control of pollution caused by WEEE; environmental impact assessment (EIA) to be undertaken for e-waste dismantling, utilization and disposal projects; definitions of responsibilities of manufacturers, importers, and retailers of EE products	Enacted September 27, 2007; Effective from February 1, 2008
Regulation on the Administration of the Recovery and Disposal of WEEE (China WEEE)	e-waste management qualification; special e-waste treatment fund; encourages partnerships in recycling of WEEE; certification for secondhand EE appliances; requirements on the environmental performance monitoring institution and data management system in recycling enterprises	Enacted February 25, 2009; Effective from January 1, 2011

Source: Chi et al. (2011)

As a substitute for the "Old for New" project, the "WEEE processing fund" was implemented in 2012. This processing fund observes the EPR principle by charging producers and importers processing fees for subsidizing processing companies. The aim of the WEEE processing fund to squeeze informal collectors out of the recovery market, to avoid WEEE being discarded only optionally or processed informally. The subsidies could save formal collection processing companies from bankruptcy. The fees charged are much lower than the subsidies, so the government might provide compensation to fill the gap.

3. Model structure, methodology, and testing

3.1 Model structure and methodology

WEEE management is a complex system consisting of producers, informal recycling peddlers, consumers, and informal and formal processors. The producers obtain profit from production and sales of electronic products. The informal recycling peddlers sell some e-waste to informal processors for dismantling, while other relatively new used electronic products will be sold to the second-hand market. The formal processors acquire profit by extracting renewable resources via dismantling electronic waste units. Consumers in China can sell electronic waste to formal and informal recyclers to earn money. By modeling the entire system, we can simultaneously observe the results of the major economic activities involved. The interests of all participants in this system are directly related to whether they have the motivation to continue their activities, which directly influences the effective operation of the whole system. Since the "processing fund" policy is a long-term established policy, it will be significant to modelling a "processing fund"-centered system to observe variations in the system. The policy was implemented to achieve environmental objectives (i.e., to increase the amount of WEEE recycled by the formal channels and reduce the amount of scrapped electronic products). These environmental objectives and economic interests are generally in conflict, so a significant purpose of the policy is reconciling the two aspects through regulation. We can evaluate the present "processing fund" policy aiming to improve it.

In our study, we try to apply the SD approach to analyze the overall WEEE management system. The reason an SD approach was selected is that it can handle systems with complex structures through a visual expression using existing software (e.g., Vensim DSS in our study). The SD model can also simulate the dynamic behavior of the system, which in turn enables an evaluation of strategies to improve it.

Before presenting the details of the system, the following assumptions should be noted: (1) WEEE generated by consumers basically flows into the formal and informal channels, i.e., discarded e-waste is not considered; (2) Recycled WEEE received by dismantling enterprises should have value, i.e., e-waste with no value is ignored; and (3) Processing enterprises can deal with the WEEE harmlessly, i.e., enterprises that cannot handle the environmental problems are ignored.

Figure 2 shows a stock flow diagram (SDF) of the WEEE management system involving four stocks (producer profit, processor profit, consumer profit, and processing fund) and other inflows and outflows. Through the structure with real world data, we might capture some vital features of the WEEE management system.

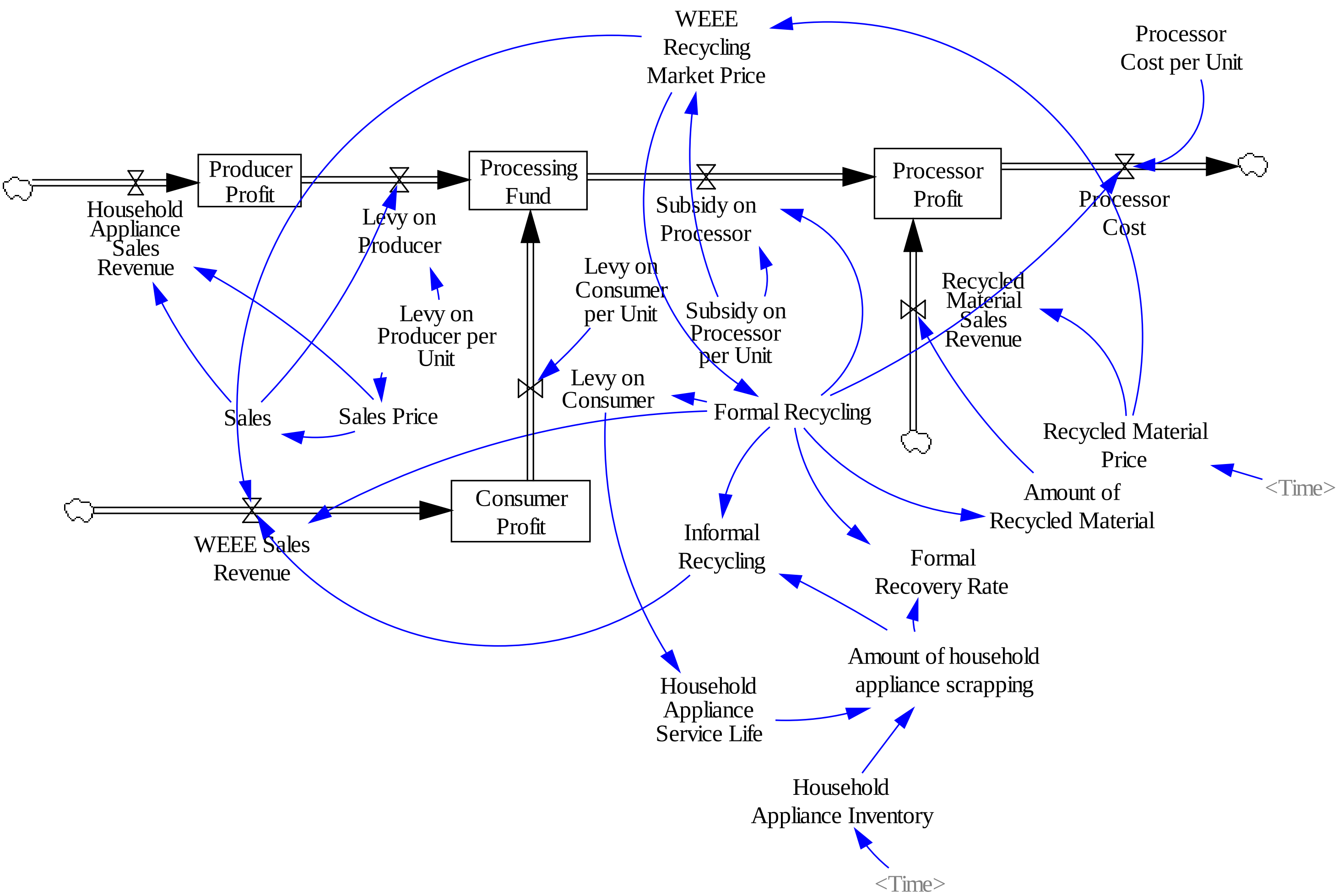


Fig 2. WEEE management system Stock Flow Diagram

3.1.1 Producer module

The producer module describes household appliance producers' economic activity, which aims to maximize producers' profit. Here we take the producer profit as industrial profit related to the processing fund. The stock variables *producer profit*, *household appliance sales revenue*, and *levy on producer* shown in Figure 2 can be represented by a time integral of the net inflow minus the net outflows. For instance, *producer profit* ($PProd$) is defined by a time integral of net inflow *household appliance sales revenue* ($HASR$) minus the net outflow *levy on producer* ($LProd$) as presented in Equation 1:

$$PProd(t) = \int_{t_0}^{t} (HASR(t) - LProd(t))dt + PProd(t_0) \tag{1}$$

$HASR$ is calculated by multiplying *sales* (S) by *sales price* (SP) and $LProd$ is calculated by multiplying *sales* (S) by *levy on producer per unit* ($LPUProd$) as presented in Equation (2):

$$\begin{aligned} HASR(t) &= S(t) * SP(t) \\ LProd(t) &= S(t) * LPUProd \end{aligned} \tag{2}$$

The critical impact of levying fees on manufacturers might be a price shift, which means $LPUProd$ has a positive impact on the sales price of household appliances.

3.1.2 Recycling module

The recycling module consists of two subsystems, the informal recycling peddler system and the formal recycling system. In this study, we mainly focus on the formal recycling system and WEEE processing parts and use just the informal recycling amount to describe the informal recycling peddler system.

The processing part describes the core of the WEEE management system, which also pursues the maximization of processors' profit. The stock variable *processor profit* ($PProc$) equals *recycled material sales revenue* ($RMSR$) plus the subsidy to the processor (SoP) minus processor cost (PC):

$$PProc(t) = \int_{t_0}^{t} (RMSR(t) + SoP(t) - PC(t))dt + PProc(t_0) \tag{3}$$

where $RMSR$ equals the *amount of recycled material* (ARM) multiplied by the *recycled material price* (RMP), SoP equals the *per unit subsidy on the processor* ($SPUProc$) multiplied by the *formal recycling* (FR), and PC equals the *formal recycling* (FR) multiplied by the *processor cost per unit* ($PUPC$):

$$RMSR(t) = ARM(t) * RMP(t)$$

$$SoP(t) = FR(t) * SPU\ Proc \tag{4}$$

$$PC(t) = FR(t) * PUPC$$

3.1.3 Consumer module

The consumer module mainly establishes consumers as the most critical participants in the system, who have both payoffs and obligations. By selling discarded household appliances to formal or informal recyclers, consumers can earn money. In contrast, following the policy implemented in Japan, levies on consumers that could subsidize recycling and processing also constrain the use of household appliances.

We presume that consumers care about their payoff when they determine how to deal with their old household appliances, so we use consumer profit to define the difference between consumers' payoff from selling a used household appliance and paying the fees to complement logistics and processing in formal recycling sectors. The *consumer profit* (CP) equals *WEEE sales revenue* (WSR) minus *levies on consumers* (LoC):

$$CP(t) = \int_{t_0}^{t} (WSR(t) - LoC(t))dt + CP(t_0) \tag{5}$$

where WSR equals the sum of *informal recycling* (IR) and *formal recycling* (FR) multiplied by the WEEE recycling market price ($WRMP$), the LoC equals *formal recycling* (FR) multiplied by the *levy on consumer per unit* ($LPUC$):

$$WSR(t) = (IR(t) + FR(t)) * WRMP(t)$$

$$LoC(t) = FR(t) * LPUC \tag{6}$$

3.1.4 Scrapping module

The scrapping module includes *household appliance service life* ($HASL$), *household appliance inventory* (HAI), *amount of household appliance scrapping* ($AHAS$), and the *formal recovery rate* (FRR). These four variables try to capture scrapping trends for household appliances, and an additional index (FRR) tries to evaluate the efficiency of formal recovery.

The longest service life of a household appliance product n is 16 years, η (in this paper we assume η to be 60% for no levies on consumers and 40% when consumers pay levies) is the average proportion of household appliance scrapping from minimum end of life to maximum end of life. $AHAS$ is related to $HASL$ and HAI following the equation below as follows (according to the inventory coefficient approach proposed by Liu et al., 2016):

$$AHAS(t) = HAI(t) * \eta / (n - HASL + 1) \quad (7)$$

where HASL can vary with different scenarios (with or without a levy on consumers, LoC) as

$$HASL = \begin{cases} m_1 & if \ LoC = 0 \\ m_2 & if \ LoC > 0 \end{cases} \quad (8)$$

We assume that if we charge consumers levies, then they will try to use their household appliances for a longer period (a shift from m_1 years to m_2 years). We estimate that they will keep a refrigerator two years longer if we charge them the fee when the appliance reaches the end of its lifespan.

The above four subsystems are connected by the *processing fund* (PF) inventory variable in our model. We consider the PF to be a capital pool that reserves the levies on producers and consumers and provides subsidies for processing enterprises as follows:

$$PF(t) = \int_{t_0}^{t} (LProd(t) + LoC(t)) - SoP(t)dt + PF(t_0) \quad (9)$$

3.2 Model testing

SD models can be tested and improved using a wide variety of approaches. Here, we first check its consistency through historical testing and assess its sensitivity under distinctive scenarios as in Georgiadis and Besiou. (2008).

3.2.1 Historical testing

We use actual data on *household appliance inventory* (namely, refrigerators) to simulate the *amount of household appliance scrapping* and examine if the model can replicate observed behavior by comparing the simulated and actual values for the *amount of household appliance scrapping* from 2013 to 2015. The test results are presented in Table 2.

Table 2. Historical fit (2013-2015)

Parameter	Theil's inequality coefficient	MAPE	Bias proportion	Variance proportion	Covariance proportion
Amount of household appliance scrapping	0.030	0.060	0.522	0.390	0.060

The mean absolute percent error (MAPE) between the simulated and actual value of *amount of household appliance scrapping* is about 6% (Table 2). The low bias, variation, and covariance proportions indicate that the errors are unsystematic, which means that the model can replicate the observed behavior.

3.2.2 Sensitivity testing

In order to test the sensitivity of this model, we focus on two variables: *formal recycling* (FR) and *amount of household appliance scrapping* (AHAS). We can assess the sensitivity by observing variation under different policy scenarios and *household appliance service lives.* (Figure 3)

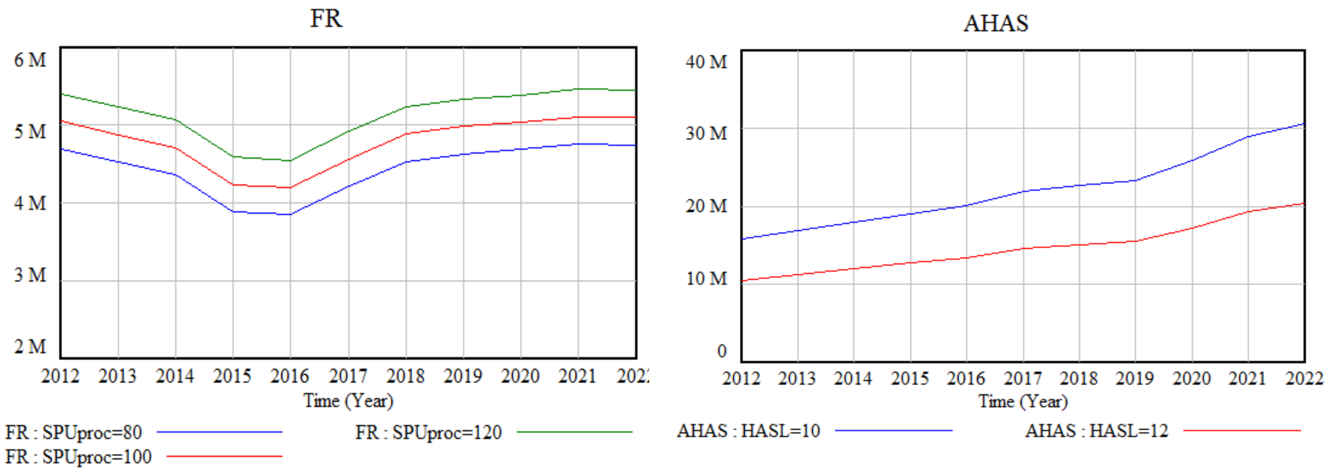


Figure 3. Sensitivity testing

Figure 3 indicates that *formal recycling* clearly varies under distinctive subsidies on processors. We can see that as *SPUProc* increases from 80 RMB to 120 RMB, *formal recycling* increases rapidly, proving the model's sensitivity. At the same time, the *amount of household appliance scrapping* drops when HASL increases from 10 years to 12 years, which also illustrates the model's sensitivity.

4. Simulation results

4.1 Data

The main data that we used in this simulation came from several specific sources. The sales of household appliance products and the spot prices of metals which can be obtained by dismantling WEEE are from the Wind database. Household appliance inventories came from the White Paper on the WEEE recycling industry in China 2013, and the actual amount of household appliance scrapping came from the White Paper on WEEE recycling industry in China 2015. We set 88% of the WEEE as being collected by informal peddlers with 12% collected by formal recyclers (Qu, 2013).

4.2 Policy setting

We implement the corresponding policy settings under different scenarios and discuss the effects of the levies and subsidies on various targeted objects under different regulatory policies in the e-waste recycling market. Consequently, the levy on manufacturers per unit, levy on consumers per unit, and subsidy on processors per unit are regarded as variables in the model that can be artificially controlled. In this sense, we can observe both economic and environmental effects of the WEEE management system under different policy settings to evaluate the “WEEE processing fund” policy. The policy settings under different scenarios are as follows:

***Scenario I*:** With no policy active, representing the operation of the WEEE management system under market mechanisms. The variables change in terms of current trends and original settings, mainly relying on internal system constraints without applying any artificial regulatory policy effects.

***Scenario II*:** Including two policy options, as shown in Table 3. It should be noted that the levy and subsidy standards are based on the "WEEE processing fund" policy that was enacted and implemented on July 1, 2012 by the Environmental Protection Administration of China. In addition, we consider the obligation of consumers by adding the “levy on consumers” setting.

We take refrigerators as example in Table 3 and give a combination of regulatory policies on the WEEE management system of the refrigerator. The specific policy combinations are described in the table. *Without policy* is the policy settings for *Scenario I*, which is the absence of any artificial control policy. *Policy 1* and *Policy 2* affiliate with *Scenario II*, which combines levying on various participants and subsidizing processors.

Table 3. “WEEE processing fund” policy settings (refrigerators)

Policy settings	Details	Policy parameter setting
Without policy	No artificial policy regulations	Levy on producer = 0 RMB/unit Levy on consumer = 0 RMB/unit Subsidy to processor = 0 RMB/unit
Policy 1: *Levy on producer* *Subsidy on processor*	Levy on producer, 12 RMB per unit; subsidy to processor, 80 RMB per unit	Levy on producer =12 RMB/unit Levy on consumer=0 RMB/unit Subsidy to processor =80 RMB/unit
Policy 2: *Levy on consumer* *Subsidy on processor*	Levy on consumer, 12 RMB per unit; subsidy to processor, 80 RMB per unit	Levy on producer = 0 RMB/unit Levy on consumer = 12 RMB/unit Subsidy to processor = 80 RMB/unit

4.3 Simulation results

4.3.1 Economic effects

The entire system will operate more stably and effectively for all participants if we can ensure that all of them have certain incentives to carry out activities that simultaneously benefit the environment and obtain profit. This section presents the simulation results for producer profit, processor profit, consumer profit, and processing fund for refrigerators under the WEEE management system for 2012-2022. Simulation results for TV sets and air conditioners are provided in the Appendix.

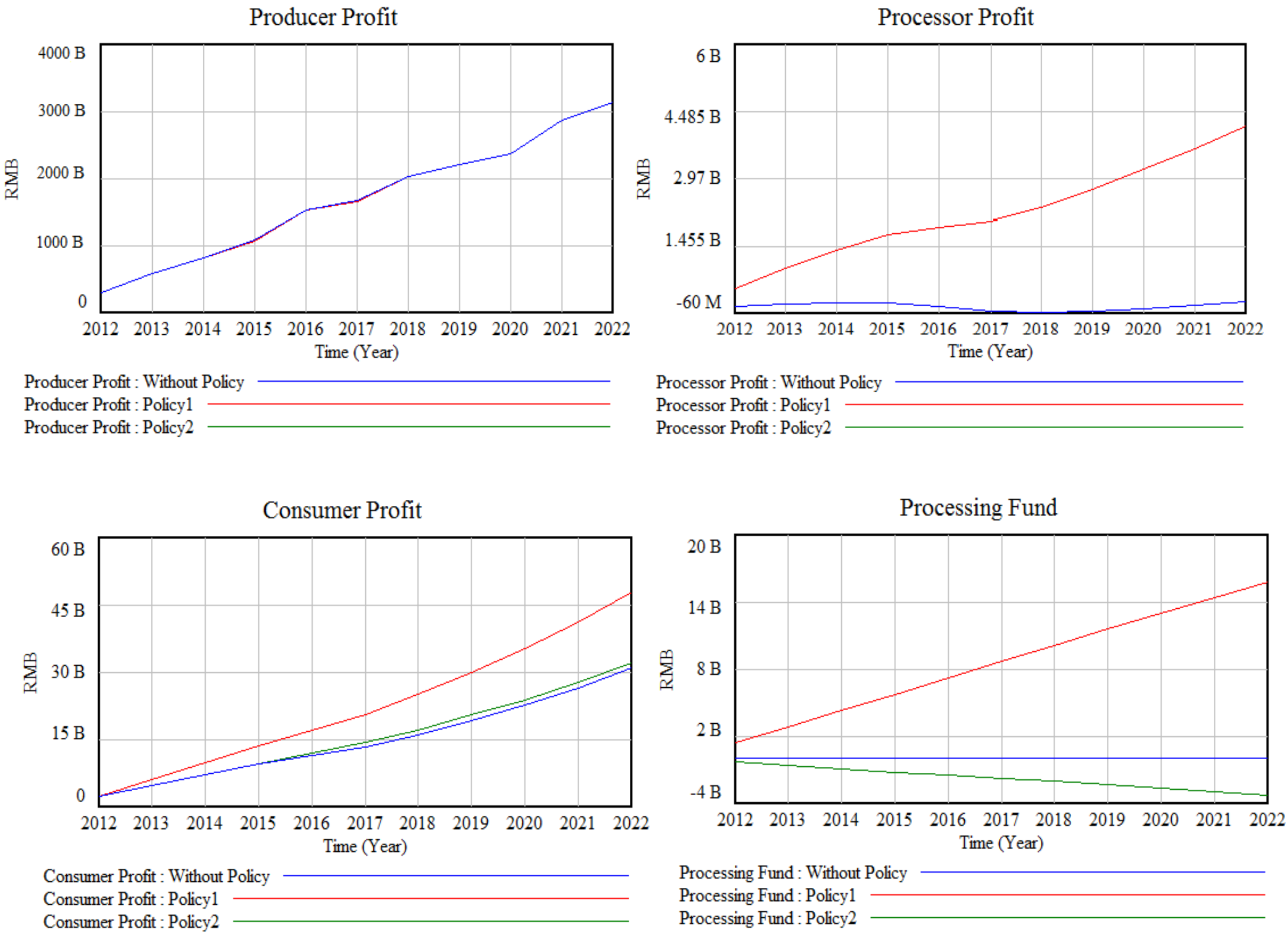


Figure 4. Economic indicators (refrigerators) in the WEEE management system

Figure 4 presents the economic indicators of the WEEE management system for refrigerators. The profits of the three participants in the system change differently under the policy scenarios. The policy does not seem to have an obvious impact on producers' profit. However, the processors' profit and consumers' profit show distinctive effects. *Policy 1* and *Policy 2* seem to boost processors' profit, in contrast to the *Without policy* setting where processors' might be less than zero for several years. Consumers' profit could increase if all three policy settings are implemented. Under *Policy 1* and *Policy 2*, their profits will be higher than under the *Without policy* scenario. In addition, because *Policy 2* has levies on consumers, their profits under *Policy 2* could be lower than under *Policy 1*. The processing fund graph indicates whether each policy needs extra government subsidies. As shown in the figure, under *Policy 1* the capital pool needs not be complemented, but under *Policy 2* it seems that the levies paid by consumers cannot pay for the subsidies transferred to processors.

4.3.2 Environmental effects

The most substantial purpose of the WEEE management system is to achieve the best environmental benefits, i.e., increasing formal recycling and reducing informal recycling and scrapping to best relieve the impact of environment pollution. This section focuses on the amounts of formal and informal recycling and the formal recovery rate for refrigerators under the WEEE management system and presents the effects of different policy settings on environmental indicators.

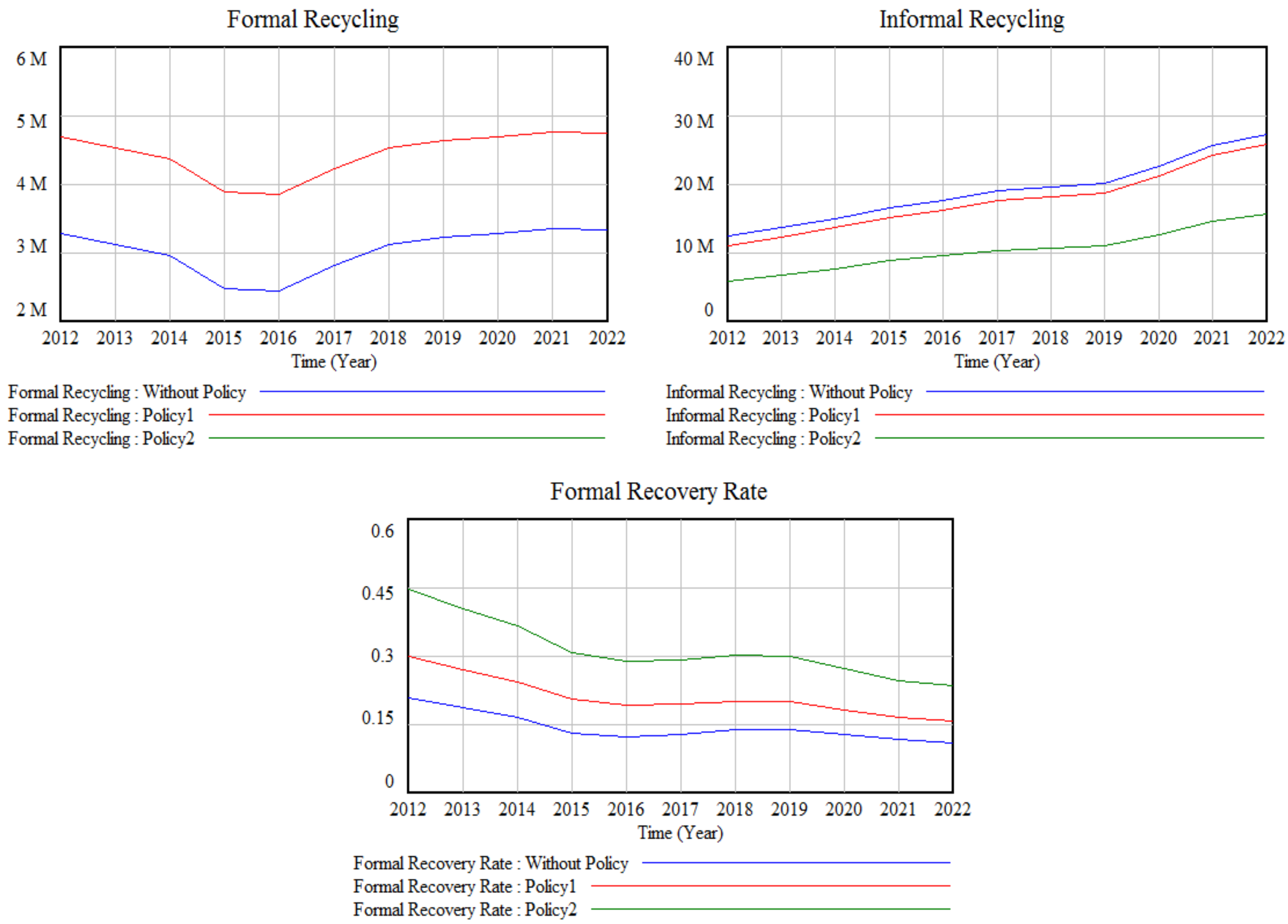


Figure 5. Environmental indicators (refrigerators) in the WEEE management system

Figure 5 shows formal recycling, informal recycling, and the formal recovery rate under the three policy settings. Relative to the situation without any policy, it is evident that *Policy 1* and *Policy 2* could improve the status of formal recycling and decrease informal recycling. We can see in Figure 5 that *Policy 2* seems have a more intense impact on informal recycling than *Policy 1*, which means under *Policy 2* informal recycling could be effectively controlled. The formal recovery rate varies distinctly under the different policy settings. When there is no policy control, the average formal recovery rate from 2012 to 2022 is about 14.23%. It reaches 20.89% when we place levies on producers and subsidize processors (i.e., under *Policy 1*) and 31.34% when we place levies on consumers instead of producers (i.e., under *Policy 2*). While on account of the increasing amount of household appliance scrapping, the tendency of formal recycling rate will generally go down as time goes on.

5. Discussion

5.1 Levies on producers could be implemented continuously

In the refrigerator WEEE management system, the producer is the target of the levies under *Policy 1*. This policy seems unbeneficial because the levy might lower producers' profits. However, as shown in Figure 5, compared to levies on consumers and/or without any policy, this policy almost has no differentiating influence on producers' profit. Meanwhile, under all three scenarios, the producers' profits keep increasing. Therefore, producers will not leave the market even if they are levied. In addition, under *Policy 1*, processors could benefit from subsidies that could persistently attract new enterprises into the market because of the positive profit of the industry. The continuously positive processing fund under *Policy 1* means the levies from producers could satisfy the subsidies given to processors, and the government would not need to fill the gap through fiscal income.

5.2 Levies on consumers could improve recycling

The simulation of *Policy 2,* in which consumers are levied, has interesting results. Compared to *Policy 1*, which levies producers, levying consumers impacts environmental indicators more prominently than economic indicators. The consumers will consider waiting longer to discard household appliances, which could efficiently decrease the amount of WEEE scrapping. Moreover, informal recycling could be controlled through this policy, which decreases the probability of unfavorable dismantling and processing. Under this policy, the formal recovery rate reaches a relative high level, which improves recycling's general efficiency, creating a greener WEEE management system.

5.3 Focus on different types of WEEE

WEEE of different types of household appliances should be treated individually. In China, the five basic household appliances are TV sets, washing machines, refrigerators, air conditioners, and computers. Different household appliances have distinctive service lives and processing costs as well as different metal contents. Recognizing this, the “WEEE processing fund” declared different levies and subsidies for various household appliances. For these reasons, we should not just use one simple policy to deal with WEEE problems, but keep an eye on the actual policy effects and change the policy dynamically. We also simulated TV set and air conditioner WEEE management system models to evaluate policy effects and show the differences among specific household appliances (see the results presented in the Appendix). We found that WEEE management systems for both TV sets and air conditioners under *Policy 1* and *Policy 2* could improve processing enterprises’ profits without harming producers. In particular, the processing fund in air conditioner management system under *Policy 2* dropped only slightly lower than zero, suggesting that the government would need to provide little or no funding for the system. This contradicts the results of other two household appliances under *Policy 2*. The formal recovery rates for TV sets and air conditioners are much lower than that of refrigerators. Air conditioners’ formal recovery rate, in particular, would still be under 10% even if *Policy 2* were implemented. Therefore, the processing fund policy should adjust subsidy amounts for specific household appliances to stimulate participation in the WEEE management system so as to attain optimum economic and environmental results.

6. Conclusion

In this paper, we constructed SD models to simulate the workings of the WEEE management system throughout the whole industrial chain. The profit of each participant and several environmental indicators were observed under different "WEEE processing fund" policy settings to evaluate whether those settings are reasonable and efficient.

Through the simulation, we found that the system could reach the Pareto equilibrium, which means that the "WEEE processing fund" project could save the formal processing industry from its current dilemma without harming household appliance producers. Meanwhile, the government could just supervise the implementation of the policy, since there is no need to provide extra assistance and the whole system could function well. Consumers have not yet had to pay levies in China. The current status of recycling in China is that consumers can benefit from selling their WEEE instead of being charged. Our simulation results indicate that the policy of placing levies on consumers, which has already been implemented in Japan, has positive environmental impacts and is worthy of being tried in China.

As one of the participants in the system and the source of WEEE production, it will be easier to constrain WEEE pollution if consumers take responsibility for their waste production. The "WEEE processing fund" dropped its subsidies (currently 60-70 RMB for television), indicating that the policy intends for subsidies to provide incentives for processing enterprises to make technology evolutions to lower processing costs, so that they can survive without policy welfare. As for consumers, the government should use appropriate measures to charge them for the cost of producing wastes, while at the same time letting them realize how they should change their WEEE recycling behavior.

Acknowledgements

Financial support from the Japanese Ministry of Education, Culture, Sports, Science and Technology through Grant-in-aid for Scientific Research (C) 15K03353 is gratefully acknowledged. All the views expressed in this paper and any errors are the sole responsibility of the authors.

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Appendix

A1. TV set simulation results

(1) Economic indicators

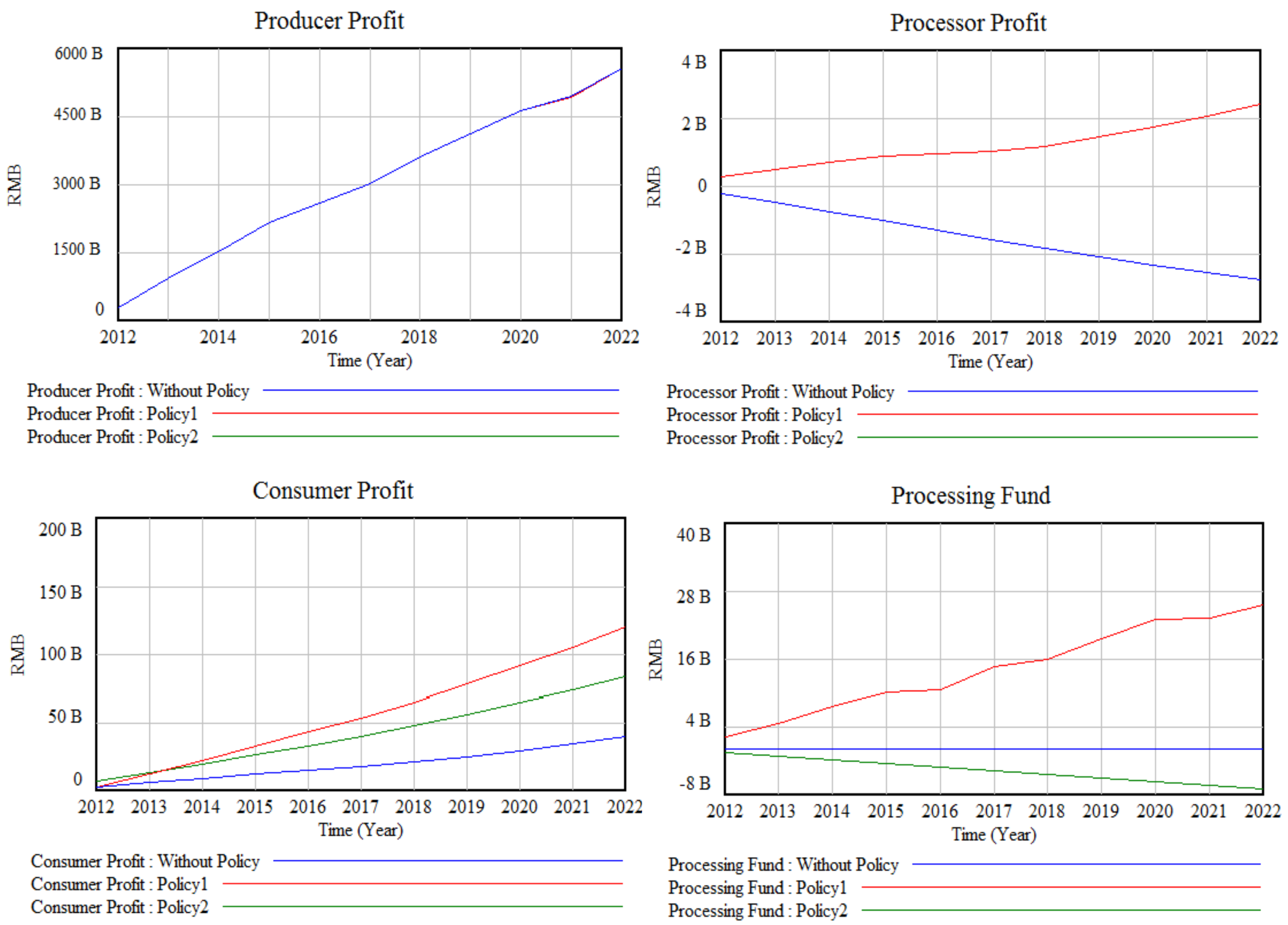
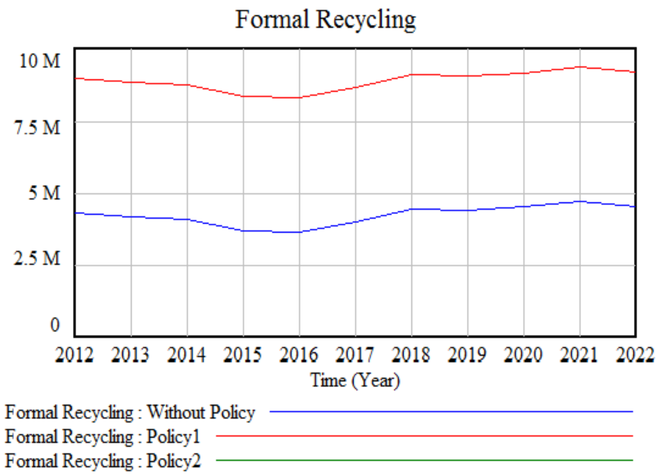
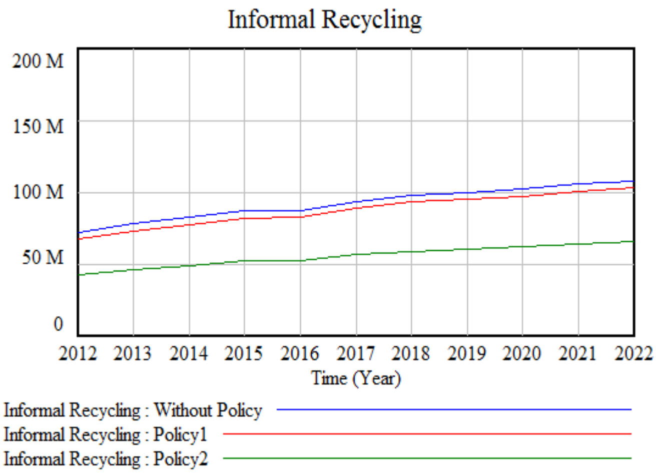


Figure A1. Economic indicators (TV sets) in the WEEE management system

(2) Environmental indicators





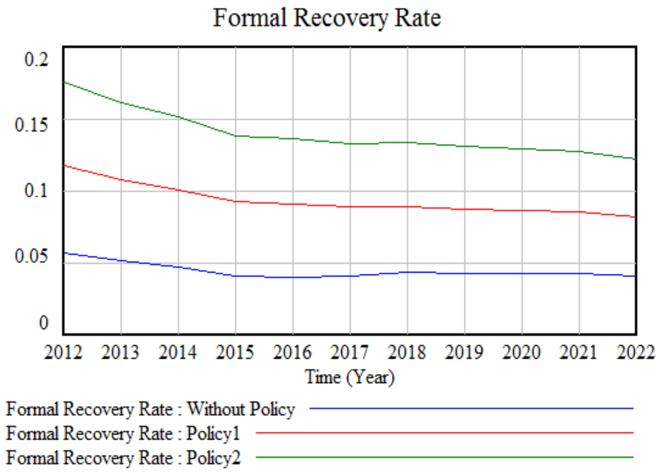


Figure A2. Environmental indicators (TV sets) in the WEEE management system

A2. Air conditioner simulation results

(1) Economic indicators

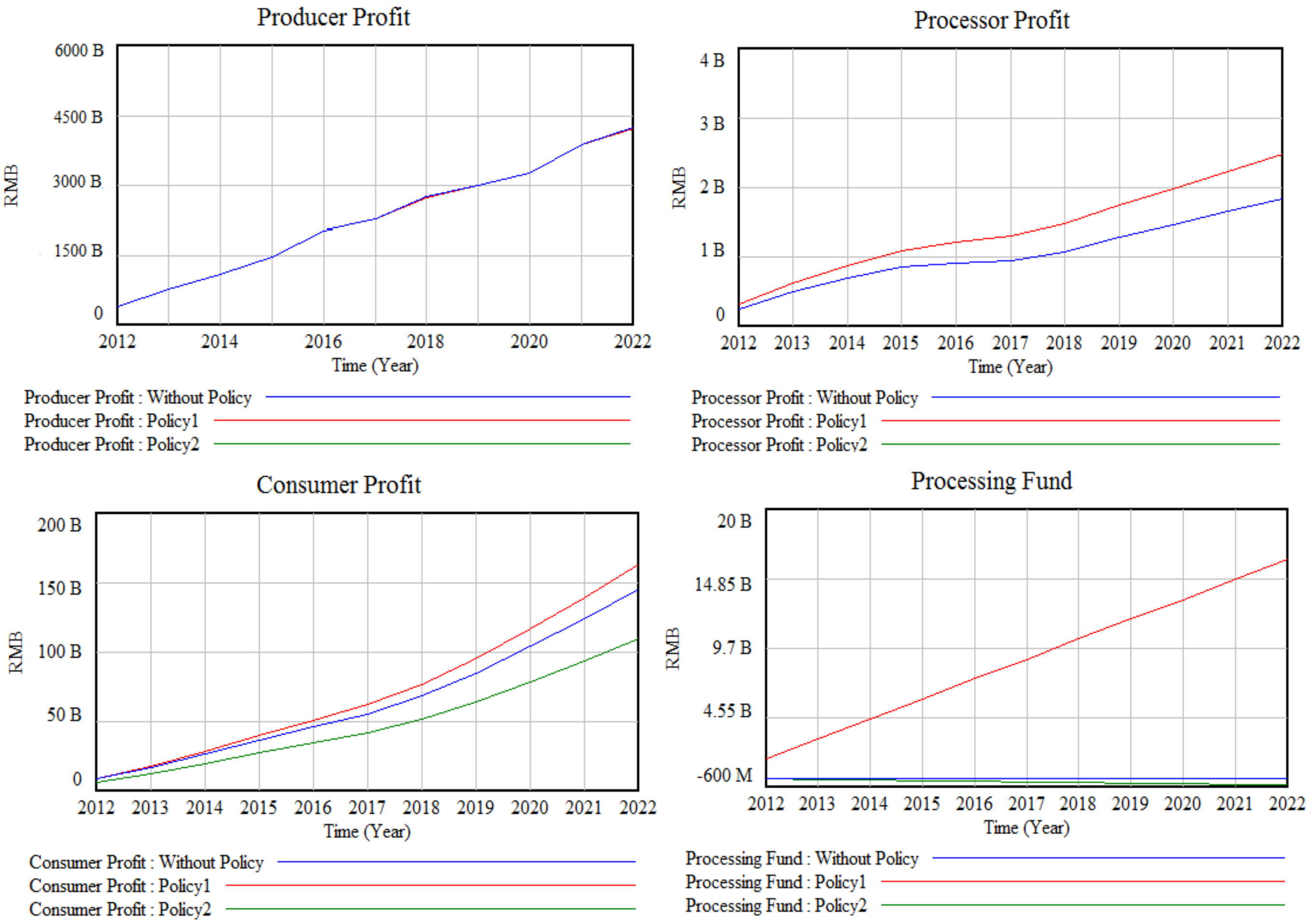


Figure A3. Economic indicators (air conditioners) in the WEEE management system

(2) Environmental indicators

Figure A4. Environmental indicators (air conditioners) in the WEEE management system