The diffusion dynamics of the informal sector and sustainable WEEE supply chain

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ABSTRACT

Literature indicates that the main obstacle to better manage existing WEEE recycling supply chain in the developing countries is lake of environmental laws and/or lax enforcement, particularly in control instruments to overcome the difficulty of informal e-waste processing firms and its supply chain. Policy makers may rely on new legislative framework to control environmental performance and the health impacts of pollution; however, this strategy is not clearly effective as the informal nature of this supply chain blocks the enforcement efforts and causes the high cost of monitoring. Hence, it is definitely crucial to understand the interaction between the environmental policy options and economic consideration when achieving the sustainability of operations across the WEEE supply chain. In this study, we propose the simplest form of epidemic spreading, namely a criss-cross epidemic model, and aim to examine the legislative stringency for observing the diffusion dynamics of informal and formal sectors in an e-waste recycling system. We find that a diffusion threshold does exist and it is related to the regulatory stringency. Effective population changes dramatically if it grows beyond this diffusion threshold. In particular, a government agency is able to layout a minimal regulatory stringency so that the participants of the informal sector diminish quickly and eventually cease while the economy remains unhurt. We use a simplified numerical study to test the proposed criss-cross epidemic model. Based on significant findings, this paper provides managerial implications for developing the new environmental legislative framework which is not only feasible but also beneficial to achieving the sustainable WEEE supply chain.

Keywords: Environmental issue, regulatory stringency issue, epidemiological model, informal sector-diffusion, sustainable WEEE supply chain

INTRODUCTION

WEEE (waste electrical and electronic equipment, or so called e-waste) management in the developing countries has its own characteristics and problems. Currently, given on the different contexts of cultures, the main different status is that the WEEE recycling supply chain in these industrializing countries is dominated by the informal sector rather than formal system. E-wastes in the informal system are treated by dangerous and inappropriate recycling practices that pose threats to occupational hazards and the environment. That is, when assessing WEEE system, the most main perceived enemy to environmental protection is this unregulated and environmentally unsound recycling industry (Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Widmer et al. 2005).

However, much suggestive evidence indicates that lack of legislations and/or lax enforcement is the key obstacle for government agencies to regulate the informal actors and its recycling supply chain. Consequently, the tighter legislations as well as new regulatory framework are viewed as the contributing factors for reforming the informal sector into formal WEEE recycling industry (Blackman 2000; Medina 2000; Spies and Wucke 2004; Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Widmer et al. 2005; Huang, Zhang, and Deng 2006; Streicher-Porte and Yang 2007).

Despite its benefits for improvements, the legislations may not be feasible and become problematic if the government agencies are unaware of the nature of the informal sector. Because as the informal firms are numerous and/or well-organized, it causes relatively high costs on enforcement (Blackman 2000) and furthermore government departments generally have limited resources for monitoring and control (Hicks, Dietmar, and Eugster 2005). Additionally, according to Sinha-Khetrival, Kraeuchi, and Schwaninger (2005), the regulated e-waste management system, like in Switzerland, will employs far fewer people and therefore has social and economic impacts on the poor in low-income economies. Hence, the new WEEE management may enhance environmental performance rather than financial profit.

According to Young (2000), the supply chain can be particularly powerful mechanism, in which enough high volume of waste makes market leverage and then residual management can be efficient and profitable. Hicks, Dietmar, and Eugster (2005) suggested that integrating sustainability concept and WEEE management is the key to result in the desired changes in practice and behavior within the relevant stakeholder. In Linton, Klassen, and Jayaraman

(2007) study, sustainability concept allows managers to look at optimizing performance in a supply chain from a broader perspective. Therefore, sustainable WEEE supply chain has emerged in this research as an important new innovation that helps researchers focus on the regulatory stringency that may effect economic of scale and environmental performance.

Our research was based on two questions: firstly, how does the regulatory stringency influence the dynamic diffusion of participants in a WEEE supply chain? Secondly, what is the diffusion threshold of the regulatory stringency which results in effective population changes dramatically? We want to understand a specific problem in the relationship between population dynamics and the environmental legislations; in doing so we may provide managerial suggestions for government authorities to develop new legislative framework.

We apply the simplest form of epidemic spreading, namely criss-cross epidemic model, to examine the regulatory stringency as the main parameter for observing population dynamics in the WEEE supply chain. In particular, this paper tests the proposed model by numerical study with estimated data. That is because that in general, the data of the informal sector is difficult to collect or estimate due to the unorganized nature of this business.

This paper is organized into four sections. Following this introduction, the second section provides further background on informal sector and reviews the relevant literature. The third section we provide the details of extending the epidemic model into propagation analysis in sociological contexts. To illustrate the applicability of the proposed epidemic model, we use estimated data and conduct a numerical study. In final section, implications of numerical results are discussed, providing managerial and academic suggestions.

THE INFORMAL E-WASTE SECTOR AND SUPPLY CHAIN

In contrast to formal recycling system, the informal sector is an illegal and unregulated WEEE processing system. Many actors are in this unregulated processing system that includes waste pickers, itinerant buyers, dealers, wholesalers, and recycling enterprises, each adding value and creating jobs at every point in the chain (Sinha-Khetrival, Kraeuchi, and Schwaninger 2005). In the informal sector, e-waste disposal is treated by an inappropriate handling technology and facilities, and thousands of people work in the threatening working condition for less than minimum wages, resulting in damages to the environment and e-waste handlers' health (Spies and Wucke 2004; Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005).

The informal sector in developing countries such as China or India, however, has a long tradition in waste recycling industry, providing employment opportunities for the poor and generating secondary usable resources for second-hand market. This unlicensed recycling system dominates the WEEE recycling market and is recognized as a case of successful industrial symbiosis which is self-organized and market-driven (Medina 2000; Hicks, Dietmar, and Eugster 2005; Widmer et al. 2005; Streicher-Porte and Yang 2007). Moreover, evidence shows that with contribution of scavenging some valuable material would be saved in landfills and dumpsites (Moreno-Sanchez and Maldonado 2006). Thus, in practice, there are economic, environmental, and social advantages associated with informal sector.

Currently, due to EU's two new directives — WEEE (Waste Electrical Electronic Equipment) and RoHS (Restriction of Hazardous Substances), governments in low-income countries have economic and ecological imperative of complying with WEEE international standards (Hicks, Dietmar, and Eugster 2005; Widmer et al. 2005). That is, there is an urgent need for some industrializing countries to better manage this unregulated e-waste system. However, configuration of an informal recycling system is a challenging and complex task, there are various obstacles as follows, which extend our understanding of role of informal sector in better managing WEEE management system,

1. The informal processing workshops are hard to manage since they basically are small-scale, numerous, and geographically dispersed (Blackman 2000).
2. So far, there are no confirmed figures and data available regarding the scale of the informal recycling businesses, the number of people they employ, how e-waste streams are in these developing countries (Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Widmer et al. 2005; Streicher-Porte and Yang 2007).
3. Without the advantages of lower labor and facility costs, certain regulatory environment and collection streams, the official recycling businesses find it difficult to

compete with the unregulated sector (Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Streicher-Porte and Yang 2007).

4. Due to different contexts of recycling behavior and management system, there are fundamental difficulties when transferring the European models of WEEE management into the developing economics (Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005).
5. It requires more efforts for local governments to raise people environmental awareness, improve slow/lax enforcement, or to set tighter legislations and practices (Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Widmer et al. 2005; Huang, Zhang, and Deng 2006; Streicher-Porte and Yang 2007).
6. Due to multi-actors in the informal sector, there is a clear need for setting up different levels of task forces at multilevel governance and cooperation (Medina 2000; Hicks, Dietmar, and Eugster 2005; Widmer et al. 2005; Streicher-Porte and Yang 2007).
7. Further research of informal system and better WEEE management rely very much on multi-disciplinary considerations: economy, environment, culture, and society (Blackman 2000; Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Widmer et al. 2005; Streicher-Porte and Yang 2007).

From a policy perspective, besides to the discussion mentioned above, viewing WEEE supply chain from a broader perspective is needed to develop a sustainable environmental policy. Consequently, we further review more literature in terms of three major dimensions: structural framework, recycling system, and impacts, which include ten sub-criteria and are used to evaluating WEEE management systems in Widmer et al. (2005) study. The main points of the literature review are summarized in Table 1. The results of impact assessment are divided into positive impacts on current WEEE management system with symbol (＋) and negative impacts with symbol (－). In addition, if current situation is contributed to increasing/decreasing population of illegal processing system, which is symbolized with (▲)/(▼). Instead, if impact assessment causes the increase/decrease of population of regulated recycling industries, which is symbolized with (△)/(▽).

Researchers suggest that optimal solution to managing current WEEE recycling systems is to reform informal sector into environmentally sound recycling system without reducing the attractiveness of this business. In addition, according to Hicks, Dietmar, and Eugster (2005), an uncertain regulatory environment and competition from the informal sector contribute the risks and difficulties of operating legal WEEE processing firms in China. Thus in this study, we only consider legislative and financial factors as main parameters in our model.

Insert Table 1 Approximately Here

THE MODEL

Modeling

The susceptible-infective-recovered (SIR) model is first developed by Kermack and McKendrick as a dynamic mathematical model and traditionally is used to estimate quantitatively population average parameters in epidemics (Murray 2003; Satsuma et al. 2004; Bettencourt et al. 2006; Castellini and Romanelli 2007). This model assumes a population comprised of three categories of individuals; those that are susceptible to the disease (S) on contact with an infected individual; those that are infected by the disease (I); and those that are recovered from a disease (R). In recent studies, it is extended as an analogy of the propagation dynamics of computer virus, social traits, addition behavior, etc. (Wu et al. 2004; Bettencourt et al. 2006; Wu and Chen 2008).

Literature shows that there are difficulties and differences when applying the epidemic model into propagation analysis in sociological context (Wu et al. 2004; Bettencourt et al. 2006). For example, recycling behavior, unlike a virus/disease, is usually selective. In other words, that people are susceptible to informal or formal sector depends on relative advantages of socioeconomic, political, cultural conditions. Moreover, characteristics of actor tend to influence on social contagion process and result in different individual behavior, while it is manifestly not so for recycling activities. In spite of these differences, SIR model still can work enough on behavior transmission of social paradigms. The reasons are the three classes of SIR model are generally similar to the phases of spread of sociology traits, and the randomness assumption is appropriate to capture the nature of interpersonal contact between members (Castellini and Romanelli 2007).

Unlike the standard population model, we consider the simplest epidemiological model, namely a criss-cross epidemic model, consisting of only two states in each informal/formal system: susceptibles (S) and infectives (I). We provide the analogous descriptions of four states summarized as Table 2.

Insert Table 2 Approximately Here

The proportion of population in these two recycling systems may pass from one state to the other, and/or even transit from one system to the other, depending on relative advantages of socioeconomic, regulatory, cultural conditions. A flow diagram in Figure 1 is used to describe such a condition as we noted above.

Insert Figure 1 Approximately Here

Drawing upon the literature summarized in the Table 1, when better managing WEEE recycling system, policy-makers should consider many aspects: economy, environment, culture, and society. Particularly, we concentrate the legislative and economic factors as main parameters. The interactive behavior of the two recycling systems is governed by the following system of differential equations (overdots denote derivatives with respect to time):

$$\dot{S} = -rSS^* + aI \quad (1)$$

$$\dot{I} = rSS^* - aI \quad (2)$$

$$\dot{I}^* = -r^*I^*I + a^*S^* \quad (3)$$

$$\dot{S}^* = r^*I^*I - a^*S^* \quad (4)$$

where the parameter r denotes a market competition that influences the proportion of population who moves into the participation state of informal sector, and the parameter a can be referred to penalty legislations, leading to a reduction of population in the participation state of informal sector. From (1) to (2), we could observe the population dynamics of informal sector; on the other hand, equation (3) and (4) describe the population dynamics of formal sector. The parameter r^* denotes a financial profit rate inhered from the regulated recycling companies, resulting in that people instead turns to the interest state of formal system. The parameter a^* is an encouraging regulatory factor.

The total actors of informal and formal sectors are constant and equal to N and N^* respectively, representing the market capacities of the two markets. With the relation,

$$S + I = N, \quad (5)$$

$$S^* + I^* = N^*, \quad (6)$$

we get

$$(N - I)(N^* - I^*) - \rho I = 0 \quad (7)$$

$$II^* - \rho^*(N^* - I^*) = 0 \quad (8)$$

where

$$\rho = \frac{a}{r} \tag{9}$$

$$\rho^* = \frac{a^*}{r^*} \tag{10}$$

The steady states, if they exist, are of (11), (12) and (13).

$$I = 0, I^* = N^*, \tag{11}$$

and

$$I = \frac{NN^* - \rho\rho^*}{N^* + \rho} \tag{12}$$

$$I^* = \frac{\rho^* N^* - \rho\rho^*}{N + \rho^*} \tag{13}$$

By solving the eigenvalue of the Hessian matrix, a threshold condition $\frac{NN^*}{\rho\rho^*}$ has been manifested. If $\frac{NN^*}{\rho\rho^*} > 1$, reaching to a non-trivial equilibrium point is possible. Along the suggestion of this condition, a government agency is able to layout a minimal regulatory stringency so that the participants of the informal sector diminish quickly and eventually cease while the economy remains unhurt.

Numerical results

Below, we analyze the diffusion dynamics of WEEE supply chain and the threshold condition of legislative stringency by estimating parameters in our model with MATLAB version 7.1.

In order to understanding how does the legislative stringency influence the dynamic diffusion of an e-waste recycling system, the market capacities of informal and formal sectors, economic competition, and regulatory stringency were estimated as summarized in Table 3. Although we consider the legislative and economic factors as main parameters, this study only control regulatory parameters to observe relationship between the environmental instruments and population dynamics of an e-waste recycling system.

Insert Table 3 Approximately Here

In Figure 2, we display time evolution of diffusion dynamics of informal and formal sectors with loose regulatory stringency a=2, a*=2. Throughout the experiments, we set the scaled market capacities of informal and formal sector to 5 and 5, respectively. That is, N=5 and N*=5. The resulting steady states of participation of informal and formal systems are 3 and 2, respectively, implying the same evidence as the prior researches: under lake of legislation, unregulated e-waste sector operates well with limited environmental protection measures and the low level of initial investment (Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005).

Insert Figure 2 Approximately Here

We also test the impact on tighter legislative stringency with a=6, a*=6, and the time evolution of diffusion dynamics of informal and formal sectors is shown as Figure 3. The equilibrium points of informal/ formal participation states are 0 and 5 respectively. In this case, the regulatory is over stringent and all informal participants are transformed to members of formal sector. Furthermore, with marginal stringency values {4.8, 4.8}, it can be seen in

Figure 4 that each trajectory of participation states appears the same trend as the Figure 3, implying that existence of steady states depends much on stringency of control instruments.

However, it is of great surprising to observe that the equilibrium points of 0 and 5 in informal/formal participation states are possibly achieved over much more time with marginal legislative setting {4.8, 4.8}, when comparing to the result of Figure 3. As a result, considering the marginal regulatory stringency is an appropriate direction in yielding the best solution to sustainable WEEE supply chain. Meanwhile, it doesn't bring much pressure on the developing countries which particularly have limited enforcement resources and financial budgets. Overall, with the suggestion of threshold condition, the environmental laws do not have to be enacted blindly so that it wastes enormous social cost or retards economical growth. Government agencies are able to enact marginal stringency of environmental laws, which is feasible and cost-affordable to facilitate enforcement.

Insert Figure 3 Approximately Here

Insert Figure 4 Approximately Here

Taking from different viewing angles, figures 5 (a) to (c) present the diffusion pattern with threshold of the regulatory stringency. The z-axis represents the population difference between formal and informal sector, I^*-I. If the threshold value greater than 1, $\frac{NN^*}{\rho\rho^*} > 1$, the effective population changes dramatically with regulatory stringency like the lower ramp part of the figures. On the other hand, the threshold condition for the steady states is $\frac{NN^*}{\rho\rho^*} < 1$, as shown in the flat red parts of the figures 5 (a) to (c) , meaning that all members in informal sector have been transformed to formal sector and tightening stringency won't have any further impact on diffusion dynamics of members in the WEEE supply chain.

Insert Figure 5 (a) Approximately Here

Insert Figure 5 (b) Approximately Here

Insert Figure 5 (c) Approximately Here

CONLUSIONS

This research uses the literature review as a starting point to understand what the socioeconomic, political, cultural conditions are for people to participate in or remove form WEEE supply chain. An examination of existing literature indicates that lack of legislations and/or lax enforcement is the key obstacle for government agencies to control environmental pollution, particularly in regulating the informal firms and its WEEE recycling supply chain, which currently has its sever impacts on the environment, human health, and the economy.

However, the new regulatory framework offers an opportunity to reform the informal sector into an environmental sound WEEE management system; it also imposes relatively high costs on enforcement efforts and is likely to do an irreparable harm the livings of the poor. Thus, government authorities have a significant struggle to balance the economic and social benefits and environmental performance when they attempt to develop new environmental laws. Such a situation highlights the regulatory stringency as a key role in reforming informal sector into a sustainable WEEE supply chain.

Then, our research attempts to apply an epidemic model to examine the regulatory stringency as the main parameter for observing the population dynamics of the WEEE supply chain. This paper proposes a criss-cross epidemic model, consisting two states, susceptibles (S) and infectives (I), in each informal and formal sector, and allowing members of each state may pass between either states or sectors. Given on controlling the legislative factor, the numerical study provides the various phenomena of diffusion dynamics with different regulatory stringency, shown as in Figures (2), (3), and (4). These figures suggest that the steady states of participation states of informal/formal sectors really rely on the stringency of environmental laws. Also the numerical study shows that "marginal" regulatory stringency captures economies of scale in managing illegal sector and minimizing enforcement effort.

As the result shown in Equation (12), (13) and Figures 5 (a) to (c), we can clearly observe the diffusion dynamics of participants in both informal and formal system with the threshold value $\frac{NN^*}{\rho\rho^*}$. The threshold condition provides further information about relationship among the market mechanism, economic factors, and legislations, implying the dynamic and complex nature when evaluating the feasibility and impacts of environmental management. However, given the dynamics of population in a WEEE supply chain with different legislative stringency, our research suggest that focusing on the marginal regulatory stringency is a necessary condition for developing a feasible and cost-affordable policy. Additionally, the threshold condition discussed in this study enhances the strategic importance of control instruments in achieving a sustainable WEEE supply chain.

Overall, the reform of WEEE recycling system in the industrializing countries requires the environmental sound and regulated processing activities, thus the feasible regulatory instruments are typically important for the country's developing legal e-waste recycling system. Most important, we conclude that considering legislative stringency is regarded as an optimal solution to develop environmental laws, providing government authorities ability of flexibility to future changes and improvements with regard to environmental impacts and financial revenue.

While more work is needed, further research may try to overcome the difficulty caused by the illegal nature of this industry, and test our proposed model by matching the empirical data. From a policy perspective, the results based on the empirical data should provide more applicability, effectiveness and efficiency of legislations for better managing e-waste recycling industry. From an academic perspective, since how to achieve a sustainable WEEE supply chain is a multi-disciplinary task, our paper suggests more new models needed to help policy makers evaluate current WEEE management situations qualitatively and quantitatively.

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TABLE 1
Summary of prior literature

Aspect and criterion	**Current situation/ Impact Assessment**	**Reference**
Infrastructure framework: - Politics and legislation	- Lake of legislation and/or lax enforcement (－)(▲)(▽)	Blackman 2000; Medina 2000; Spies and Wucke 2004; Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Widmer et al. 2005; Huang, Zhang, and Deng, 2006; Streicher-Porte and Yang 2007
- Economy	- Increasing volumes of secondary products/components (＋)(▲)(△)	Streicher-Porte et al. 2005; Streicher-Porte and Yang 2007
- Society and	- Lower level of environmental	Blackman 2000; Medina 2000; Hicks,

culture	awareness (－)(▲)(▽) - Initiatives developed by NGOs and private sector (＋)(▼)(△) - Different recycling culture and contexts (－)(▽)	Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Streicher-Porte et al. 2005; Widmer et al. 2005; Huang, Zhang, and Deng, 2006
- Science and technology	- Lake of best affordable technology and qualifying labor (－)(▽)	Hicks, Dietmar, and Eugster 2005; Widmer et al. 2005
Recycling system: - Material flow -Technologies - Financial	- Poor quality of recovered material (－)(△) - Decreasing the load of EEE waste (＋) - No securing economic efficiency and sustainability of WEEE management system (－ (△) - Recovered precious metal materials create the greatest monetary value (＋)(▲)(△)	Streicher-Porte et al. 2005; Huang, Zhang, and Deng, 2006; Streicher-Porte and Yang 2007
Impacts: -Environment - Human health - Labour	- Emissions of hazardous substances and illegal dumping (－)(△) - Threaten working condition and dangerous processing practices (－)(△) - A significant source of employment in poor residential areas (＋)(▲)(▽)	Blackman 2000; Medina 2000; Spies and Wucke 2004; Hicks, Dietmar, and Eugster 2005; Sinha-Khetrival, Kraeuchi, and Schwaninger 2005; Widmer et al. 2005; Huang, Zhang, and Deng, 2006; Streicher-Porte and Yang 2007

TABLE 2
Summary of state analogous descriptions

State	**Analogous descriptions**
S	Actors are on contact with an individual who is receptive to the informal WEEE recycling activities
I	Actors become participants of the informal sector
S^*	Actors are instead on contact with a actor who is receptive to the formal WEEE recycling activities

I^*	Actors become participants of the formal sector

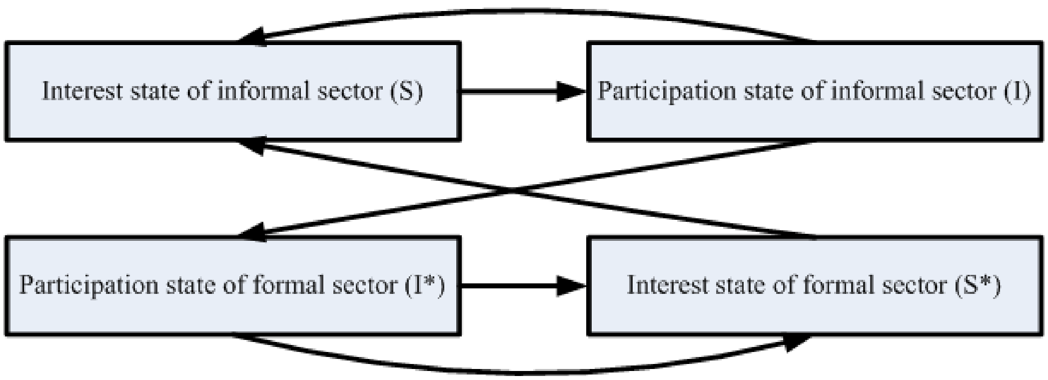

FIGURE 1

A flow diagram of population dynamic of WEEE recycling supply chain

TABLE 3

Estimates of the market capacities of informal/formal sectors, economic competition, and regulatory stringency

N	N^*	r	r^*	a	a^*	$\rho = \frac{a}{r}$	$\rho^* = \frac{a^*}{r^*}$
5	5	1	1	2	2	2	2
5	5	1	1	6	6	6	6
5	5	1	1	4.8	4.8	4.8	4.8

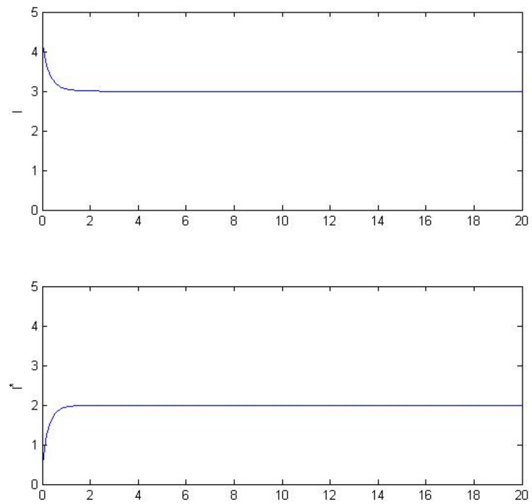

FIGURE 2

The evolution of diffusion dynamics of participation states of WEEE supply chain with loose regulatory stringency {2, 2}

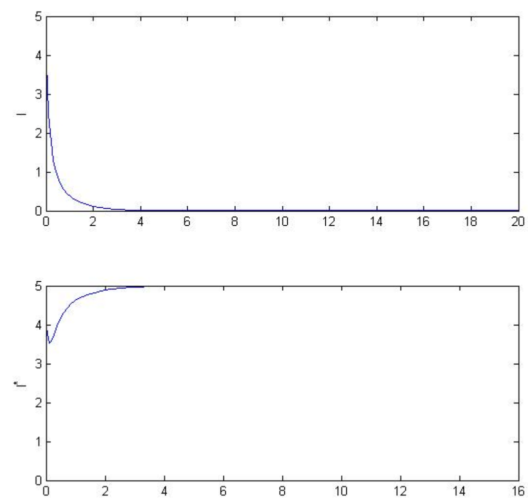

FIGURE 3

The evolution of diffusion dynamics of participation states of WEEE supply chain with tighter regulatory stringency {6, 6}

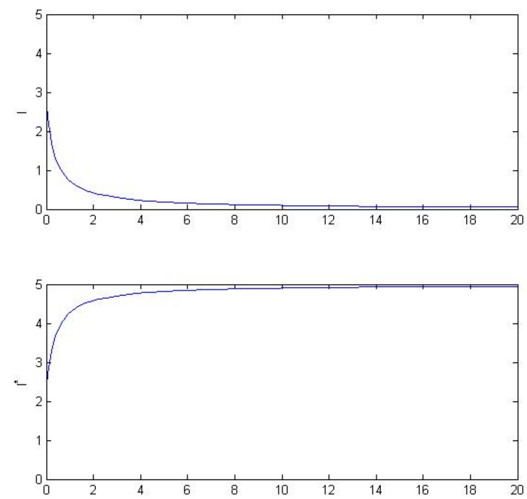

FIGURE 4

The evolution of diffusion dynamics of participation states of WEEE supply chain with marginal regulatory stringency {4.8, 4.8}

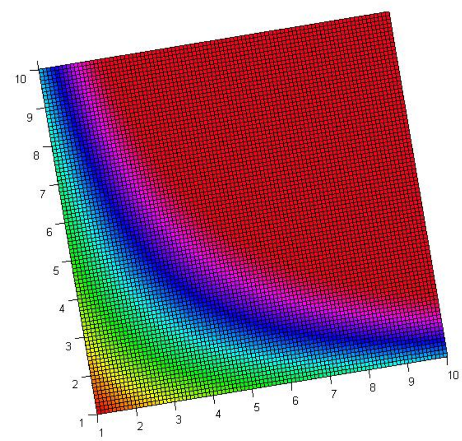

FIGURE 5(a)

A 3D-view of diffusion pattern with the threshold of regulatory stringency (bottom view)

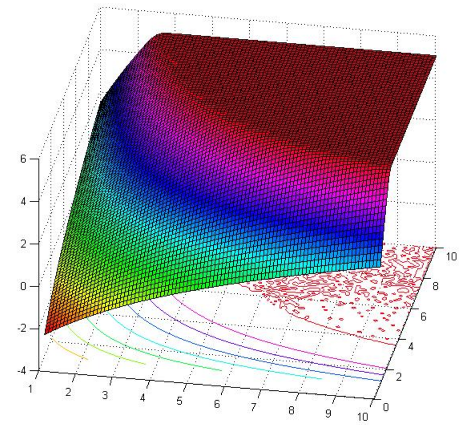

FIGURE 5(b)
A 3D-view of diffusion pattern with the threshold of regulatory stringency (front view)

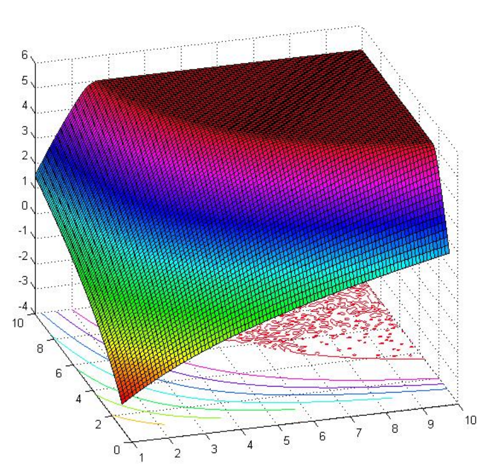

FIGURE 5(c)
A 3D-view of diffusion pattern with the threshold of regulatory stringency (side view)