Resource Cyclical Dynamics of Electric and Electronic Equipment Waste

Man-Hyung Lee, Ph.D
Professor
Department of Urban Engineering,
Chungbuk National University
12 Gaeshin-Dong, Heungduck-Gu, Cheongju, Chungbuk, 361-763, Korea
Tel: 82-43-261-2369/Fax: 82-43-276-2369
E-mail: manlee@cbu.ac.kr

Tae-Yong Kim, Ph.D
General Manager
Samsung Global Environment Research Center
467-14, Dogok-2Dong, Gangnam-Gu, Seoul, 135-856, Korea
Tel: 82-2-3458-3142/Fax: 82-2-3459-3149
E-mail: ty77.kim@samsung.com

and

Moonseo Park, Ph.D
Assistant Professor
Department of Architecture,
Seoul National University
San 56-1 Shinrim-dong, Kwanak-Gu, Seoul, 151-742, Korea
Tel: 82-2-880-5848/Fax: 82-2-871-5518
E-mail: mspark@snu.ac.kr

Abstract

As a practical means to upgrade urban sustainability, this paper focuses on resource cyclical systems concerned with electric and electronic equipment waste (EEEW) in Korea. Borrowing System Dynamics concepts and approaches, it examines behavioral changes of EEEW dynamics to see whether the existing management methods can be readjusted. The measurement is based upon both reuse and material and thermal recycle simulation works in the individual stage of EEEWdischarge, collection, and treatment, going beyond the traditional recycle-onlycustoms. This research estimates that the newly introduced Extended Producer Responsibility (EPR) system would definitely exert a significant impact on the final stage of EEEW treatment, decreasing the final treatment volume in the first half of the research period. The trend, nonetheless, would be reversed in the second half, mainly owing to the additional waste volume originated from the local government and recycling center. Sensitivity analysis poses, among others, that the local government-supported reuse center should take charge of a pivotal role in the EEEWmanagement and treatment in the long run. The research also shows that sufficient and necessary conditions for the EEEW management and treatment should be given to the combined efforts,both from the private sectors and the public domains. Based on these research findings, the paper recommends that key stakeholders including theproducer and the public organizations should devise how to carry out specific agenda centered around partnership or network buildings.

Keywords: Resource CyclicalSystems, System Dynamics, Electric and Electronic Equipment Waste (EEEW), Extended Producer Responsibility (EPR)

1. Introduction

This study examines treatment characteristics of electric and electronic equipment waste (hereafter EEEW), borrowing conceptsderived from the System Dynamics (SD). Most of the existing documents focusing on the resource cyclical society system have provided theoretical tools or practical means, going beyond the statistical data analyses. For example, Mashayekhi (1993), Sudhir, Srinivasan, and Muraleedharan (1997), Ulli-Beer (2003), and Ulli-Beer, Richardson, and Anderson (2004) used SD modeling to analyze solid waste treatment issues. Ford in his *Modeling the Environment* (1999) also suggested various SD models related to the environment system. These studies point out structural relationships embedded in feedback, time delay, and non-linearity, which provide a conceptual basis for this research.

As the EEEW discharge and collection channels are so complicated, it is essential to understand the system as a whole, ahead of suggesting any specific treatment method. Research questions are centered around how causal relationships are formed throughout the EEEW life cycles and discuss what types of variables and feedbacks should be strengthened or not. The research covers both explicit and implicit factors in dealing with the EEEW management in

Korea. The former emphasizes in-depth analysis of the current status quo and unresolved tasks. In contrast, the latter stresses diagram formation and scenario experiment, reflecting bottleneck and time delay factors. All of them would contribute to reassigning appropriate roles among the key stakeholders including the consumer, the producer, the local government, reuse centers, and recycling centers.

Following the introduction, the EEEW conceptual models are proposed as the cornerstones for the causal map and flow-stock modeling works. After quantitative model building and calibration, sensitivity analyses are carried out to test the robustness of the model. In order to develop policy leverages, policy feasibility and applicability are experimented in both quantitative and qualitativemanners. Finally, the key research findings and discussion topics are highlighted as the conclusion of this research.

II. EEEW Loops and Dynamics

1. EEEW Conceptual Loops

The electric and electronic equipment defined in this paper refers to the typical household durable goods like televisions, refrigerators, air conditioners, and etc. The equipment life cycle is composed of a series of activities, covering material input, production, delivery, consumption, and discard.

The resource cyclical social system to be proposed in this study aims at minimizing the discard volume per se. That is, if reuse and recycle methods were adopted by the major stakeholders, it would contribute to minimizing the final treatment volume. Reuse exemplifies the most appropriate type for the resource cyclical social system, as it implies the fact that consumer(s) would use the old product or its components, which have been discharged by the aboriginal owners. Material and thermal recycles are also essential for the resource cyclical social system, as raw materials and energy, all of which are extracted from the discharged electric and electronic components, are again put into production-consumption processes. If these circular flows work, it would be possible for both producers and consumers to save money.

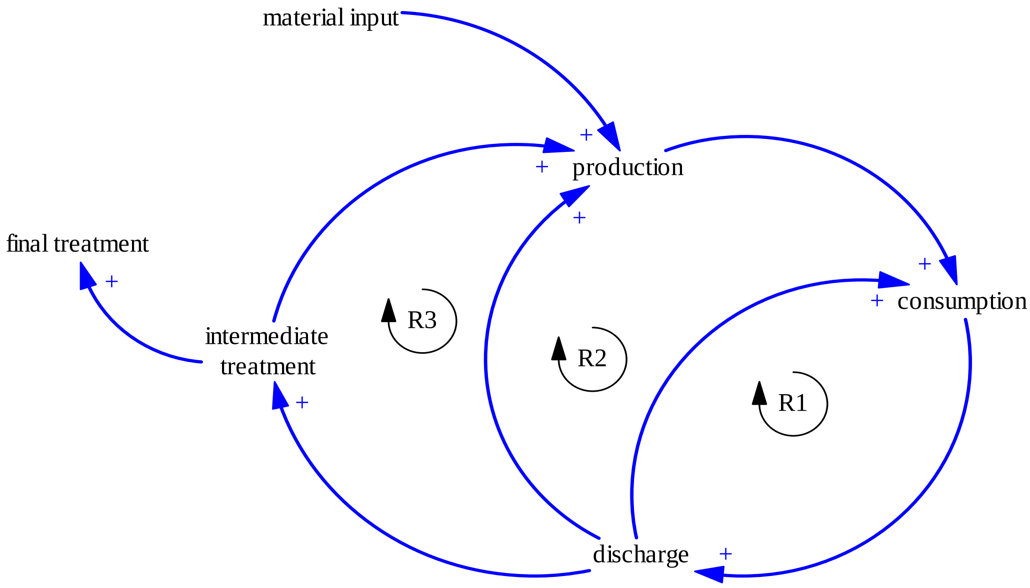

Figure 1: Basic EEEW Structure for the Resource Cyclical Social System

From this perspective, Figure 1 presents the basic dynamic EEEW structure for the resource cyclical social system. It shows how the key variables interact in the processes of equipment production, consumption, discharge, and treatment. R1 focuses on continuous reuse of the discharged product as the second-hand product. In contrast, R2 simply means component reuse. Lastly, the R3 loop explains recycle circulation derived from the intermediate treatment. As mentioned above, the shortest route for the resource cyclical social system should be given to both R1 and R2 loops. If recycle-oriented policy resorts to a convenient and inexpensive alternative to satisfy the pre-allocated volume prescribed in the Extended Producer Responsibility (EPR) rules, it might result in a dilemmaticsituation, meaning that the raw material input has to be increased over time, which would produce the increased volume of the final treatment.

2. Electric and Electronic Resource Cyclical Loops

The reuse causal loops in Figure 2 are composed of 2 reinforcing and 3 balancing loops. Higher consumer consciousness on reuse and recycle leads to more use of the second-hand electric and electronic equipment, which also increases the total reuse volume (R1 and R2). In contrast, as consumer consciousness expands the average product lifetime, it reduces the discarded equipment volume, which in turn lowers collection activities in the local government and reuse center (B1, B2, and B3).

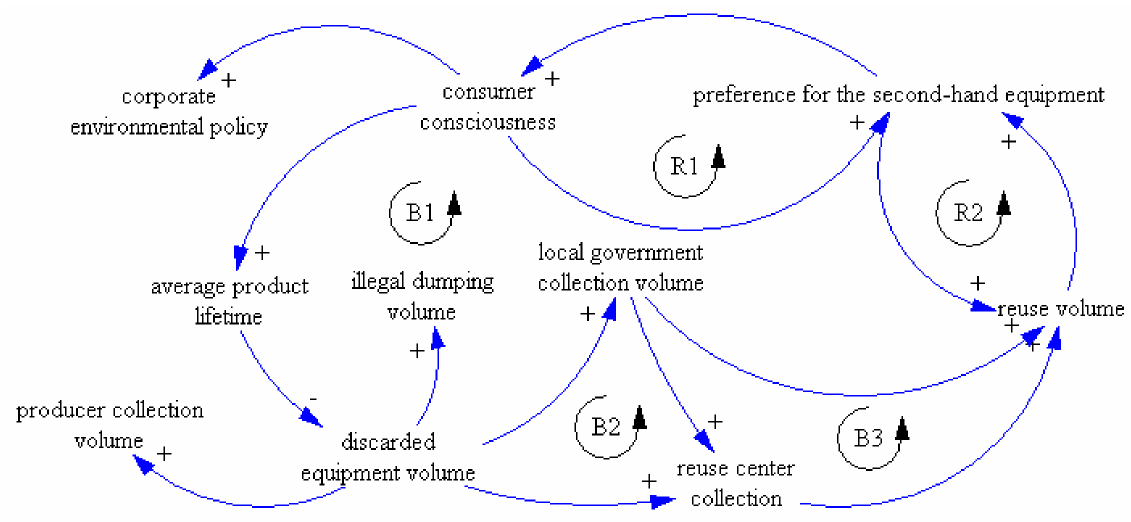

Figure 2: EEEW Reuse Causal Loops

Secondly, Figure 3 presents the basic recycle causal loops. Here 5 reinforcing and 3 balancing loops are interrelated to each other. The recycled product and components exert negative impacts on the average product lifetime. If the product lifetime becomes longer, it would dampen the brand-new sales volume, reducing the producer-collected waste volume (R1). If the producer has to increase the replacement demand, the recycled volume would be expanded (R2). In a similar context, there also exists a positive relationship between the discharged product and components and the collection volume by the local government unit or the reuse center. Therefore, the recycle volume would be increased if the local government unit or local reuse center has to handle more electric and electronicwaste (R3, R4, and R5). Reflecting the corporate environmental policy, however, the business willingness for the product recycle would yield a couple of balancing loops. First of all, the producer has to deal with the extra burden originated from the recycle cost. In addition, as the central government would levy a huge amount of fines when the prearranged recycle target number is not achieved, the producer's top priority is given on how to minimize the recycle volume (B1, B2, and B3).

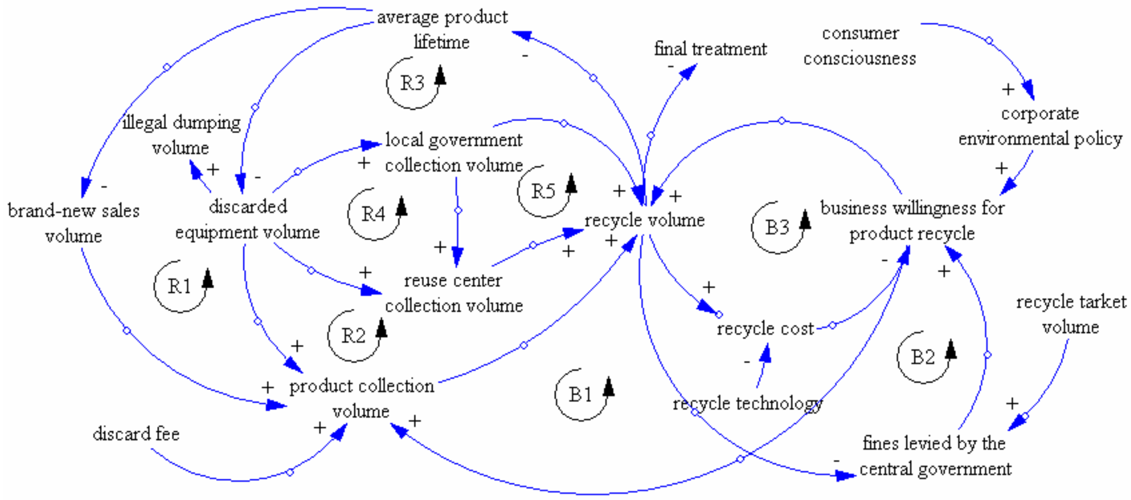

Figure 3: EEEW Recycle Causal Loops

Thirdly, illegal dumping in Figure 4 reveals 2 reinforcing and 3 balancing loops. In fact, the reinforcing loops are the same as shown in Figure 2. Up to now, illegally dumped electric and electronic waste has been handled either by the individual consumer or the local government. This suggests that to reduce illegal dumping, consumer consciousness should be upgraded. In addition, if the average product lifetime is expanded and if both the local government and reuse center facilitate product and component transaction in the second-hand market, it would also contribute to the reduction of the illegally dumped volume (B1, B2, and B3).

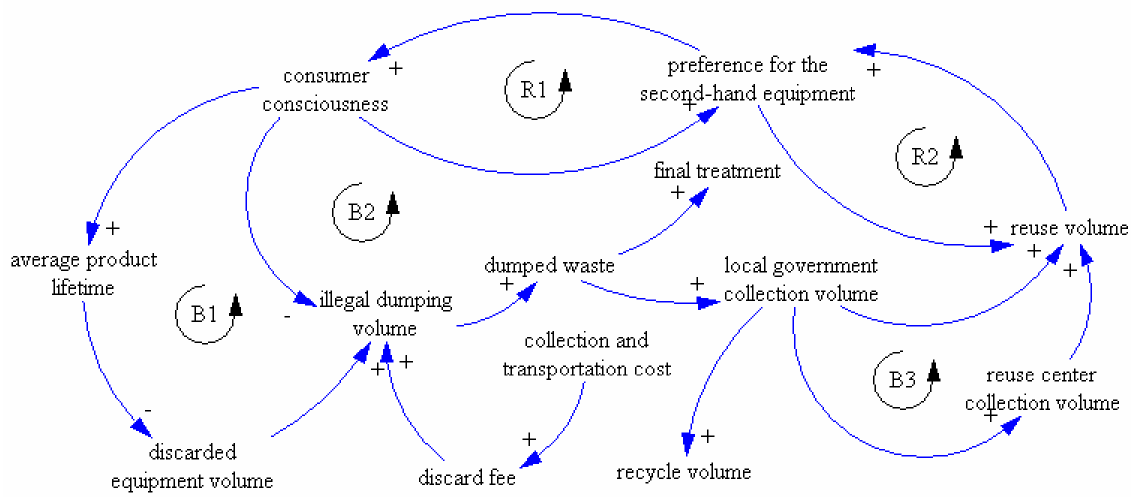

Figure 4: EEEW Illegal Dumping Causal Loops

In sum, Figure 5 represents the resource cyclical system, in which the EEEW treatment processes are synthesized.

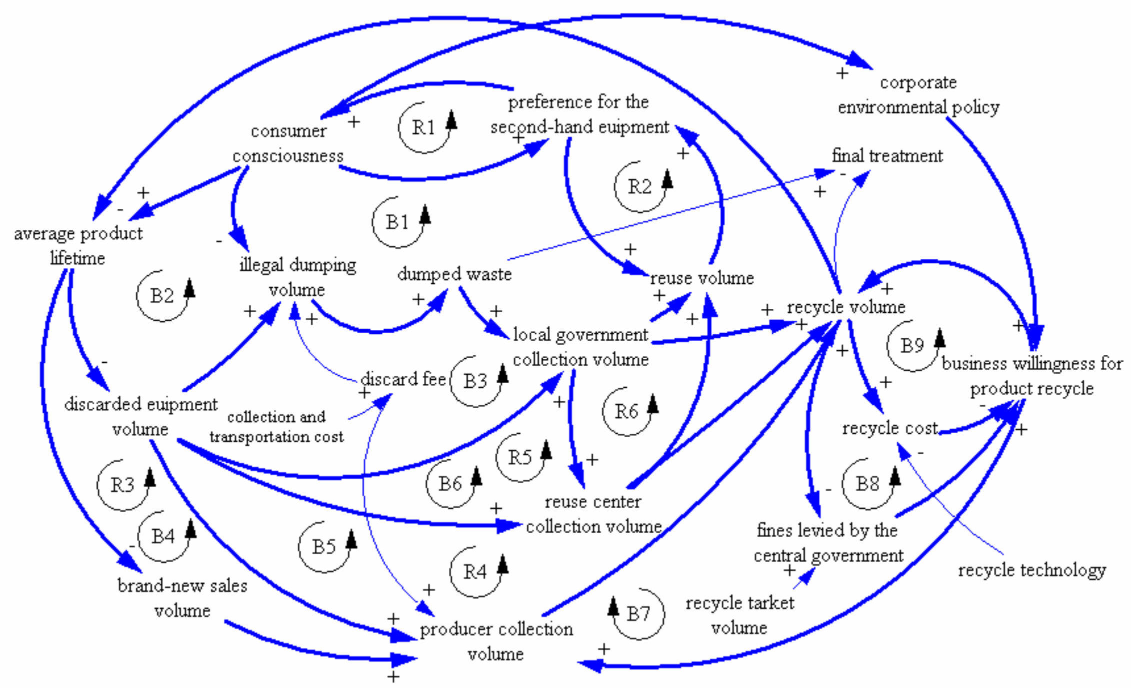

Figure 5: EEEW Casual Loops for the Resource Cyclical Social System

3. Electric and Electronic Resource Cyclical Dynamics

Figure 6 highlights resource cyclical dynamics, representing the lifecycle of electric and electronic equipment with stocks and flows. First of all, the aggregation of domestic and imported product decides the total volume of brand-new supply. Commonly, consumers use these durable goods for a certain period of time. Once a consumer discharges the electric and electronic equipment and its components, the law and ordinances make sure that the used product should be properly collected either by the local government unit, reuse center or producer in Korea. In the case of illegal dumping, the local government is the first organization to take care of illegally dumped waste within its jurisdiction.

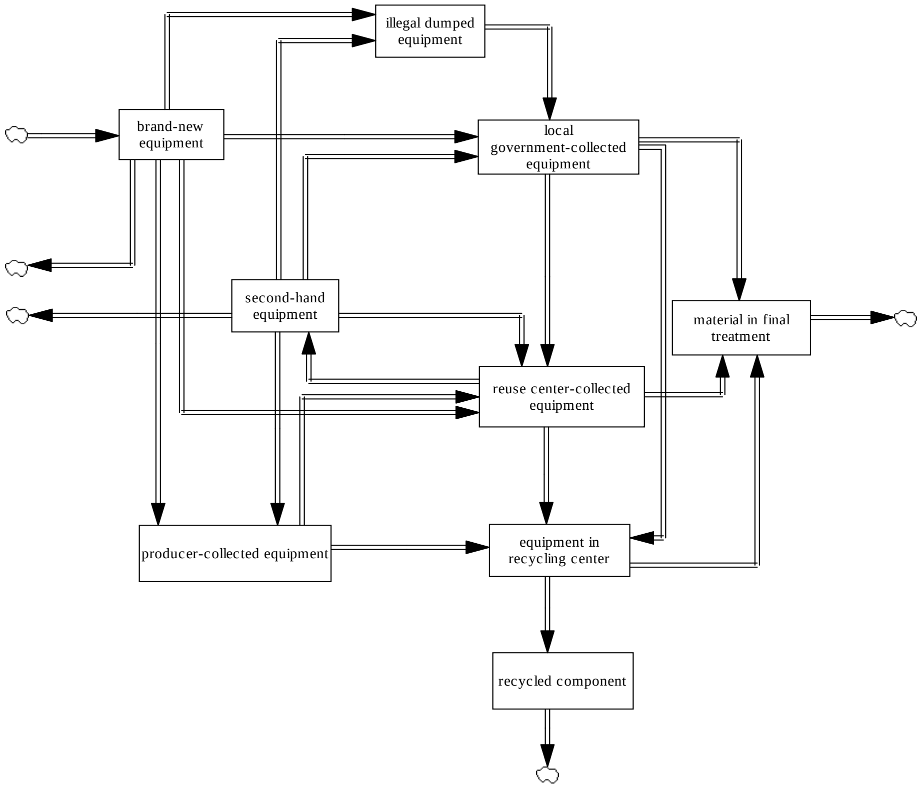

Figure 6: EEEW Stock-Flow Model for the Resource Cyclical Social System

If the collected product is reused by the local government unit, reuse center or producer, it once again follows the same routes. The model assumes that in the best scenario, around 70 percent of used electric and electronic products and components are exported or in the worst scenario, treated as useless waste. It means that neither of them is further considered in the model experiment. Even though the local government joins the collection processes, the actual reuse works are usuallyintermediated by the reuse center, except a few cases.

At present, the total volume of the electric and electronic waste collected by the producer has been directed to therecycling processes, without exception. For the policy experiment based on the reuse-oriented alternative, however, the model also presupposes that the producer-collected electric and electronic equipment would be on the reuse circle.

Lastly, the final treatment volume consists of incinerated and landfilled materials handled by either the local government or reuse center and residuals provided by the recycling center.

III. Modeling Building and Policy Experiment

1. Major variables

Using the theoretical frames derived from the previous researches, this research puts emphasis on dynamic analyses based on status quo data. The major variables in the model cover electric and electronic sales volume, supply ratio, and collection volume from the local government unit, reuse center, and producer. It also tries to figure out the reused and recycled volume originated from various collection activities, in addition to the final treatment volume.

Table 1: Major Variables and Their Contents

Major Variables	Contents
Equipment supply ratio	-Household supply ratio of major equipment in 2002 (TV: 1.35, refrigerator: 1.25, washing machine: 1.15, air conditioner: 0.26 units/household, respectively) -Non-household equipment in 2002: 20 % of household volume
Imported equipment sales	-Imported equipment sales (1989-2003)
Domestic equipment sales	-Domestic equipment sales (1985-2003)
Producer collection	-Producer-collected waste data (1995-2002)
Exporting	-Exported volume as the second-hand product or treated useless industrial waste (70.1% of the total discard volume in 2002)
Reuse center collection	-Volume collected by the reuse center (1995-2002)
Local government collection	-Volume collected by the local government (1995-2002)
Local government reuse	-Reused volume collected by the local government (1999-2002)
Local government recycle	-Recycled volume collected by the local government (1999-2002)
Reuse center reuse	-Reused volume collected by the reuse center (1999-2002)
Reuse center recycle	-Recycled volume collected by the reuse center (1999-2002)
Reuse center treatment	-Incinerated or landfilled volume among the reuse center-collected waste (1999-2002)
Local government treatment	-Incinerated or landfilled volume among the local government-collected waste (1999-2002)
Illegal dumping	-Illegally dumped volume (5.2% of the local government-collected volume in 2000)
Recycle	-Volume recycled by the local government, reuse center, and producer (1999-2002)
Final treatment	-Volume treated by local government and reuse center or untreated materials from the recycling center (9.1% of the total EEEW measured by the weight average)
Recycle ratio	-90.9% of the total EEEW measured by the weight average (metals: 49.2%, nonferrous metals: 13.4%, plastics: 22.4%, others: 15.0%).
Producer collection recycle	-Recycled volume collected by producer (1995-2002)

Note: Purely modeling purposes, this research depends on internal data either from Korean Association of Electronics Environment or Samsung Electronics Co., Ltd.

Due to available data, a handful of variables depend on the estimated figures. For example, using internal documents kept at Korea Electronics Association, the model recalculates the illegal dumping volume. Judging from the existing household supply ratio, the model also assumes that non-households such as administrative units, hospitals, schools, and other types of offices would account for almost 20 percent of the household supply ratio. In a similar context, the collected waste volume would be around 30 percent of the estimated waste volume in a given period. Table 1 summarizes key variables and their attributes.

2. Model Calibration

Model calibration works for the resource cyclical system hinged on electric and electronic equipment waste are carried out inthree steps. As diagramed in Figure 7, the first job is concerned with data input and the second with feedbacks. The third loop in the figure symbolizes the synthesized calibration that has been done for the EEEW model.

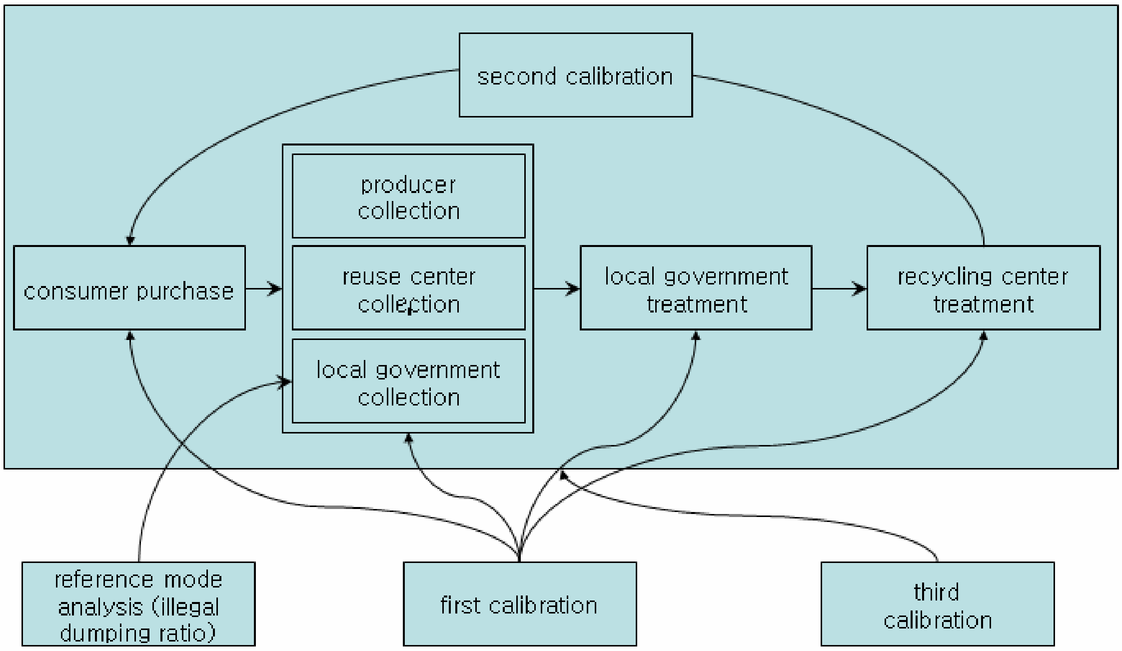

Figure 7: Calibration of EEEW Dynamic Model

In the procedures, the extended Bass models, which represent the aggregation of both external and internal factors, have been used for the auxiliary variables. Table 2 shows a list of the calibrated variables. In order to minimize the gap between real data and the prototype scenario-based data, the model tries to calculate innovation and imitation coefficients of each constraint.

Table 2: Calibrated Variables and Attributes

Variables and Constraints	Contents
Objective variable	minimize (model itself − model inputted data)^2

Constraints	0≤purchase, word of mouse coefficient=0.0399004≤0.1 0≤purchase, word of mouse coefficient · income coefficient=0.412232 0≤purchase imitation coefficient≤1 0≤income-purchase delayed period=0.00662686 0≤maximization supply volume by purchase =1.11816e+008 0≤brand-new purchase weight in 1985=0.8≤1 0≤discard weight advertisement coefficient by purchase of brand-new product=0≤1 0≤discard weight, word of mouse coefficient by purchase of brand-new product=0.118582≤1 0≤discard maximization weight by purchase of brand-new product =0.194669≤1 0≤reuse center, recycle weight of collection volume=0.518219≤1 0≤reuse center, delayed period=0.111493≤1 0≤reuse center, final treatment weight=0.434356≤1 0≤reuse center, ratio of second-hand to brand-new=0≤1 0≤weight per reuse center=0.000887322 0≤reuse center, advertisement coefficient=1.17894 0≤reuse center, word of mouse coefficient=9.91629e-005 0≤decreasing rate of collection by local government=9.12077e-005≤1 0≤collection by local government, dumping weight=0.0296964≤0.1 2≤collection by local government, ratio of second-hand to brand-new=19.9448≤20 0.05≤collection by local government, weight of charged portion 1985=0.0564076≤1 0≤reuse base weight by local government=0.129754≤1 0≤reuse by local government, collection base weight of brand-new product by reuse center=0.0258447 0≤reuse by local government, coefficient of second-hand product weight=0≤1 0≤reuse by local government, reuse center coefficient=0.830288 0≤weight per final treatment of local government=0.0046249≤1 0≤local government, final treatment facility imitation coefficient=0.3331122 0≤local government, number of final treatment facility 0≤local government, final treatment facility innovation coefficient=0.0008321 0≤local government, recycle base weight≤1 0≤local government, sense coefficient for recycle

3. Sensitivity Analysis on Illegal Dumping

Illegal dumping data derived from the existing documents at Korea Electronics Association require a sensitivity analysis to measure the degree of their impact on the system. Specifically, this study focuses on measuring the impact on brand-new purchase, final treatment, and ferrous material volumes. It covers a time span from 1985 to 2025.

After repeated experiments, the study confirms that the illegal dumping exerts minimal impact on both brand-new purchase and final treatment volumes, even though the recycled ferrous materials yield a relatively high degree of impact. Among them, Figure 8 represents the sensitivity result on the final treatment volume.

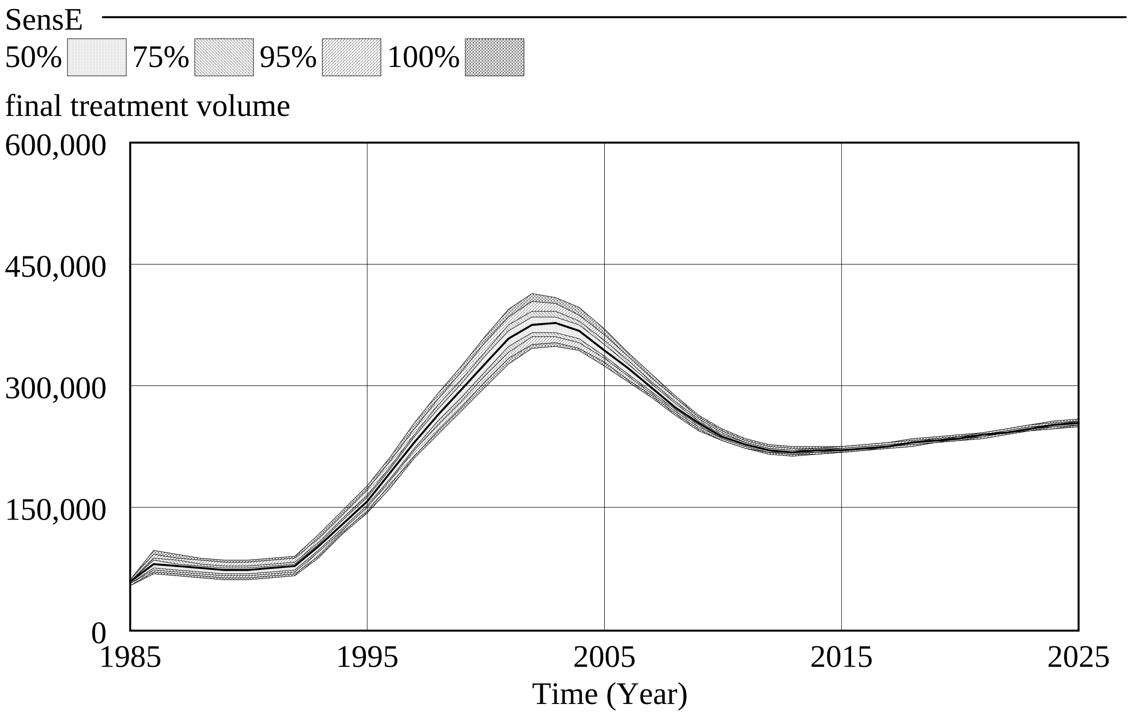

Figure 8: Sensitivity Results on the Final Treatment Volume by the Illegal Dumping

4. Base Models

Base models are derived from the dynamic movement of key variables. First of all, purchase behavior (1989 - 2003)is represented in Figure 9. The purchase volume dropped abruptly during the so-called 'Asian foreign exchange crisis' period. Aside from this, the ever-increasing trend in the purchase pattern has been observed.

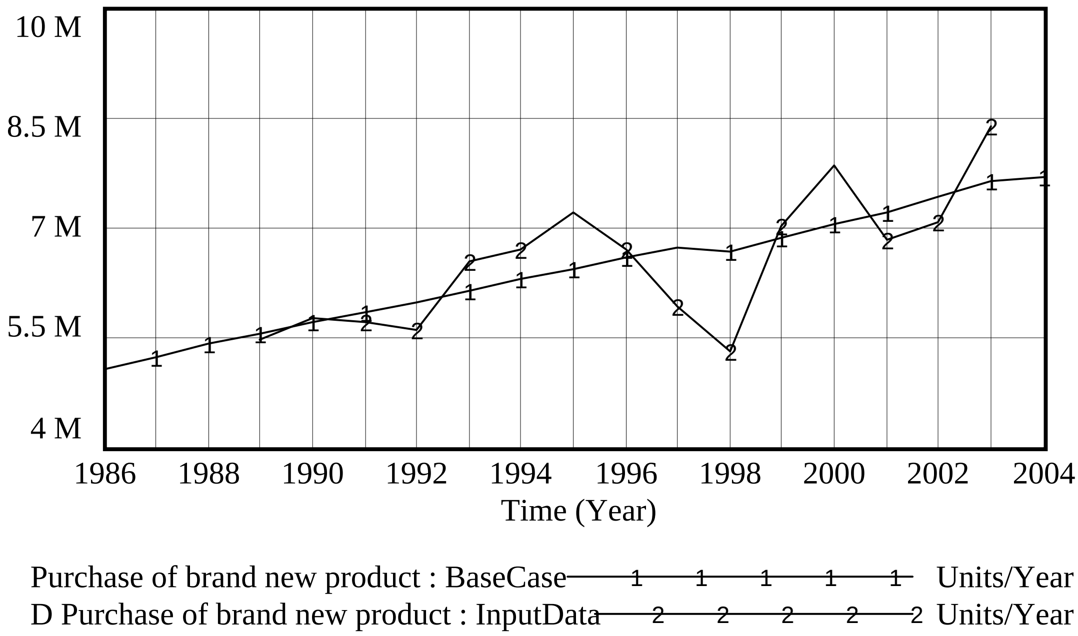

Figure 9: Electric and Electronic Equipment Purchase Pattern

Figure 10 presents the movement of producer collection (1995 - 2003). Even though any producer collection activity did not exist until 1992, its movement has shown a skyrocketing pattern since the adoption of the Extended Producer Responsibility (EPR)in 2000. It is expected that producer collection will be accelerated in the near future as the consumer is entitled to trading of the old product without any charge when she/he purchases a brand-new one.

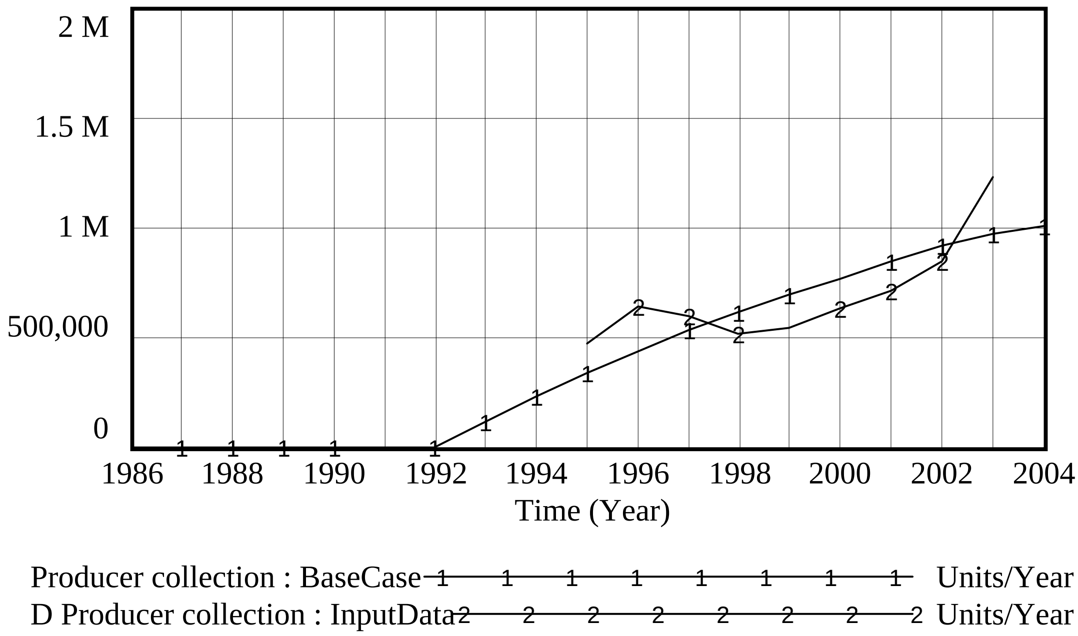

Figure 10: Producer Collection of Electric and Electronic Equipment Waste

In Korea, many local governments run the reuse center or financially support it. Figure 11 yields the collection volume handled by the reuse center, from 1995 to 2002. Even though the reuse center has been under heavy pressure to expand its capacity, the increase rate has become rather weakened over time.

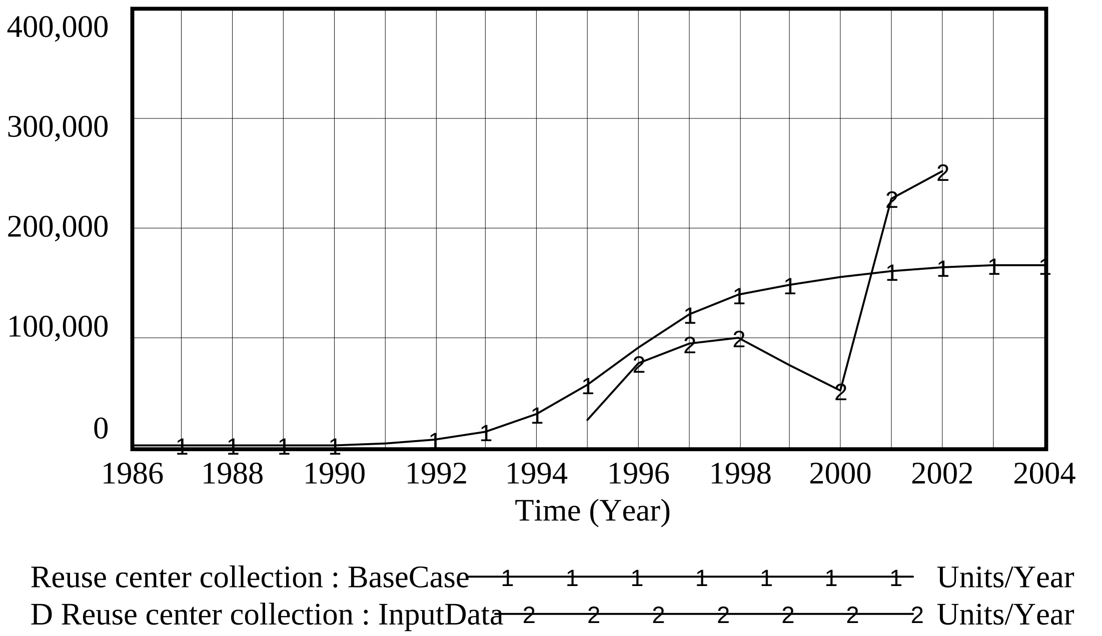

Figure 11: Reuse Center Collection of Electric and Electronic Equipment Waste

Local government collection (1995 - 2002) is shown in Figure 12. The total volume collected by the local government is separatedbetween legal discharge with due levy and illegal dumping without any payment. As referred in the above, this research has configuredillegal dumping data based on the existing documents and expert group's judgment. In general, even though the local government collection has been in stable condition, recently, a diminishing trend has been observed, probably owing to the increased producer collection.

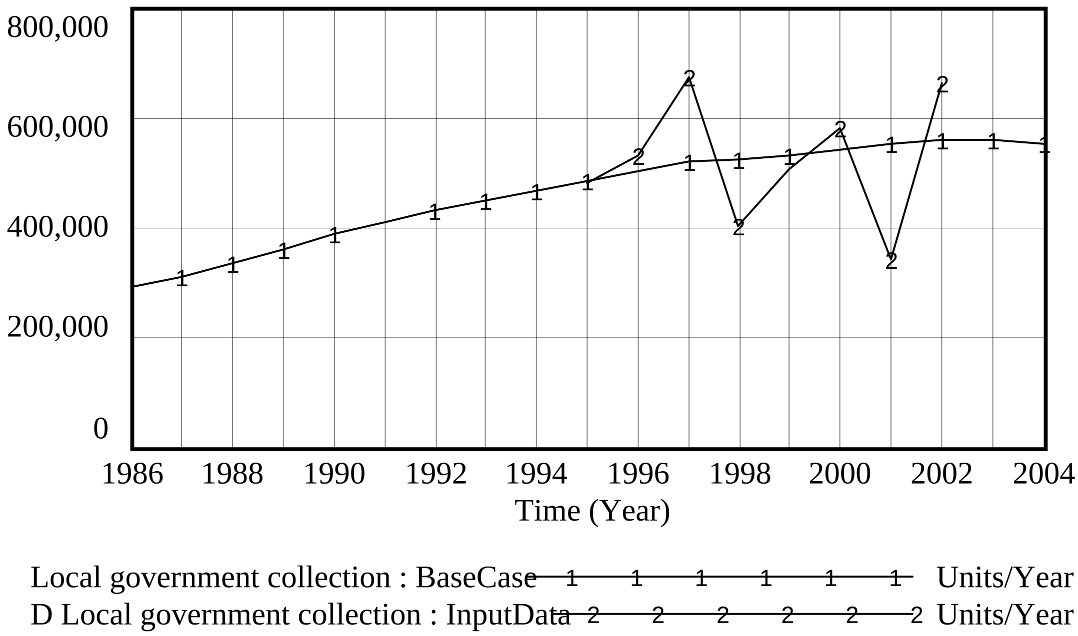

Figure 12: Local Government Collection of Electric and Electronic Equipment Waste

This study has built a series of base scenarios to enhance the models'relevance. Among them, a base scenario dealing with the final treatment volume through either incineration or landfill is presented in Figure 13. Annual treatment volume reveals an overshoot-collapsing pattern, culminating in 2002. It may have originated from the fact that a producer had to maximize its recycled volume after the government legally institutionalized the producer recycling duty in 2003.

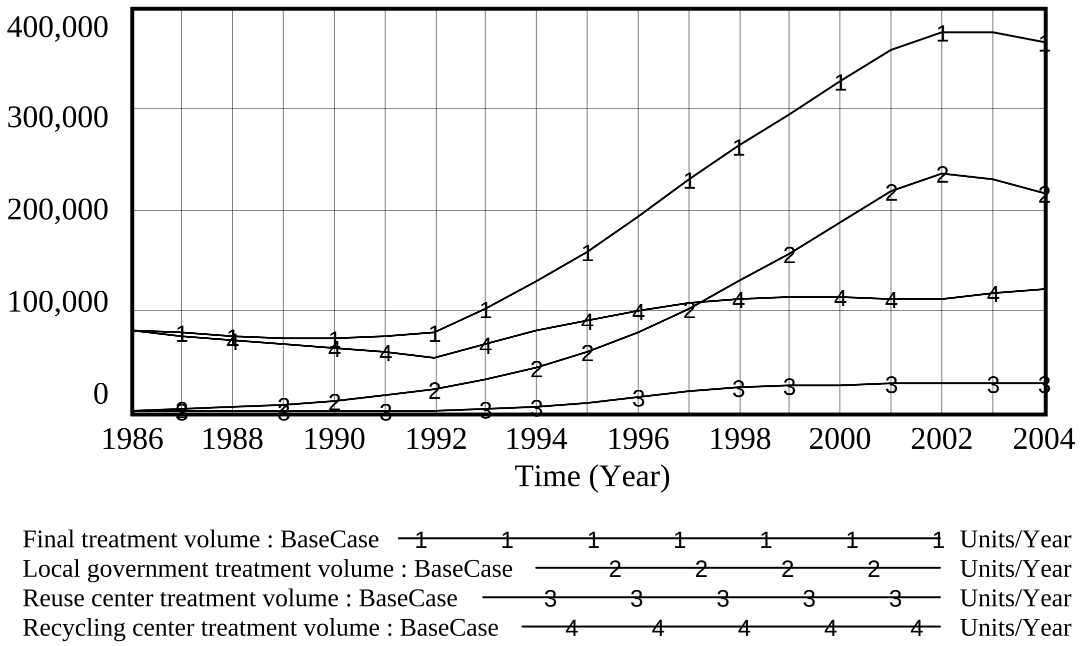

Figure 13: Final Treatment Volume Pattern

5. Policy Experiment

1) Policy Experiment Scenarios

This research develops three different types of policy alternative scenarios, as summarized in Table 3. At present, all of the producer collection volume is confined to material or thermal recycle, regardless of equipment quality. Therefore, Alternative 1 assumes that the reuse center supported by the local government would handle 20 percent of producer collection volume. In contrast, Alternative 2 presupposes that all the EEEW volume collected by the local government and reuse center is put into material or thermal recycle processes, departing from the existing customs hinged on a partial collection. The last Alternative 3 tests waste movement if these two alternatives are concurrently adopted. The analytical time span covers from 2005 to 2025.

Table 3: Summary of Policy Experiment Scenarios

Categories	Contents

Alternative 1	Reuse center supported by the local government would handle 20 percent of producer collection volume
Alternative 2-1	All the EEEW volume collected by the local government is put into material or thermal recycle processes
Alternative 2-2	All the EEEW volume collected by the reuse center is put into material or thermal recycle processes
Alternative 2-3	Combining Alternative 2-1and Alternative 2-2
Alternative 3	Concurrently adopting Alternative 1 and Alternative 2-3

2) Policy Implications

As summarized in Table 4, if Alternative 1 is adopted, the new purchase rate would be significantly reduced over time: 211,986 units in 2006 to 364,032 units in 2025. It may come from the fact that 20 percent of producer collection volume would be handled by the reuse center supported by the local government in the model. However, Alternative 2 gives only minimal impact on the brand-new product. In fact, even if Alternative 2-3 is adopted, under which all the EEEW volume collected by the local government and reuse center is put into material or thermal recycle processes, its impact on a new phase for electric and electronic equipment is 47,104 units in 2006 and 37,376 units in 2025, respectively. Its amount is about 10 to 20 percent of Alternative 1's. The same movement is observed in Alternative 3, in which Alternative 1 and Alternative 2 are concurrently combined. In deciding Alternative 3's value, Alternative 1 is relatively stronger than Alternative 2.

The results partially explain why producers have not actively joined the reuse movement of electric and electronic equipment. As the producer collection volume is negatively interrelated to the new purchase rate, a producer would resist any waste policy bound for equipment reuse. Even though a producer well acknowledges the fact that reuse-oriented policy would lead to resource cyclical society in the long run, it would definitely hesitate to accept the reuse campaign which might significantly dampen a consumer's purchasing power. Furthermore, as the Extended Producer Responsibility (EPR)stipulates the fact that a producer has to spend its own money to collect the used equipment for the material and thermal recycle, it seems unlikely to expect that a producer would welcome the reuse program.

Table 4: Impact on Brand-New Equipment Purchase

Categories	2006	2010	2015	2020	2025
Base Run	7,923,200	8,423,424	8,991,744	9,545,728	10,168,320
Alternative 1	211,968	238,080	281,088	323,072	364,032
Alternative 2-1	18,944	2,048	512	1,024	0
Alternative 2-2	28,672	29,184	32,256	34,816	36,864
Alternative 2-3	47,104	30,720	32,768	35,328	37,376
Alternative 3	258,048	268,800	313,856	358,912	403,456

Note: Numbers in Base Run represent the expected brand-new equipment volume (unit). Other numbers imply the expected saving volume (unit)derived from the individual policy alternative.

In contrast, simulation works on the final treatment suggest thatAlternative 2 is comparatively superior to Alternative 1. As spotlighted in Table 5, the reduced final treatment volume based on Alternative 2-1would be 154,216 units in 2006 whereas that of Alternative 1 is 17,374 units in the same year. As in the case of the new purchase rate, Alternative 3, or the combined effort, presents the highest reduced number.

Table 5: Impact on the Final Treatment

Categories	2006	2010	2015	2020	2025
Base Run	321,502	237,859	220,897	235,122	254,176
Alternative 1	17,374	15,926	18,113	20,568	22,368
Alternative 2-1	154,216	66,686	36,072	32,336	35,883
Alternative 2-2	28,187	28,939	32,340	36,316	40,333
Alternative 2-3	182,507	95,889	68,609	68,867	76,516
Alternative 3	200,523	113,584	87,787	90,322	99,938

Note: Numbers in Base Run represent the expected final treatment volume (unit). Other numbers imply the expected saving volume (unit)derived fromthe individual policy alternative.

If Alternative 2-3 is not available, it would bebetter to differentiate a time schedule between Alternative 1 and Alternative 2. In the first half, it may be more effective for the local government to take initiatives, adopting Alternative

2-1. In the second half, nonetheless, we should keep in mind that the reuse center supported by the local government should take care of major roles for the EEEW treatment, reflecting Alternative 2-2.

6. Discussion

As a derivative approach to social dynamic systems models, this study demonstrates how to build resource cyclical society based on the dynamic cycles of the electric and electronic equipment waste (EEEW), as a practical means to upgrade urban sustainability. Major discussion topics are as follows.

First of all, owing to the Extended Producer Responsibility (EPR) adopted in 2003, the equipment producers in Korea are now burdened with the EEEW recycling duty. Judging from the simulation experiments, the EPR system would significantly contribute to the reduction of the final treatment volume in the first half of the research period. The final treatment volume, which recorded the highest in 2003, is supposed to be continuously diminished up to 2013. However, the trend would be reversed after that point. It implies that the EPR system alone may be at best insufficient or at worst useless in the second half.

Furthermore, as a producer has to collect the predetermined recycled units whose volume is usually given by the Ministry of Environment in Korea, its top priority is given to how to retrieve all the old equipment. For the replacement demand, the producer does not hesitate to take back the old one free of charge. In order to satisfy the target number for the recycled units, a producer knows well that it may be a cheaper and more convenient way than buying junk items on the black market.

Then, what happens if a producer adopts the reuse-oriented strategy? The simulation results, among others, present two different signals. If the reuse center supported by the local government reuses part of the producer-recycled volume, it would definitely reduce both the required quantity of raw materials and the final treatment volumes altogether. However, this strategy would be confronted with unprecedented objection from the business arena, which is extremely sensitive to the market trends. In the 20-percent scenario, the reduced consumption volume of a brand-new product would be around 0.2 to 0.4 million units per year. Therefore, without appropriate incentive provisions, it would be difficult for the producers to voluntarily join the reuse-centered movement.

This research also confirms that the final treatment volume would be significantly reduced with minimal impact on the brand-new product consumption, if the local government transforms all the incinerated and landfilled volume into thermal and material recycle. The reuse center's experiment also repeats the similar trends, with a relatively weaker impact on the final treatment volume. To enjoy the synergy effect, both the local government and the reuse center togethershould take immediate actions to discourage the existing customs hinged on incinerationlandfill treatment. Furthermore, they should prepare concrete plans to implement a recycle-oriented strategy.

Particularly, the reuse volume handled by the local government has been decreased over time. But the reuse center has shown the opposite trends whose phenomena seem more preferable for the resource cyclical society. This research also confirms that the reuse center is the most sensitive organization in treating the electric and electronic equipment. The role and function of the reuse center should be strengthened to enhance the level of resource cyclical society.

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