Optimization and Governance of Reverse Supply Chain for E-waste Treatment

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Optimization and Governance of Reverse Supply Chain for E-waste Treatment

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Abstract

Development and optimization of reverse supply chain (RSC) for electronic waste (e-waste) treatment has attracted increasing interests worldwide due to the economic value and environmental influence of e-waste. RSC is generally defined as the series of activities required to retrieve a used product from a customer and either dispose of it or recycle/reuse it. Compared to informal RSC, formal RSC is usually used to refer the RSC that comply with environmental-friendly requirements for e-waste treatment. Due to the concerns of the adverse influence on environment and human health, it urges the development of formal RSC to replace the rampant informal RSC in most developing countries. Furthermore, a well-designed formal RSC is essential considering the inherent advantages of informal RSC.

In this end, this study focuses on the development of formal RSC and its optimization and governance, in order to promote the proper and appropriate treatment of e-waste. The study pays major attention to the prominent problems practically encountered in formal RSC in China. Wherein the prominent problems are summarized as the suitable collection channel structure and facility layout of formal RSC, and channel coordination between formal and informal RSCs. Specifically, this study firstly ① explores the optimal formal channel structure from different aspects; then ② discusses and compares the effectiveness of different policies on formalizing the collector in informal RSC; finally ③ conducts location planning of recycling centers for waste mobile phones (WMPs) treatment in China.

This study firstly focuses on the competitive formal and informal RSCs. By modelling the influence of collection efforts, green technology investment and the government subsidy, this study establishes three game theoretic models that corresponding respectively to three different dual-channel structures. These models are used to analyze the optimal collection strategy and channel structure of formal RSC under the competitive formal and informal RSCs, and indicate the optimal government subsidies. Then, this study considers the coordination of formal and informal RSCs for its benefits on e-waste treatment. A game theory model is built to analyze how to effectively promote the formalization of informal collectors. Based on the model, we discuss and compare the influences of four different policies (two subsidies and two penalties). Finally, the study pays attention to the development and rational layout of recycling centers in formal RSC. This study establishes several forecasting models to estimate and forecast the provincial WMPs of mainland China and develops a mixed-integer programming model for location planning of corresponding recycling infrastructures.

Based on the theoretical models and related numerical analysis, several key findings are concluded. The study firstly analyzes the optimal formal channel structures from the perspectives of formal recycler, consumer and government respectively. It is concluded that there exists the conflict of interests when deciding the optimal formal channel structure. The results further indicate that formal recyclers should positively implement collection efforts in order to improve the collected quantity and the profit of the formal channel even they outsource collection activities to independent collectors. Besides, the optimal subsidies are calculated for different formal channel structures from the aspect of minimizing the profit of informal RSC. Thirdly, the study concludes that both the subsidy and penalty policies can promote the formalization of informal collectors. And there is no difference between the subsidy to informal collectors and formal recyclers (penalty on informal collectors or informal recyclers) regarding the change of recycling quantity. It is noteworthy that there exist the decremental effect of subsidy and the incremental effect of penalty on promoting formalization activity. Lastly, the study estimates the WMPs in all 31 provinces of mainland China from year 1992 to 2036. Through the location planning study, it indicates the concrete locations of recycling centers and the WMPs flows across provinces, and concludes that a total of 175 recycling centers are required for WMPs treatment in China in 2036. Accordingly, this study indicates major managerial implications for both the government and the recycler in formal RSC. The implications for the government include prudently designing and implementing policies, simplifying the supervision system and improving its responsiveness, and promoting the co-construction of recycling centers and cooperation on WMPs treatment across provinces in China. For formal recyclers, they are suggested to establish their own collection channel or to centralize other independent collection channels, to positively implement activities to promote consumers' participation, and to establish its recycling centers following the planned locations.

In summary, the whole study can benefit the development and optimization of RSC as follows. Firstly, the whole study can help maximize the economic profit of formal RSC and benefit the environment. Secondly, the study can help promote the collection rate of formal RSC through the optimized formal channel structure and the efficiently coordinated formal and informal RSCs. Thirdly, because of the optimized locations of recycling centers, the study can contribute to the rational layout of recycling centers in formal RSC.

Chapter 1 Introduction

1.1 Background

Proper and appropriate treatment of electronic waste (e-waste) is attracting increasing interests worldwide. E-waste, also known as waste electrical and electronic equipment (WEEE), refers to various electronic products after use, mainly including washing machines, refrigerators, TVs, air conditioners, computers, and mobile phones. As one fast-growing stream of waste, e-waste is expected to increase to 52.2 Mt by 2021 globally (Balde et al., 2017). E-waste is a complex mixture of base metals (e.g. Fe, Al, Cu), precious metals (e.g. Au, Ag, Pd), critical and rare-earth elements (e.g. Nd, Ta, Dy etc), toxic elements (e.g. Pb, Cr, As), and various plastics and other materials (Cucchiella et al., 2015). Because of that, e-waste not only has an attractively economic value but also may cause major environmental and health problems if improperly treated (EC, 2020). While the latter makes the proper and appropriate treatment of e-waste essential and necessary.

The achievement of proper e-waste treatment closely relates to a well-designed formal reverse supply chain (RSC), which is deeply influenced by the precise estimation of e-waste quantity, effective and efficient collection and recycling system, adequate and well-distributed infrastructures, proper governance and so forth. RSC is generally defined as the series of activities required to retrieve a used product from a customer and either dispose of it or recycle/reuse it (Guide and Wassenhove, 2002). It not only determines the collected quantity of e-waste but also contributes to the economic benefits of e-waste treatment activities. Formal RSC is mainly distinct from informal RSC in that the former one is compliance with environmental-friendly requirements when conducting the treatment of e-waste. Compared to formal RSC, informal RSC dominates the market of most developing countries, such as China, India, Ghana and Nigeria, etc (Chi et al., 2014; Widmer et al., 2005; Lundgren, 2012). The environmental pollution and health damage of informal RSC make the governance or elimination of informal recycling activities essential and urge a complete and well-designed formal RSC.

A complete RSC includes mainly product acquisition, reverse logistics, and e-waste treatment (Doan et al., 2019). Strategically speaking, the collection strategy (e.g. who and how to implement collection activities), supply chain coordination and governance (e.g. contracts and incentives), and network design (e.g. location and size of collection and recycling centers), etc. are fundamental issues for a successful RSC.

The collection strategy of RSC has a vital influence on the collected quantity of e-waste. Savaskan et al. (2004) first modeled the influence of varied collectors and indicated that ceteris paribus, the agent, who is closer to the customer (i.e., the retailer), is the most effective undertaker of product collection activity for the manufacturer. Thereafter, a series of booming studies indicated and designed the optimal collection strategy of RSC by considering different channel power structures, competitive channels, different collection cost structures and the effects of product quality levels, etc. (Huang et al., 2013; Atasu et al., 2013; Giovanni and Zaccour, 2014; Maiti and Giri, 2015; He et al., 2019). As the highly hibernated waste stream, the achievement of a high e-waste collection rate is greatly affected by consumers' participation (Xiao et al., 2017). Considering collection efforts to promote consumers' participation, Gao et al. (2016) explored the influence of different channel power structures on the performance of closed loop supply chain. Jian et al. (2019) modeled collection efforts implemented by two independent entities and explore the influence of different collection efforts cost sharing mechanisms. One critical issue that who is the best collector and who is the best collection effort implementer in RSC has not been jointly explored.

Coordination and governance are crucial to contribute to the environmental and economic benefits of RSC. A fruitful of studies have paid attention to vertical coordination of different levels in a RSC. For instance, Zhang and Zhang (2015) studied the coordination of a RSC with marketing strategies and government subsidies and indicated the achieved socially optimal outcome. Focusing on horizontal coordination, Feng et al. (2017) proposed a two-part tariff contract and a profit-sharing contract respectively to coordinate a traditional and an online recycling channel. Savaskan and Wassenhove (2006), Jena and Sarmah (2014), and He et al. (2019) separately analyzed the coordination of two collection channels dominated respectively by two retailers, two manufacturers, or one manufacturer and one retailer. There are limited studies focus on the coordination of formal and informal RSCs. Besiou et al. (2012) investigated the effect of informal collectors using system dynamics methodology and concluded that incorporating informal collectors into the formal RSC performs better in economic, environmental, and social sustainability than ignoring or prohibiting their participation. Similar to the model of Besiou et al. (2012), Ghisolfi et al. (2016) analyzed the impact of legal incentives and the bargaining power obtained by the volume of collected waste on the effective formalization of waste pickers in the context of Brazil. Based on a mixed integer multi-objective linear programming model, Li and Tee (2012) studied the influence of a designed penalty for the producer according to emissions (greenhouse gas and lead) of the informal RSC on integrating the formal and informal RSCs. Li et al. (2017) demonstrated the benefit of coordinating the formal and informal RSCs through a game theoretic model and provided a two-tariff pricing contract to coordinate the dual RSCs. How to effectively integrate informal and formal RSCs? The influence of different interventions (e.g. subsidies and penalties) on the coordination of different RSCs deserves further analysis and comparison.

The adequate and well-distributed infrastructures in RSC are the foundation and practical guarantee for the proper treatment of e-waste and the benefits maximization. E-waste possesses some special characteristics and features that make its network design unique from forward supply chain. RSC is a process from dispersion to convergence (many consumers' sites to limited recycling sites). RSC of e-waste treatment starts from the collection of e-waste, which involving multiple factors along with a higher degree of uncertainties such as quantity, quality and time (Chen and He, 2010). Multiple studies have focused on network design of RSC and the details can be browed through some review papers (Islam and Huda, 2018; Pokharel and Mutha, 2009). It is noteworthy that reliable data is helpful for establishing an economically strong recycling industry and efficiently expanding the recycling infrastructure (Linton and Yeomans, 2003; Saphores et al., 2009).

As one of the world's largest electronic products manufacturing and consumption countries, China generates the highest e-waste quantity (7.2 Mt in 2016) both in Asia and in the world (Balde et al., 2017). However, the informal sector is still leading the collection and recycling business of e-waste due to a range of social and economic factors. It is reported that nearly 80% of the domestically generated e-waste was passed into the informal recycling channel in China (Chi et al., 2014). Considering the environmental pollution and health damage of these informal activities, the development of formal RSC becomes necessary in the context of China. Based on the extended producer responsibility

(EPR) policy, the Chinese government has launched a subsidy for formal processing enterprises to promote the formal RSC through enhancing their competitiveness (CPGPRC, 2012). Under such a subsidy, the study of the optimal collection strategy and the optimal channel structure has a profound practical significance. Promotion of formal RSC undoubtedly involves the competition against the existing powerful informal RSC. It is investigated that up to 18 million people are documented to be active in informal waste treatment in China (Gu et al., 2016). The government could not explicitly prohibit informal activities nationwide. Importantly, many studies have indicated the improved economic benefits of incorporating these informal activities instead of eliminating them costly and unrealistically (Besiou et al., 2012; Li et al., 2017). Taking all these into account, an effective and efficient approach (i.e. subsidy or penalty) to incorporate informal RSC deserves detailed analysis and will be meaningful. In RSC, inadequate infrastructure is one prominent issue for the proper e-waste treatment in China. As the booming mobile phone industry, the magnitude of waste mobile phones (WMPs) becomes outstanding in China. The WMPs have both a high economic value and environmental influence considering the huge volume in China (Figure 1-1), which making their treatment attractive. Since March 1st, 2016, WMPs have been officially included in the new version of "Catalogue of Disposal of Waste Electrical and Electronic Products (2014 Edition)" in China (NDRC, 2015). Besides, the Chinese government has proposed to establish recycling network according to the principle of rational layout, industrial clusters and ecological environmental protection (OSC, 2011; 2017). The upcoming government subsidy and the fundamental guidance policy will both promote and push the development and scientific planning of WMPs recycling infrastructures and recycling network system.

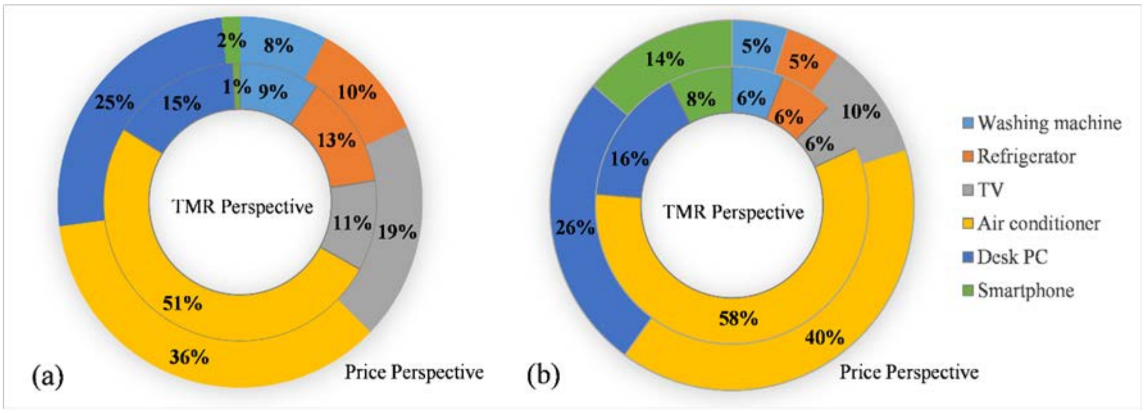

Figure 1-1 Proportion of the six major e-waste measured in the Total Material Requirement (TMR) and Price: (a) Unit proportion; (b) Proportion according to the overall quantity in 2018 in China; (Appendix A)

1.2 Purpose of the Study

In this end, the study focuses on the optimization and governance of RSC for e-waste treatment from the strategical perspective in order to fill the theoretical gaps, satisfy the practical requirements, and provide decision-making base and managerial recommendations. Specifically, this study first ① discusses the influence of the Chinese government subsidy on the formal and informal RSCs and explores the optimal formal channel structure from different aspects; then ② indicates the most effective approach to integrate informal RSC through a comparison of four different kinds of interventions (subsidies and penalties); finally ③ conducts a comprehensive estimation of WMPs in 31 provinces of mainland China and implements location planning of recycling centers for WMPs treatment (Figure 1-2).

The goals of this study are achieved through mathematic models and case studies, which are mainly based on the knowledge of operations research, management science and microeconomics. In details, game-theoretic models are established to study the optimal formal channel structure and to analyze the integration of formal and informal RSCs. Forecasting models are applied to estimate and forecast the WMPs for the context of China. A mixed-integer programming model is employed to conduct a location planning of recycling centers.

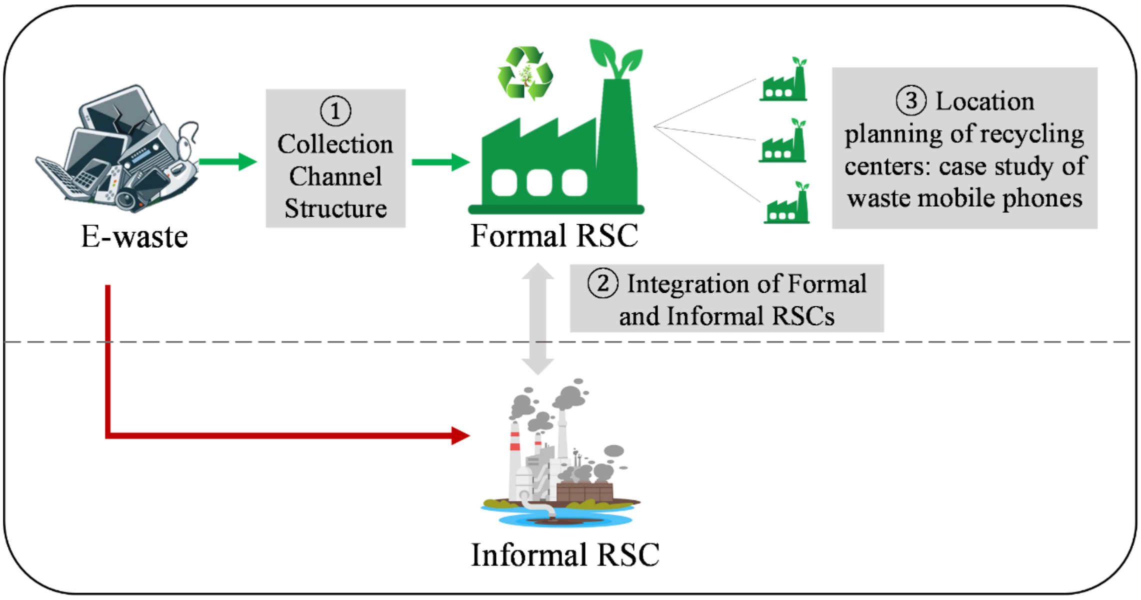

Figure 1-2 Abstract of the objective and scope of the study

1.3 Structure of Chapters

Chapter 2 focuses on analyzing the optimal channel structure of formal RSC under government subsidy. A comprehensive literature review is provided after a brief introduction. Then, three mathematic models are developed based on three model structures. Thereafter, the study analyzes the influence of the subsidy, makes a comparison of the three models, and calculates the optimal unit subsidies for the three models respectively and indicates the optimal unit subsidy given the goal of minimizing the informal channel's profit. Finally, we present the conclusion.

In Chapter 3, we study the possibility of incorporating informal collectors and compare the influences of different interventions. Following the introduction and a literature review, we present the model assumptions and notations applied in this chapter. Then, the benchmark model and the policy model are established respectively. And the influences of different factors and the effects of different policies are analyzed. Thereafter, the formalization extent for the context of China is studied and the effects of different policies are visualized based on numerical data. Finally, we summarize our main conclusions.

In Chapter 4, the waste mobile phones (WMPs) in provincial level of China are firstly estimated and then a location planning model is established to scientific plan the recycling centers. Firstly, three different estimation models are applied to estimate and forecast the per capita model phones and the best suited model is selected for the estimation of WMPs. Thereafter, a mixed-integer programming model is established for location planning of recycling centers with the help of the forecasted data of WMPs in 31 provinces of China in 2036, followed by a conclusion.

Chapter 5 summarizes the managerial implications from the whole study, including the optimal channel structure, the recommendations on promoting the formalization of informal collectors and so on. In Chapter 6, a conclusion of the whole research is put forward.

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Chapter 2 Channel structure of formal RSC under government subsidy

2.1 Introduction

A complete RSC is connected with consumers in the upstream and with re-businesses (e.g. recycling) or landfill in the downstream. It is noted that consumers' participation is the most important factor for achieving a high e-waste collection rate and formal processing enterprises should be encouraged to invest in the improvement of the e-waste processing ability (Tan et al., 2018; Xiao et al., 2017; Zhang et al., 2015). In the upstream, it should well plan the collector and the collection efforts implementer, wherein the collection efforts comprised of publicizing and disseminating the necessity of e-waste recycling is implemented to promote the participation of consumers. In the downstream, the e-waste processing ability including the environmentally-friendly treatment ability and recycling efficiency should be improved through the development and adoption of green technology. Besides, informal RSC is an inevitable external competitor for the development of formal RSC considering the abundant informal activities in most developing countries (Chi et al., 2014; Lundgren, 2012). Specific to the context of China, a subsidy for formal recyclers has been launched to promote formal RSC and to eliminate informal RSC (Gu et al., 2017; CHEARI, 2018). By combining the upstream, the downstream, the external competitor, and the incentive, this study mainly solves the following questions that are beneficial for understanding the mechanism of the system and promoting the development of formal RSC:

How and to what extent does the subsidy affect collection efforts, green technology investment and the performances of formal and informal channels? What difference does the varied formal channel structures lead? What are the optimal subsidies in different models?

How does the varied collector and/or the varied collection efforts implementor affect collection efforts, green technology investment and the performances of formal and informal channels? Who is the optimal collection efforts implementer? Which is the optimal formal channel structure for formal recyclers or the government?

The rest of this paper is organized as follows. Section 2 provides a comprehensive literature review, including studies related to formal and informal reverse channels, studies on the subsidy in China and on influences of and/or on various subsidies, selection of collection channel structure, collection efforts and green technology investment. In section 3, three models are developed and the equilibrium solutions for these models are calculated. While the influence of the subsidy and a comparison of the three models are analyzed in section 4 and section 5 respectively. Given the goal of minimizing the informal channel's profit, section 6 calculates the optimal unit subsidies for the three models respectively and indicates the smallest optimal unit subsidy. Finally, Section 7 presents the conclusion of this study.

2.2 Literature review

There are four main streams of research that closely relate to this study. They are: studies related to formal and informal recycling activities of e-waste, studies on the subsidy in China and on influences of and/or on government subsidies, selection of collection channel structure, collection efforts and green technology investment.

Formal and informal reverse channels for e-waste recycling widely coexist in many developing countries. The informal sectors are featured as high flexibility and mobility, closer to consumers, small scale, usually without trading licences, do not pay taxes, and are excluded from government funding schemes (Ezeah et al., 2013; Chi et al., 2011; Wilson et al., 2006). Based on system dynamics methodology, Besiou et al. (2012) studied the effect of informal collectors on the operations of the formal recovery system of e-waste. Liu et al. (2016) explored the equilibrium acquisition prices of formal and informal channels through a quality-based price competition model. Li et al. (2017) analyzed the performances of formal and informal channels based on both the differences of their marginal benefit functions and the consumers' channel preferences. Some studies also tried to coordinate or integrate informal sectors by focusing on governance mechanisms or incentives (Li and Lee, 2012; Liu et al., 2016; Li et al., 2017; Ghisolfi et al., 2017; Wang et al., 2020). Most of these studies paid attention to the difference between formal and informal channels, without specifying the influence of channel structures. And none of above studies modelled collection efforts or green technology investment of the formal channel.

Incentives are extrinsic motivators which reward actions to yield a desired outcome. In order to promote the development of formal recycling system, a subsidy for formal recyclers has been launched in China according to the completed recycling quantity (Gu et al., 2017; CHEARI, 2018). Some studies analyzed the influences of and/or on the government's subsidy (Yu et al., 2014; Gu et al., 2016; Gu et al., 2017; Wang et al., 2018; Zhang et al., 2020). Both Yu et al. (2014) and Wang et al. (2018) indicated the effectiveness of the subsidy and Wang et al. (2018) specifically concluded that the government's subsidy can make formal e-waste recycling industry profitable and is an effective way to increase the scale of the formal sector. There are limited studies focused on the quantitative analysis of the influences of and/or on the subsidy. Based on a questionnaire survey of obsolete television in Beijing and multi-agent cost-benefit analysis, Gu et al. (2016) concluded that the subsidy is mostly shared by collectors and intensifies the confusion of the recovery market. Besides, Gu et al. (2006, 2017) separately brought up two redesigned subsidy collection forms to achieve the sustainability of the subsidy system. Based on a game theory model, Zhang et al. (2020) analyzed whether recyclers choose to join the funding system to gain the subsidy and obey the environmental regulation. They concluded that the government's subsidy must exceed the profit difference between formal and informal recycling enterprises after deducting the incremental cost incurred for environmental compliance. All these quantitative studies followed the path of "subsidy improves formal channel's offering price to consumers then enhances its competitiveness against informal channel" when modelling the influences of the subsidy in China.

Focusing on the effects of tax and/or subsidy policy on market competition between green and traditional manufacturing firms, Hu et al. (2014) indicated that product characteristics and market structures can significantly impact the Pigouvian tax and subsidy policies. He et al. (2019a) considered a dual-channel closed-loop supply chain where a manufacturer can distribute new products through an independent retailer and sell remanufactured products via a third-party firm in the presence of possible government subsidy. They derived the pricing decisions and government's optimal subsidy level under these three channel structures. Their study concluded that government can encourage the manufacturer to adopt desired channel structures by setting appropriate subsidy levels. Hafezalkotob (2017) studied the roles of government financial policy in a green supply chain and concluded that the government financial intervention can essentially affect the energy-saving efforts and products retail prices.

Under the subsidy in China, how and to what extent the formal channel implements collection efforts and green technology investment have not been studied. Besides, the influences of the subsidy on formal and informal channels under different formal channel structures deserve further analysis.

Many papers studied the performances of different collection channels by considering different collectors, different channel power structures, competitive channels, different collection cost structures and the effects of product quality levels, etc. (Savaskan et al., 2004; Huang et al., 2013; Atasu et al., 2013; Giovanni and Zaccour, 2014; Maiti and Giri, 2015; He et al., 2019b). These studies mainly indicate the optimal collection channel structures from the aspect of maximizing the profit of the collection entities or channel.

Among all these studies, Savaskan et al. (2004) first modelled collection efforts and set the structure of the collection efforts cost. Gao et al. (2016) explored the influence of different channel power structures on optimal closed loop supply chain collection efforts, sales efforts and performance. Jian et al. (2019) modelled collection efforts implemented by two independent entities and explored the influence of different collection efforts cost sharing mechanisms. However, who is the best to implement collection efforts is seldomly under discussion. For a recycler, it can choose to collect e-waste by itself or through an independent collector, meanwhile, it can motivate the participation of consumers by implementing collection efforts directly or through the independent collector. This paper is to analyze the influences of the varied collectors or collection efforts implementors on both the formal and informal channels.

Most of the green technology investment studies focused on the entities in the forward supply chain in order to study their resource conservation and emission reduction investment (Toptal et al., 2014; Dong et al., 2016; Chen et al., 2016; Welling 2016; Sun et al., 2019; Shi et al., 2019; Bigerna et al., 2019). Toptal et al. (2014) compared a retailer's joint decisions on carbon emission reduction investment and inventory replenishment under carbon cap, tax and cap-and-trade policies. Welling (2016) explored companies' renewable electricity investment under governmental support. Sun et al. (2019) analyzed the optimal green investment strategy in a two-echelon supply chain consisted of manufacturers and material suppliers under a government subsidy policy. Considering the uncertain market demand and the subsidy in Italian, Bigerna et al. (2019) investigated the optimal investment decision in renewables and found that a higher subsidy level induces the firm to invest earlier with a smaller investment capacity. Different from above studies, this paper pays attention to green technology investment of recyclers in the reverse supply chain and discusses the influences of the subsidy and different channel structures on the green technology investment.

The current study explores the influences of the subsidy for formal recyclers on formal and informal reverse channels considering the collection efforts and green technology investment of the formal channel. To the best knowledge of the authors, this paper is the first to model both the collection efforts and green technology investment in a dual-channel reverse supply chain. Second, three formal channel structures with different collectors or collection efforts implementers are modelled. Accordingly, the study analyzes and compares the influences of the subsidy on formal and informal channels under different formal channel structures. Moreover, the optimal formal channel structures are provided from various aspects, including the extent of collection efforts and green technology investment, and minimizing the informal channel's profit with the minimum unit subsidy.

2.3 Model development and equilibrium solutions

This paper considers a dual-channel reverse supply chain of e-waste treatment under Chinese government subsidy. Wherein one is formal channel (F) and the other is informal channel (I). A recycling quantity-based subsidy is granted to formal recyclers in the formal channel. By jointly considering the varied decisions of the formal recycler, three models are developed in the study (Figure 2-1). The three models are different in the collection channel structure and collection effort implementer of the formal channel. In Model A, the formal recycler (FR) collects e-waste and implements collection effort directly. In Model B, FR implements collection effort directly but outsources the e-waste collection activity to an independent formal collector (FC). In Model C, FR also outsources the e-waste collection activity to FC. However, FC rather than FR implements the collection effort in Model C. All the three models incorporate FR's decision on green technology investment.

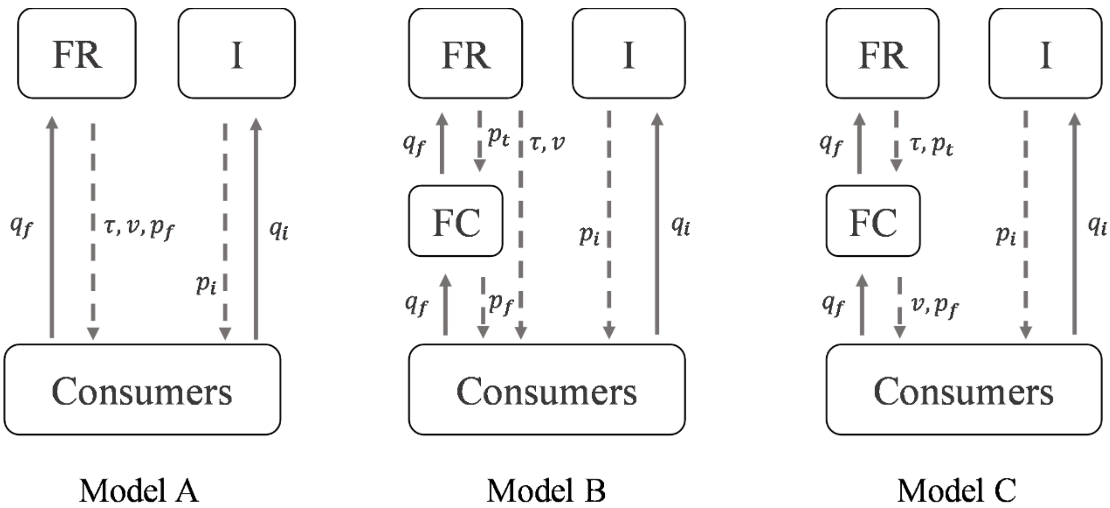

Figure 2-1 Dual-channel formal and informal recycling activities structures in this study

Collection quantity

Similar to the study of (Wu 2012; Gao et al., 2016; Guo et al., 2018), a linear price and collection effort dependent collection quantity is applied. Gao et al. (2016) and Guo et al. (2018) considered only one channel in their studies without considering the price competition influence and the spillover effect of collection effort on the other channel. Wu (2012) modelled a competitive dual channel and applied the linear price and service dependent sales quantity. In his study, he modelled the service influence of each channel and considered a negative influence of one channel's service on the other. Different from their studies, we consider both the price competition and the positive influence of the formal channel's collection effort on the informal channel.

The collection quantities of the formal and informal channels are as follows in this study:

$$q_f = \alpha_f + ap_f - bp_i + \lambda kv \qquad (2\text{-}1)$$

$$q_i = \alpha_i + ap_i - bp_f + (1-\lambda)kv \qquad (2\text{-}2)$$

q_f and q_i are the collection quantities of the formal and informal channels respectively. Formal channel competes with informal channel in collecting e-wastes. α_f and α_i are the collection market base of the formal and informal channels when the collection prices (p_f, p_i) and collection effort (v) are zeroes. Since informal channel always has a superior power to acquire e-waste considering its flexibility and mobility (Ezeah et al., 2013; Chi et al., 2011), $\alpha_i > \alpha_f$ always hold. In this study, $1 > \alpha_i > \alpha_f = 0$ is adopted without loss of generality. The collection quantity of the formal channel (q_f) is positively affected by its collection price (p_f) and negatively affected by the collection price of the informal channel (p_i). Whereas the collection quantity of the informal channel (q_i) is the opposite.

a and b are the self-price sensitivity and cross-price sensitivity respectively on collection quantity. In terms of e-waste collection in China, Qu et al. (2019) investigated that the main reasons for not disposing waste mobile phones are “Fear of information leakage” (42.1%) and “Lack of knowledge how to dispose” (38.6%). Moreover, Ramzan et al. (2019) concluded that the reasons for not participating in formal e-waste recycling practices in China include low awareness and information about environment and sustainable practices, weak formal collection system, data safety concerns, and less effective government policies. Both the results indicate that the collection effort rather than collection price can improve the overall collection quantity. In order to be consistent with the condition, we set $a = b$ in this study, which representing that increasing collection price would not enlarge the overall collection quantity of e-waste but only influence the channel preference and the channel with a higher collection price is more preferred. In the following analysis, $a = b = 1$ is adopted for the sake of simplicity.

v $(0 \leq v)$ represents the collection effort extent and k $(0 < k \leq 1)$ is the scale parameter. k indicates the influence magnitude of collection effort on the collected quantity of the dual channels. When it increases, the influence magnitude varies from insignificant to significant. In practice, when promoting consumers’ participation, it cannot determine which channel they will choose. In addition, due to closer to consumers and high mobility, informal channel can easily become the free rider of formal channel’s collection effort. Because of the collection effort and the phenomenon of free-rider, both the q_f and q_i can be improved by the collection effort of the formal channel, and λ $(0 < \lambda < 1)$ represents the ratio that the formal channel benefits from the collection effort. The multiply of λ and k can indicate the influence magnitude of collection effort on the collected quantity of the formal channel.

Per unit e-waste treatment profit

The treatment of e-waste consists of the collection and recycling activities of e-waste. For the informal channel, let P be the per unit recycling profit, wherein P is the difference of recycling revenue and recycling cost. Considering the collection cost (collection price paid to consumers: p_i), the per unit e-waste treatment profit of the informal channel is calculated as:

Informal channel: $P - p_i$ (2-3)

The per unit e-waste treatment profit of the formal channel is similar to the informal channel, however, there are three differences. Firstly, the recycling profit of formal channel is relatively low compared to informal channel because of environmentally-friendly treatment requirements. Therefore, a discounted recycling profit (τ_0, $\tau_0 \leq 1$) is assigned to the formal channel, and $\tau_0 P$ is the formal channel's original recycling profit. Secondly, the green technology investment aiming at promoting the recycling efficiency or purification of recycled materials can improve the recycling profit of the formal channel. Let τ ($0 \leq \tau$) be the green technology investment extent, then the increased recycling profit of the formal recycler can be represented as $m\tau P$, wherein m ($0 < m \leq 1$) is the scale parameter. As the increase of m, the influence magnitude of green technology investment on the profit of the formal channel increases from insignificant to significant. Thirdly, the formal channel's profit is also improved by the government subsidy in China. Chinese government is implementing a fixed per unit subsidy (s, $0 \leq s$) to the recyclers of formal channel according to their recycling quantities. Therefore, considering the collection price (p_f), the per unit profit of the formal channel is:

Formal channel: $s + (\tau_0 + m\tau)P - p_f$ (2-4)

In Model A, the formal recycler operates the formal channel directly, therefore, the per unit profit of the formal recycler in Model A is:

Formal recycler in Model A: $s + (\tau_0 + m\tau)P - p_f$ (2-5)

In Model B and Model C, the formal recycler pays a transferring price (p_t) to an independent collector to acquire e-waste, then the per unit profit of the formal recycler and collector can be divided into:

Formal recycler in Model B and C: $s + (\tau_0 + m\tau)P - p_t$ (2-6)

Formal collector in Model B and C: $p_t - p_f$ (2-7)

P is standardized as 1 in following analysis without loss of generality.

Investment cost

Besides the collection prices, the collection efforts and green technology investment incur additional investment costs to the formal channel. Similar to the studies of (Wu, 2012; Gao et al., 2016; Guo et al., 2018; He et al., 2019b), the convex increasing investment cost form is used in this study. The relation between the cost and the collection efforts or green technology investment is $\frac{1}{2}\eta_1 v^2$ or $\frac{1}{2}\eta_2 \tau^2$ respectively, wherein η_1 and η_2 are the scale parameters. Since we focus on the influence of the subsidy rather than the cost difference between v and τ, $\eta_1 = \eta_2 = 1$ is assigned thereafter without loss of generality.

Model A

The formal recycler is treated as the Stackelberg leader in all the models. As the Stackelberg leader, the formal recycler decides the collection efforts (v), green technology investment (τ), and collection price (p_f) firstly, based on which the informal channel sets its collection price (p_i).

$$\begin{cases} \pi_f = \pi_{fr} = \left(s + \tau_0 + m\tau - p_f\right)\left(p_f - p_i + \lambda k v\right) - \frac{1}{2}v^2 - \frac{1}{2}\tau^2 \\ \qquad s.t. \pi_i = (1 - p_i)(\alpha_i + p_i - p_f + (1 - \lambda)kv) \end{cases} \tag{2-8}$$

The equilibrium results can be solved through backward induction. Firstly, the best response of the informal channel (follower) can be solved by setting $\frac{\partial \pi_i}{\partial p_i} = 0$. It is calculated that $p_i = \frac{1-\alpha_i+p_f-(1-\lambda)kv}{2}$, wherein the p_i is represented by a function of the Stackelberg leader's decisions (v, τ, p_f). Then by substituting p_i into π_f, the payoff function of the formal recycler can be changed to:

$$\pi_f = \pi_{fr} = \left(s + \tau_0 + m\tau - p_f\right)\frac{p_f-(1-\alpha_i)+(1-\lambda)kv+2\lambda kv}{2} - \frac{1}{2}v^2 - \frac{1}{2}\tau^2 \tag{2-9}$$

Setting $\begin{cases} \frac{\partial \pi_f}{\partial v} = 0 \\ \frac{\partial \pi_f}{\partial \tau} = 0 \\ \frac{\partial \pi_f}{\partial p_f} = 0 \end{cases}$, it can calculate the optimal decisions (τ^A, v^A, ${p_f}^A$) of the formal recycler (Stackelberg leader) by combining these three equations. Finally, we can solve the optimal decision (${p_i}^A$) of the informal channel (follower) by substituting the τ^A, v^A and ${p_f}^A$ into p_i. Table 2-1 summarizes the equilibrium results of Model A.

Table 2-1 Equilibrium results of Model A

$$\tau^A=\frac{m(s+\tau_0-(1-\alpha_i))}{4-m^2-(k(1+\lambda))^2}$$

$$v^A=\frac{k(1+\lambda)(s+\tau_0-(1-\alpha_i))}{4-m^2-(k(1+\lambda))^2}$$

$$p_f{}^A=\frac{\left(2-(k(1+\lambda))^2\right)(s+\tau_0)+(2-m^2)(1-\alpha_i)}{4-m^2-(k(1+\lambda))^2}$$

$$p_i{}^A=\frac{-\left(k^2(1+\lambda)-1\right)(s+\tau_0-1)-\left(3-m^2-\lambda k^2(1+\lambda)\right)\alpha_i+4-m^2-(k(1+\lambda))^2}{4-m^2-(k(1+\lambda))^2}$$

$$q_f{}^A=\frac{s+\tau_0-(1-\alpha_i)}{4-m^2-(k(1+\lambda))^2}$$

$$q_i{}^A=\frac{\left(k^2(1+\lambda)-1\right)(s+\tau_0-1)+(3-m^2-\lambda k^2(1+\lambda))\alpha_i}{4-m^2-(k(1+\lambda))^2}$$

$$\pi_f{}^A=\pi_{fr}{}^A=\frac{(s+\tau_0-(1-\alpha_i))^2}{2(4-m^2-\left(k(1+\lambda)\right)^2)}$$

$$\pi_i{}^A=\frac{(\left(k^2(1+\lambda)-1\right)(s+\tau_0-1)+(3-m^2-\lambda k^2(1+\lambda))\alpha_i)^2}{(4-m^2-\left(k(1+\lambda)\right)^2)^2}$$

Model B

As the Stackelberg leader, the formal recycler decides its collection efforts (v), green technology investment (τ), and the transferring price (p_t) firstly, then the formal collector and informal channel compete to conduct collection campaigns by setting the collection prices (p_f, p_i) separately.

$$\begin{cases}\pi_{fr}=(s+\tau_0+m\tau-p_t)\left(p_f-p_i+\lambda kv\right)-\frac{1}{2}v^2-\frac{1}{2}\tau^2\\ \qquad s.t.\begin{cases}\pi_{fc}=\left(p_t-p_f\right)\left(p_f-p_i+\lambda kv\right)\\ \pi_i=(1-p_i)(\alpha_i+p_i-p_f+(1-\lambda)kv)\end{cases}\end{cases} \tag{2-10}$$

Table 2-2 Equilibrium results of Model B

$\tau^B=\frac{m(s+\tau_0-(1-\alpha_i))}{6-m^2-(k(1+\lambda))^2}$
$v^B=\frac{k(1+\lambda)(s+\tau_0-(1-\alpha_i))}{6-m^2-(k(1+\lambda))^2}$
${p_t}^B=\frac{(3-(k(1+\lambda))^2)(s+\tau_0)+(3-m^2)(1-\alpha_i)}{6-m^2-(k(1+\lambda))^2}$
${p_f}^B=\frac{(2-(k(1+\lambda))^2)(s+\tau_0)+(4-m^2)(1-\alpha_i)}{6-m^2-(k(1+\lambda))^2}$
${p_i}^B=\frac{-(k^2(1+\lambda)-1)(s+\tau_0-1)-\left(5-m^2-\lambda k^2(1+\lambda)\right)\alpha_i+6-m^2-(k(1+\lambda))^2}{6-m^2-(k(1+\lambda))^2}$
${q_f}^B=\frac{s+\tau_0-(1-\alpha_i)}{6-m^2-(k(1+\lambda))^2}$
${q_i}^B=\frac{(k^2(1+\lambda)-1)(s+\tau_0-1)+(5-m^2-\lambda k^2(1+\lambda))\alpha_i}{6-m^2-(k(1+\lambda))^2}$
${\pi_{fc}}^B=\frac{(s+\tau_0-(1-\alpha_i))^2}{(6-m^2-(k(1+\lambda))^2)^2}$
${\pi_{fr}}^B=\frac{(s+\tau_0-(1-\alpha_i))^2}{2(6-m^2-(k(1+\lambda))^2)}$
${\pi_f}^B={\pi_{fr}}^B+{\pi_{fc}}^B=\frac{(8-m^2-(k(1+\lambda))^2)(s+\tau_0-(1-\alpha_i))^2}{2(6-m^2-(k(1+\lambda))^2)^2}$
${\pi_i}^B=\frac{((k^2(1+\lambda)-1)(s+\tau_0-1)+\left(5-m^2-\lambda k^2(1+\lambda)\right)\alpha_i)^2}{(6-m^2-(k(1+\lambda))^2)^2}$

The equilibrium results can be solved through backward induction. Firstly, setting $\begin{cases}\frac{\partial\pi_i}{\partial p_i}=0\\ \frac{\partial\pi_{fc}}{\partial p_f}=0\end{cases}$, then it calculates $\begin{cases}p_i=\frac{p_t+2(1-\alpha_i)-\lambda kv-2(1-\lambda)kv}{3}\\ p_f=\frac{2p_t+1-\alpha_i-2\lambda kv-(1-\lambda)kv}{3}\end{cases}$ by combining these two equations. Substituting p_i and p_f into π_{fr}, after arrangement:

$$\pi_{fr}=(s+\tau_0+m\tau-p_t)\frac{p_t-(1-\alpha_i)+2\lambda kv+(1-\lambda)kv}{3}-\frac{1}{2}v^2-\frac{1}{2}\tau^2 \qquad (2\text{-}11)$$

Setting $\begin{cases} \frac{\partial \pi_{fr}}{\partial v} = 0 \\ \frac{\partial \pi_{fr}}{\partial \tau} = 0 \\ \frac{\partial \pi_{fr}}{\partial p_t} = 0 \end{cases}$, the optimal decisions (τ^B , v^B , ${p_t}^B$) of the formal recycler (Stackelberg leader) can be calculated by combining these three equations. Finally, we can solve the optimal decision (${p_f}^B$, ${p_i}^B$) of the formal collector and informal channel (followers) by substituting the τ^B , v^B and ${p_t}^B$ into p_f and p_i . Table 2-2 lists the equilibrium results of Model B.

Model C

As the Stackelberg leader, the formal recycler decides the green technology investment (τ) and the transferring price (p_t) firstly. Then the formal collector sets the collection price (p_f) and collection efforts (v) while the informal channel decides its collection price (p_i) simultaneously.

$$\begin{cases} \pi_{fr} = (s + \tau_0 + m\tau - p_t)(p_f - p_i + \lambda k v) - \frac{1}{2}\tau^2 \\ s.t. \begin{cases} \pi_{fc} = (p_t - p_f)(p_f - p_i + \lambda k v) - \frac{1}{2}v^2 \\ \pi_i = (1 - p_i)(\alpha_i + p_i - p_f + (1 - \lambda)kv) \end{cases} \end{cases} \tag{2-12}$$

In order to solve the equilibrium result of Model C, the p_i, p_f and v are jointly calculated as $\begin{cases} p_i = \frac{(1-\lambda k^2(1-\lambda)-(\lambda k)^2)p_t+(2-(\lambda k)^2)(1-\alpha_i)}{3-\lambda k^2(1-\lambda)-2(\lambda k)^2} \\ p_f = \frac{(2-\lambda k^2(1-\lambda)-2(\lambda k)^2)p_t+1-\alpha_i}{3-\lambda k^2(1-\lambda)-2(\lambda k)^2} \\ v = \frac{\lambda k(p_t-(1-\alpha_i))}{3-\lambda k^2(1-\lambda)-2(\lambda k)^2} \end{cases}$ by setting $\begin{cases} \frac{\partial \pi_i}{\partial p_i} = 0 \\ \frac{\partial \pi_{fc}}{\partial p_f} = 0. \\ \frac{\partial \pi_{fc}}{\partial v} = 0 \end{cases}$

Substituting p_i, p_f and v in π_{fr}, then,

$$\pi_{fr} = (s + \tau_0 + m\tau - p_t)\frac{p_t-(1-\alpha_i)}{3-\lambda k^2(1-\lambda)-2(\lambda k)^2} - \frac{1}{2}\tau^2 \tag{2-13}$$

Let $\begin{cases} \frac{\partial \pi_{fr}}{\partial \tau} = 0 \\ \frac{\partial \pi_{fr}}{\partial p_t} = 0 \end{cases}$, the optimal decisions (τ^C, ${p_t}^C$) of the formal recycler (Stackelberg leader) can be calculated by combining these two equations. Finally, we can solve the optimal decision (v^C, ${p_f}^C$, ${p_i}^C$) of the formal collector and informal channel (followers) by substituting the τ^C and ${p_t}^C$ into v, p_f and p_i. The equilibrium results of Model C are recorded in Table 2-3.

Table 2-3 Equilibrium results of Model C

$$\tau^C = \frac{m(s+\tau_0-(1-\alpha_i))}{6-2\lambda k^2(1+\lambda)-m^2}$$

$$v^C = \frac{\lambda k(s+\tau_0-(1-\alpha_i))}{6-2\lambda k^2(1+\lambda)-m^2}$$

$${p_t}^C = \frac{(3-\lambda k^2(1+\lambda))(s+\tau_0)+(3-\lambda k^2(1+\lambda)-m^2)(1-\alpha_i)}{6-2\lambda k^2(1+\lambda)-m^2}$$

$${p_f}^C = \frac{(2-\lambda k^2(1+\lambda))(s+\tau_0)+(4-\lambda k^2(1+\lambda)-m^2)(1-\alpha_i)}{6-2\lambda k^2(1+\lambda)-m^2}$$

$${p_i}^C = \frac{-(\lambda k^2-1)(s+\tau_0-1)-(5-\lambda k^2(1+2\lambda)-m^2)\alpha_i+6-2\lambda k^2(1+\lambda)-m^2}{6-2\lambda k^2(1+\lambda)-m^2}$$

$${q_f}^C = \frac{s+\tau_0-(1-\alpha_i)}{6-2\lambda k^2(1+\lambda)-m^2}$$

$${q_i}^C = \frac{(\lambda k^2-1)(s+\tau_0-1)+(5-\lambda k^2(1+2\lambda)-m^2)\alpha_i}{6-2\lambda k^2(1+\lambda)-m^2}$$

$${\pi_{fc}}^C = \frac{(2-(\lambda k)^2)(s+\tau_0-(1-\alpha_i))^2}{2(6-2\lambda k^2(1+\lambda)-m^2)^2}$$

$${\pi_{fr}}^C = \frac{(s+\tau_0-(1-\alpha_i))^2}{2(6-2\lambda k^2(1+\lambda)-m^2)}$$

$${\pi_f}^C = {\pi_{fr}}^C + {\pi_{fc}}^C = \frac{(8-\lambda k^2(2+3\lambda)-m^2)(s+\tau_0-(1-\alpha_i))^2}{2(6-2\lambda k^2(1+\lambda)-m^2)^2}$$

$${\pi_i}^C = \frac{((\lambda k^2-1)(s+\tau_0-1)+(5-\lambda k^2(1+2\lambda)-m^2)\alpha_i)^2}{(6-2\lambda k^2(1+\lambda)-m^2)^2}$$

2.4 Equilibrium analysis

In all the three models, τ, v, p_f, p_i, p_t, q_f, q_i, π_{fc}, π_{fr}, π_f and π_i are all non-negative, therefore $s + \tau_0 - (1 - \alpha_i) > 0$ and $4 - m^2 - (k(1 + \lambda))^2 > 0$ should always hold. All proofs for the remaining parts of Chapter 2 are recorded in the Appendix B.

2.4.1 Influences of the subsidy

Proposition 2-1. The subsidy for formal recyclers (s) promotes the collection efforts (v) and green technology investment (τ) regardless of the formal channel structure.

Proof of Proposition 2-1.

$$\frac{\partial \tau^A}{\partial s} > 0, \frac{\partial \tau^B}{\partial s} > 0, \frac{\partial \tau^C}{\partial s} > 0, \frac{\partial v^A}{\partial s} > 0, \frac{\partial v^B}{\partial s} > 0, \frac{\partial v^C}{\partial s} > 0.$$

Collection efforts including publicizing and disseminating the necessity of e-waste recycling can promote the participation of consumers and therefore reduce the hibernated e-waste (Xiao et al., 2017). Because of the decreased environmentally-friendly treatment cost and/or the increased recycling efficiency, green technology investment not only can benefit the profit of formal channel but also contribute to the benign environment. From these aspects, the subsidy is beneficial since it can promote both of them.

Proposition 2-2. (1) The collection quantity of the formal channel (q_f) in all the three models can be improved by the subsidy (s);

(2) When $k^2(1 + \lambda) > 1$, the increase of s improves ${q_i}^A$ and ${q_i}^B$, when $k^2(1 + \lambda) < 1$, the increase of s lowers ${q_i}^A$ and ${q_i}^B$;

(3) The subsidy (s) has a negative influence on ${q_i}^C$.

The insufficient collection quantity is a serious problem for the development of formal channel in most countries (Ramzan et al., 2019; Fu et al., 2018). Considering the enlarged collection quantity q_f, the subsidy is concluded helpful for the development of formal reverse supply channel regardless of the formal channel structure. Counterintuitively, it deserves to emphasize that the implementation of the subsidy may enlarge the collection quantity of the informal channel (q_i), wherein the enlarged q_i is a consequence of the promoted consumers' participation and the superior characteristics of the informal channel (free rider of formal channel's collection efforts). Further improve and perfect formal channel (e.g. high mobility) will effectively minimize and even eliminate this phenomenon. It is noteworthy that the subsidy always has a negative influence on the collection quantity of the informal channel in Model C.

Proposition 2-3. (1) When $k(1+\lambda) < \sqrt{2}$, ${p_f}^A$ and ${p_f}^B$ increase as s increases, when $k(1+\lambda) > \sqrt{2}$, ${p_f}^A$ and ${p_f}^B$ decrease as s increases;

(2) When $k(1+\lambda) < \sqrt{3}$, the increase of s leads an increase in ${p_t}^B$, when $k(1+\lambda) > \sqrt{3}$, the increase of s leads a decrease in ${p_t}^B$;

(3) When $k^2(1+\lambda) > 1$, the increase of s lowers ${p_i}^A$ and ${p_i}^B$, when $k^2(1+\lambda) < 1$, the increase of s improves ${p_i}^A$ and ${p_i}^B$;

(4) The subsidy (s) has a positive influence on ${p_t}^C$, ${p_f}^C$, and ${p_i}^C$.

The subsidy can improve the transferring price, the collection prices of the formal and informal channels in Model C. However, it may lower the collection prices of the formal and informal channels in Model A and Model B, and the transferring price in Model B.

For consumers, Model A and Model B may lead them to face a situation that their interests are damaged. Model B may also fail to satisfy the independent collector.

Corollary 2-1. The subsidy not always induce a fiercer price competition between the formal and informal channels.

Considering the possibility of lowering the collection prices of the formal and informal channels (p_f and p_i when $k(1+\lambda) > \sqrt{2}$) in Model A and Model B, Corollary 2-1 can be drawn. Whether Corollary 2-1 holds depends on the effects of the collection efforts, including the enlarged e-waste supply (higher k) and/or the increased collection quantity of the formal channel (higher λ). When there is a sharp increase in e-waste supply (higher k), both formal and informal channels can easily access to enough e-waste without encountering a fiercer price competition. While the increased collection quantity of the formal channel (higher λ) makes the formal channel side prefer to lower its collection price (p_f) to gain a higher profit (π_f). Correspondingly, the informal channel side can also adjust its collection price (p_i) accordingly. Therefore, a lower collection price competition can also occur along a higher λ. Corollary 2-1 indicates the complex influence of the subsidy.

Proposition 2-4. (1) The subsidy improves the profit of the formal channel (π_{fc}, π_{fr}, π_f);

(2) When $k^2(1+\lambda) > 1$, s increases, ${\pi_i}^A$ and ${\pi_i}^B$ increase, when $k^2(1+\lambda) < 1$, s increases, ${\pi_i}^A$ and ${\pi_i}^B$ decrease. s has a negative influence on ${\pi_i}^C$.

Due to the enlarged profit (π_{fc}, π_{fr}, π_f), formal recycling activities can gain much attention and unprecedented development. Since the implementation of the subsidy, more than one hundred enterprises have been certified and subsidized in China (CHEARI, 2018). It becomes increasingly important to further optimize formal recycling activities, specifically to improve their environmental and economic sustainability. The environmental and economic sustainability can be improved through positive collection efforts and green technology investment, which the former can reduce the hibernation of e-waste while the latter can lower the environmentally-friendly treatment cost and/or raise the recycling efficiency.

2.4.2 Influences of other parameters

Proposition 2-5. (1) k has a positive influence on τ, v, q_f, q_i, π_{fr}, π_f, π_i and a negative influence on p_f, p_i in all the three models. Meanwhile, it has a positive influence on ${p_t}^C$, ${\pi_{fc}}^B$ and a negative influence on ${p_t}^B$, ${\pi_{fc}}^C$;

(2) λ and k have the same kind influence (either positive or negative) on τ, v, q_f, p_f, p_t, π_{fc}, π_{fr}, π_f, however, when $2 - m^2 - 2\lambda + k^2(1+\lambda)^2 > 0$, the increase of λ improves ${q_i}^A$, ${\pi_i}^A$ and lowers ${p_i}^A$, otherwise, the opposite stands; when $4 - m^2 - 4\lambda + 2k^2\lambda^2 > 0$ the increase of λ improves ${q_i}^C$, ${\pi_i}^C$ and lowers ${p_i}^C$, otherwise, the opposite stands; the increase of λ improves ${q_i}^B$, ${\pi_i}^B$ and lowers ${p_i}^B$;

(3) τ_0 and m have the same kind influence with s.

It is note that k always has a positive influence on q_i and π_i. This attributes to the characteristic of collection efforts and the superior characteristics of informal channel. Collection efforts including publicizing and disseminating the necessity of e-waste recycling can promote the participation of consumers however collection efforts cannot determine which channel they will choose. In addition, due to closer to consumers and high mobility, informal channel can easily become the free rider of formal channel's collection efforts. As the influence magnitude of the collection efforts on collection quantity, k hence can promote q_i and π_i.

The results show that λ can improve q_i and π_i in specific conditions. λ represents the ratio that the formal channel benefits from the collection efforts. It is noteworthy that λ always has a negative influence on p_f and a positive influence on q_f. Even though the increased λ lowers the benefit as a free rider ($k(1-\lambda)$), the informal channel side can adjust its collection price (p_i) according to p_f appropriately to ensure a higher collection quantity. Therefore, the increased λ yet can improve q_i. When the benefit of the increased collection quantity (q_i) is sufficient to offset the increased cost (p_i), the profit of the informal channel (π_i) yet can be improved. As the increase of λ, the benefit of the increased collection price difference ($p_i - p_f$) is insufficient to offset the loss as a free rider ($k(1-\lambda)$), which eventually leads to the decreased q_i and π_i. It is note that whether λ positively affect q_i and π_i highly depends on m and k. And the smaller the m is or the bigger the k is, the wider the range of the conditions that λ can improve q_i and π_i. When m is close to 0, λ can improve q_i and π_i regardless of the value of k. m represents the influence magnitude of green technology investment on the profit of the formal recycler and k represents the influence magnitude of the collection efforts on collection quantity. When m is small, the increased λ significantly influences the collection efforts of the formal channel side in spite of a small k. When m increases, the increased λ yet significantly influences the collection efforts of the formal channel side if k is huge enough. In summary, when m is small, or when m increases and k is huge, the formal channel side prefers to significantly enlarge the collection efforts as the increase of λ. The benefit from the enlarged collection efforts eventually makes the formal channel decrease its collection price (p_f) considerably to gain a higher profit (π_f). Consequently, the informal channel side has a wider range to adjust its collection price (p_i) according to p_f appropriately. Because of this, the range of the conditions that λ can improve q_i and π_i is highly influenced by the m and k.

It deserves to note that the influences of m and $k(\lambda)$ are opposite in terms of q_i, p_f, p_i, π_i in specific conditions. The multiply of λ and k can indicate the influence magnitude of collection efforts on the collection quantity of the formal channel while m can represent the influence magnitude of green technology investment on the profit of the formal recycler. When the formal channel side plans to implement collection efforts or green technology investment, Proposition 2-5 can serve its decision-making. For instance, Proposition 2-5. (1) and (2) indicate that k and λ always have a positive influence on ${\pi_i}^B$, while Proposition 2-5. (3) and Proposition 2-4. (2) conclude that m has a negative influence on ${\pi_i}^A$ and ${\pi_i}^B$ when $k^2(1+\lambda) < 1$ and it always has a negative influence on ${\pi_i}^C$. If the formal channel side is extremely reluctant to do what is good for the informal channel side, it is recommended to implement collection efforts prudently in Model B and to adopt a priority on the green technology investment rather than on the collection efforts when choosing Model C.

Proposition 2-6. α_i has a positive influence on τ, v, q_f, q_i, π_{fc}, π_{fr}, π_f, π_i while a negative influence on p_f, p_i, p_t in all the three models.

Proposition 2-6 indicates that α_i has a positive influence on q_f, π_{fc}, π_{fr}, π_f. α_i is the collection quantity of the informal channel when the collection prices of the formal and informal channels are zeroes. A bigger α_i ensures a larger e-waste supply to the informal channel side and makes it a lower intention to offer a higher collection price (p_i) in e-waste collection. Correspondingly, the formal channel side will reduce its collection price (p_f) appropriately on the premise of acquiring enough e-waste. Meanwhile, because of the decreased p_i and p_f, the unit profit of either the formal or informal channel will increase. As a result, all the q_f, q_i, π_{fc}, π_{fr}, π_f, π_i will be improved by α_i. The decreased p_f and p_i in Proposition 6 prove the interpretation.

2.5 Comparison of the three models

Proposition 2-7. (1) $\tau^A > \tau^B > \tau^C$, $v^A > v^B > v^C$, ${q_f}^A > {q_f}^B > {q_f}^C$, ${\pi_{fr}}^B > {\pi_{fr}}^C$, ${\pi_{fc}}^B > {\pi_{fc}}^C$, ${\pi_f}^A > {\pi_f}^B = {\pi_{fr}}^B + {\pi_{fc}}^B > {\pi_f}^C = {\pi_{fr}}^C + {\pi_{fc}}^C$;

(2) ${p_t}^B < {p_t}^C$, ${p_f}^B < {p_f}^C$, ${q_i}^B > {q_i}^C$, ${p_i}^B < {p_i}^C$, ${\pi_i}^B > {\pi_i}^C$ always hold; when $k(1+\lambda) > \sqrt{2}$, ${p_f}^A > {p_f}^B$, otherwise, ${p_f}^A < {p_f}^B$, when $4 + k^2(1+\lambda)(\lambda k^2(1+\lambda)^2 + m^2 - 4(1+\lambda)) > 0$, ${p_f}^A > {p_f}^C$, otherwise, ${p_f}^A < {p_f}^C$; when $k^2(1+\lambda) < 1$, ${q_i}^A > {q_i}^B$, ${p_i}^A < {p_i}^B$, ${\pi_i}^A > {\pi_i}^B$, otherwise, ${q_i}^A < {q_i}^B$, ${p_i}^A > {p_i}^B$ ${\pi_i}^A < {\pi_i}^B$; when $-2 - \lambda k^4(1+\lambda)^2 + k^2(5 - m^2 + 2\lambda + \lambda^2) > 0$, ${q_i}^A > {q_i}^C$, ${p_i}^A < {p_i}^C$, ${\pi_i}^A > {\pi_i}^C$, otherwise, ${q_i}^A < {q_i}^C$, ${p_i}^A > {p_i}^C$, ${\pi_i}^A < {\pi_i}^C$.

Corollary 2-2. The independent collector impedes the collection efforts and green technology investment. Besides, in order to improve the collection efforts, green technology investment, the collection quantity and the profit of the formal channel (τ, v, q_f, π_{fc}, π_{fr}, π_f), the formal recycler rather than the independent collector is better to implement collection efforts.

When comparing Model A with Model B and jointly comparing the three models, Corollary 2-2 can be derived. Corollary 2-2 reveals a possible misunderstanding that recyclers can get rid of the collection efforts once outsourcing collection campaigns to independent collectors. Considering the collection quantity and the profit of the formal channel (q_f, π_{fc}, π_{fr}, π_f), formal recyclers should positively implement collection efforts regardless of the formal channel structure.

Corollary 2-3. In order to maximize the collection efforts and green technology investment, and the collection quantity and the profit of the formal channel, Model A is always the optimal model structure while Model C is the worst. However, Model C is not the worst model structure for consumers.

Considering the improved collection quantity and profit, the formal channel structure in Model A should be adopted in a dual-channel formal and informal reverse supply chains from the perspective of the formal channel side. Meanwhile, Model A can lead to the highest collection efforts and green technology investment, which are beneficial for the environmental and economic sustainability. It is noteworthy that Model C is always the worst for the formal channel side. Since ${p_f}^B < {p_f}^C$ and ${p_i}^B < {p_i}^C$ always hold, the unit profit of consumers never be the smallest in Model C. Therefore, it concludes that Model C wouldn't be the last choice while Model B won't be the optimal choice of consumers. Corollary 2-3 indicates an interesting finding that there may exist a conflict of interest between the formal channel side and the consumers.

2.6 Optimal unit subsidy

Specific to China, it is investigated that nearly 80% of the domestically generated e-waste is passed into informal recycling channel (Chi et al., 2014). Chinese government has launched a subsidy for formal recyclers in order to promote the treatment of e-waste that comply with environmental requirements (Gu et al., 2017; CHEARI, 2018). Taking the environmental pollution and the health damage of informal channel into account, minimizing informal activities and even expelling them will be highly appreciated and can be treated as one of the goals of the subsidy. Accordingly, this paper optimizes the subsidy from the aspect of minimizing the profit of the informal channel.

Proposition 2-8. In order to minimize the profit of the informal channel, the optimal unit subsidies are $s^{*A} = \frac{1-k^2(1+\lambda)+(3-m^2-\lambda k^2(1+\lambda))\alpha_i}{1-k^2(1+\lambda)} - \tau_0$, $s^{*B} = \frac{1-k^2(1+\lambda)+(5-m^2-\lambda k^2(1+\lambda))\alpha_i}{1-k^2(1+\lambda)} - \tau_0$ and $s^{*C} = \frac{1-\lambda k^2+\left(5-\lambda k^2(1+2\lambda)-m^2\right)\alpha_i}{1-\lambda k^2} - \tau_0$ in the three models respectively.

Corollary 2-4. From the aspect of minimizing informal channel's profit with the minimum unit subsidy, it is concluded that Model B performs the best, and Model C performs better than Model A when the influence magnitudes of collection efforts and/or green technology investment are significant. Otherwise, the opposite stands.

Areas of the smallest optimal unit subsidy among the three models can be depicted in Figure 2-2. Even though the subsidy for formal recyclers can benefit the formal channel side, the fiscal deficit caused by a large number of subsidies deserves high attention. Therefore, minimizing informal activities with the lowest unit subsidy is preferred by the government. Given the external circumstance, Corollary 2-4 is helpful for the promotion of the preferred formal channel structure.

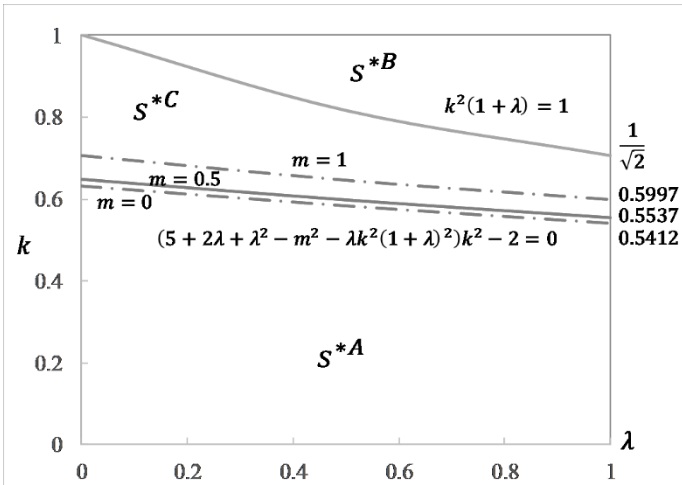

Figure 2-2 Areas of the smallest optimal unit subsidy among the three models

2.7 Conclusion

This paper aims at studying the influences of the subsidy for formal recyclers on both formal and informal reverse channels considering the collection efforts and green technology investment of the formal channel. Three formal channel structures with different collectors or collection efforts implementers are modelled. This paper first derives the collection quantity functions and the profit functions of different entities by introducing collection efforts and green technology investment. Then the equilibrium results for the three models are solved. Accordingly, this research analyzes the influences of the subsidy and other parameters, compares the results differences of the three models and derives the optimal unit subsidies for them. Moreover, the optimal formal channel structures are provided from different aspects, including the minimum unit subsidy, the extent of collection efforts and green technology investment.

The contributions of this paper are summarized as follows. Firstly, the paper studies the influence mechanism and path of the subsidy and reveals its complex influences. Even though the subsidy is beneficial for the formal channel side, it may also promote the development of the informal channel in specific conditions. And the subsidy not always induce a fiercer price competition between the formal and informal channels. The optimal subsidies are also calculated given the goal of minimizing the profit of the informal channel. Secondly, the decisions and preference of implementing collection efforts and green technology investment are explored for the formal channel side. The formal channel side prefers to improve both the collection efforts and green technology investment under the subsidy. And the decisions of implementing either collection efforts or green technology investment should be highly deliberated given different formal channel structures in order to avoid stimulating informal activities. Thirdly, the study compares the differences of the three models and concludes that the formal recycler is more suitable than the independent collector to conduct collection campaigns and to implement collection efforts in order to improve collection efforts and green technology investment. Lastly, this paper analyzes the optimal formal channel structures and indicates the conflict of interests of different entities when deciding the optimal formal channel structure. For the formal recyclers, Model A is always the optimal model structure while Model C is the worst. However, Model C is not the worst model structure for consumers. For the government (from the aspect of minimizing the informal channel's profit with the minimum unit subsidy), Model B performs the best, and Model C performs better than Model A when the influence magnitudes of collection efforts and/or green technology investment are significant. Otherwise, the opposite stands.

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Chapter 3 Integration of formal and informal RSCs

3.1 Introduction

Regarding the informal RSC, it has long been criticized for the environmental pollution and workers' health damage (Medina, 2000). However, the benefits of informal RSC should be noted as well. Informal RSC undertakes intensive collection and small-scale recycling activities. The former activity can significantly contribute to waste collection and the reduction of landfill volume, meanwhile to provide working opportunities for the low-income group (Wilson et al., 2012; Linzner and Lange, 2013). However, the latter activity pollutes the environment and damages the workers' health due to its dated and environmentally unfriendly technologies (Medina, 2000). The collection activity mostly be conducted by peddlers, waste pickers, etc with their tricycles while family backyard workshops always undertake the recycling activity in several notorious areas in China, such as Taizhou of Zhejiang, Guiyu of Guangdong and Linyi of Shandong Province (Cao et al., 2016a; Yang et al., 2008). And majority of the collected e-waste are sent to those informal recycling areas.

Comprehensively considering the benefits and harmfulness, as well as the players differences, one constructive proposal that we claim is to incorporate those collection activities into the formal RSC while expelling informal recycling activities from the market. Denoting peddlers, waste pickers, etc that aiming mainly to collect e-waste as informal collectors and family backyard workshops as informal recyclers, our specific claim becomes incorporating informal collectors and expelling informal recyclers. It has been confirmed that incorporating informal collectors can increase the collection rate with a minimized overall collection cost, which is much cheaper than expelling informal collectors through strict policy or through fierce market competition (Campos, 2014; Li and Tee, 2012). Besides, incorporating the informal collectors (waste pickers activities) into the formal waste recovery system (instead of either ignoring or prohibiting their participation) is beneficial for economical, environmental and social sustainability (Besiou et al., 2012). Moreover, incorporating informal collectors into the formal channel can benefit the income stability and social identity of informal collectors. Meanwhile, expelling informal recyclers can reduce environmental pollution through eliminating the low-end backward equipment and technology. It is noteworthy that up to 18 million people are documented to be active in informal waste treatment in China (Gu et al., 2016), which makes the formalization of informal collectors of great practical significance. In this end, this study is conducted to comprehensively analyze the possibility and extent of formalizing informal collectors, and explore the effective interventions.

The remainder of this study is organized as follows. A literature review is provided in section 2. Section 3 presents the model assumptions and notations. Section 4 and section 5 comes up with the details of the benchmark model and the policy model. The influences of different factors and the effects of different policies are analyzed in these sections. Thereafter, the formalization extent for the context of China is studied and the effects of different policies are visualized based on numerical data in section 6. Finally, we summarize our main conclusions in section 7.

3.2 Literature Review

Two closely related literature streams including supply chain coordination and the formalization of informal sectors are reviewed successively.

Supply chain coordination is widely involved in RSC or CLSC. In terms of vertical coordination of different levels in a RSC, a fruitful of studies have been conducted. For instance, Zhang and Zhang (2015) studied the coordination of a RSC with government subsidies and marketing strategies and indicated the achieved socially optimal outcome. Focusing on horizontal coordination, Feng et al. (2017) proposed a two-part tariff contract and a profit-sharing contract respectively to coordinate a traditional and an online recycling channel. Savaskan and Wassenhove (2006), Jena and Sarmah (2014), and He et al. (2019) separately analyzed the coordination of two collection channels dominated respectively by two retailers, two manufacturers, or one manufacturer and one retailer.

The formalization of informal channels has been a hotspot worldwide. Velis et al. (2012) and Serrona et al. (2014) separately developed two analytical frameworks to evaluate and analyze the integration and formalization of informal sectors. By using an analytical framework and tool named “InteRa”, the integration of informal recycling sector had been analyzed in Pakistan and Madagascar as case studies (Masood and Barlow, 2013; Andrianisa et al., 2017). Several quantitative studies also focus on the integration of formal and informal RSC. Besiou et al. (2012) investigated the effect of informal collectors using system dynamics methodology and conclude that incorporating informal collectors into the formal RSC performs better in economic, environmental, and social sustainability than ignoring or prohibiting their participation. Similar to the model of Besiou et al. (2012), Ghisolfi et al. (2016) analyzed the impact of legal incentives and the bargaining power obtained by the volume of collected waste on the effective formalization of waste pickers in the context of Brazil. Based on a mixed integer multi-objective linear programming model, Li and Tee (2012) studied the influence of a designed penalty for the producer according to emissions (greenhouse gas and lead) of the informal RSC on integrating the formal and informal RSCs. Li et al. (2017)

demonstrated the benefit of coordinating the formal and informal RSCs through a game theoretic model and provided a two-tariff pricing contract to coordinate the dual RSCs.

Unlike these previous works, the study aims to reveal the formalization extent of informal collectors and to indicate the effective interventions of the government (e.g. subsidies and penalties). The subsidy delay (time between apply and receive the subsidy) that used to represent the response speed of subsidy system is firstly included in this study. As investigated, there is a tedious process from the application to the obtain of the subsidy for formal processing enterprises in China (Cao et al., 2016b). In summary, our research features innovation points as follows: 1) To the best of our knowledge, our study is the first focus on the formalization extent of informal collectors in a dual channels consisted of competitive formal and informal RSCs; 2) Both the subsidies and penalties on formal (informal) collectors or recyclers are included and the effects of these policies are analyzed and compared. In addition, this study also includes the bargaining power between different recyclers on selling recycled materials and introduces the subsidy delay to represent the response speed of subsidy system.

3.3 Model assumptions and notations

In this study, we consider a dual-channel model consisting of formal and informal collection and recycling activities simultaneously (Figure 3-1).

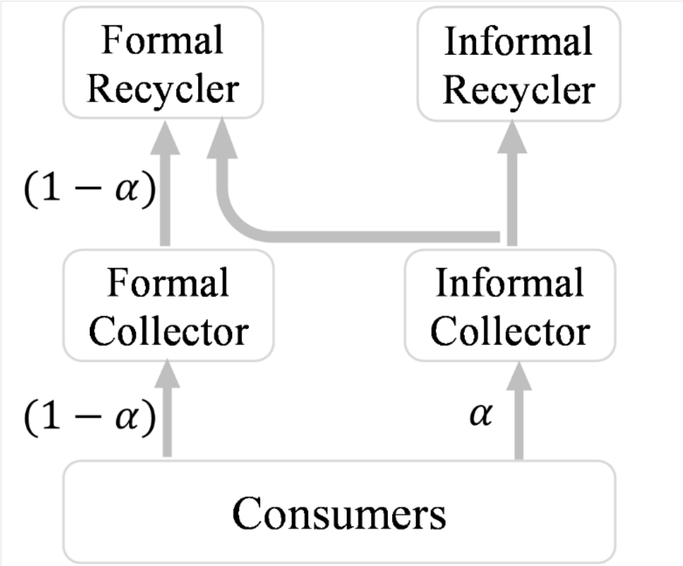

Figure 3-1 Structure of the considered problem

Table 3-1 lists the notations used in this study. In the rest of this paper, some assumptions are made.

Table 3-1 Notations

Parameter	Definition
v	reluctance of sending e-waste to formal recyclers, $0<v<1$.
α	Collected quantity of same kind e-waste by informal collectors, $0\leq\alpha\leq1$.
β	Bargaining power of the informal recycler, $0\leq\beta\leq1$.
θ	Unit collection price of informal collectors when the collected quantity is α, $0 \leq \theta$.
c_1	Unit minimum recycling cost.
c_2	Unit additional cost of the formal recyclers.

P	Unit sale price of recycled materials from the formal recyclers.
X_{ic}	Unit penalty on informal collectors when they send e-waste to informal recyclers.
X_{ir}	Unit penalty on informal recyclers.
S_{ic}	Unit subsidy to informal collectors when they send e-waste to formal recyclers.
S_{fr}	Unit subsidy to formal recyclers. *
R	Subsidy delay (due to time delay of paying the subsidy to formal recyclers, represented as Discount rate).
P_i	Unit payoff to informal collectors paid by informal recyclers.
P_f	Unit payoff to informal collectors paid by formal recyclers.
q_i	The quantity of e-waste recycled by informal recyclers.
q_f	The quantity of e-waste recycled by formal recyclers.
q_{if}	E-waste sent from informal collectors to formal recyclers.

* note that if the subsidy for formal recyclers only targets the e-waste from informal collectors, formal recyclers will never accept the e-waste from formal collectors. Even they accept these e-waste, they will cheat and claim that these e-waste are from informal collectors to gain the subsidy. Therefore, the target of this subsidy is the total quantity of e-waste recycled by formal recyclers.

Assumption 1. The total amount of same kind of e-waste can be collected by formal and informal collectors is 1.

Generally, three direct destinations for e-waste are collected by either formal or informal collectors directly (including all kinds of collection activities, such as door-to-door collection, retailer collection), disposed together with municipal solid waste directly and hibernated at home. The hibernation is a temporary activity and the hibernated e-waste will finally flow to the other two destinations. Therefore, only the e-waste in the former two destinations are treated as "the e-waste can be collected" in this study. Because of the potential value, the directly disposed quantity of e-waste is small. Moreover, even being disposed of directly, the e-waste can always be collected indirectly by waste-pickers, one kind of informal collectors.

Assumption 2. Collectors make their decisions based on last period payoff paid by recyclers. And the recyclers decide current payoff based on the completed collection activities in current period.

Given the last period payoff paid by recyclers, there must be a set of collection price and collected quantity as an optimal solution for either formal or informal collectors. Given the collection price of informal collectors as θ ($0\leq\theta$) and the collection price of formal collectors, the corresponding collected quantity of same kind of e-waste as α and $(1-\alpha)$ for informal and formal collectors can be determined according to assumption 1. It is noteworthy that the collection prices vary among informal collectors. For instance, different door-to-door collectors may offer different collection prices to consumers. Besides, the collection prices between a door-to-door collector and waste pickers may vary a lot since the waste pickers pay zero apart from labor efforts. In this study, the collection prices of informal collectors are assumed continuous and evenly distributed.

Based on the completed current collection activities, the amount of e-waste collected by both formal and informal collectors are determined. According to the known collected quantity, the formal and informal recyclers will compete with each other in order to maximize their profit.

Assumption 3. Informal collectors have incentives to send the collected e-waste to formal recyclers.

Informal collectors are always treated as pure profit-seekers. Comparing to formal recyclers, informal recyclers would pay informal collectors more to gain their e-waste. Under such condition, the informal collector prefers to send e-waste to informal recyclers. However, the payoff by informal recyclers is highly relevant to the quantity and quality of e-waste, which are uncertain and influenced by the up-front, such as the attitude and behavior of consumers. Hence, the revenue of informal collectors is uncertain and risky if they choose to do business with informal recyclers. Besides, informal collectors and informal recyclers are always regarded as dirty, unregulated and environmental trouble-maker (Wilson et al., 2006; Ezeah et al., 2013). Relevant practitioners often feel inferior to others due to lack of social identity. In contrast, if being formalized, the revenue risk of informal collectors can be reduced and the social identity of them can be improved even though the direct unit payoff is relatively low. For instance, the formal recycler can provide a minimum salary to informal collectors to reduce their income risk and uncertainty once being formalized. Considering these, this study assumes that informal collectors have incentives to send the collected e-waste to formal recyclers to a certain extent.

Assume the reluctance of sending e-waste to formal recyclers as v, and v is a discounted rate of the collection price θ. Given the payoff paid by formal and informal recyclers as P_f and P_i, the utility of informal collectors can be denoted as $U_{f(\theta)} = P_f - v\theta$ or $U_{i(\theta)} = P_i - \theta$ when sending e-waste to formal or informal recyclers.

Considering informal collectors only trade with some economic gains, it can be concluded that the informal collector will send e-waste to formal recyclers only the following condition is satisfied $\{\theta \big| U_{f(\theta)} \geq U_{i(\theta)}, U_{f(\theta)} \geq 0\,, (P_f - \theta) \geq 0\,\}$. Likewise, they will choose informal recyclers as a destination when the utility satisfies $\{\theta \big| U_{i(\theta)} \geq U_{f(\theta)}, U_{i(\theta)} \geq 0\}$.

Accordingly, when $P_f > \frac{P_i}{2-v}$, the informal collector who offers collection price among $[\frac{P_i - P_f}{1-v},\ P_f]$ will choose formal recyclers as their destination, while the informal collector who offers collection price among $[\,0,\ \frac{P_i - P_f}{1-v}]$ prefers sending e-waste to informal recyclers. When $vP_i < P_f \leq \frac{P_i}{2-v}$, and $P_f \leq vP_i$, the informal collector will never consider formal recyclers as their destination while the informal collector offers collection price among $[0,\ \frac{P_i - P_f}{1-v}]$ and $[0,\ P_i]$ will choose informal recyclers.

Assumption 4. Formal collectors will only send the collected e-waste to formal recyclers. Informal collectors have two choices, either sending the collected e-waste to formal or informal recyclers. And both of them will clean up the stock of all the collected e-waste in each period.

Based on above assumptions, the total amount of e-waste received by formal and informal recyclers can be summarized as follows:

$$q_f = \begin{cases} \alpha \frac{(2-v)P_f - P_i}{P_f(1-v)} + (1-\alpha) & P_f > \frac{P_i}{2-v} \\ 1-\alpha & vP_i < P_f \leq \frac{P_i}{2-v} \\ 1-\alpha & P_f \leq vP_i \end{cases} \tag{3-1}$$

$$q_i = \begin{cases} \alpha \frac{(P_i - P_f)}{P_f(1-v)} & P_f > \frac{P_i}{2-v} \\ \alpha & vP_i < P_f \leq \frac{P_i}{2-v} \\ \alpha & P_f \leq vP_i \end{cases} \tag{3-2}$$

Assumption 5. The formal recycler will offer the same payoff to either the formal or informal collectors.

Apparently, the unequal payoff will disorder the participation of either the formal or informal collectors.

Assumption 6. Compared to formal recyclers, a lower bargaining power in selling the recycled materials is assigned to informal recyclers.

Generally, the formal recycler is the one who has advanced equipment and technology, with which more pure and higher quality materials can be recycled. Besides, upon the promotion of formal recycling from the governments' side, the possibility and efficiency of the formal recycler to get access to sufficient cash flow can be improved. In contrast, the informal recycler is always recognized as backyard working associated with dated technology and small scale (Wilson et al., 2006; Chi et al., 2011; Ezeah et al., 2013). The higher quality of recycled materials and the sufficient cash flow make the formal recycler a higher bargaining power on selling recycled materials compared to informal recyclers.

Given the sale price of the formal recycler as P, the sale price of the informal recycler will be βP given a lower bargaining power as β. Therefore, the average benefit of the informal and formal recyclers are $B_i = \beta P - P_i - c_1$ and $B_f = P - P_f - c_1 - c_2$, where c_1 is the minimum recycling cost for each recycler and c_2 is the additional cost for formal recyclers. The additional cost mainly consists of environmental protection and waste treatment cost. The average benefit B_i and B_f are both no less than zero, otherwise, neither formal nor informal recyclers will conduct the recycling activity.

Combining with the quantity, the profit function of the formal and informal recyclers are as follows:

$$\pi_f = \left(P - P_f - c_1 - c_2\right) * \begin{cases} \alpha \frac{(2-v)P_f - P_i}{P_f(1-v)} + (1-\alpha) & P_f > \frac{P_i}{2-v} \\ 1-\alpha & vP_i < P_f \leq \frac{P_i}{2-v} \\ 1-\alpha & P_f \leq vP_i \end{cases} \quad (3\text{-}3)$$

$$\pi_i = (\beta P - P_i - c_1) * \begin{cases} \alpha \frac{\left(P_i - P_f\right)}{P_f(1-v)} & P_f > \frac{P_i}{2-v} \\ \alpha & vP_i < P_f \leq \frac{P_i}{2-v} \\ \alpha & P_f \leq vP_i \end{cases} \quad (3\text{-}4)$$

When $vP_i < P_f \leq \frac{P_i}{2-v}$ and $P_f \leq vP_i$, informal collectors will never send the collected e-waste to formal recyclers, which means the formalization extent is zero under such condition. Only when $P_f > \frac{P_i}{2-v}$, the informal collector chooses to send e-waste to formal recyclers, and the formalization extent is varied accordingly. Considering the main target of this study, we will focus on the condition of $P_f > \frac{P_i}{2-v}$ in the following sections.

3.4 Benchmark model

The formal recycler is considered as the Stackelberg leader in the competition with informal recyclers. In the formal recycler Stackelberg game model, the formal recycler decides its optimal price P_f first. Then, the informal recycler makes its pricing decision P_i based on the optimal price P_f. The model is formulated as follows:

$$\begin{cases} First: \max \pi_f(P_f) \\ Then: \max \pi_i(P_i) \\ \quad s.t. \quad P_f > \frac{P_i}{2-v} \end{cases} \quad (3\text{-}5)$$

Proposition 3-1 (Proof in Appendix C): When $\sqrt{\frac{\alpha(P-c_1-c_2)(\beta P-c_1)}{2(1-v)(1-\alpha)+\alpha(3-2v)}} > \frac{\beta P-c_1}{3-2v}$ is satisfied, the optimal price are $P_f = \sqrt{\frac{\alpha(P-c_1-c_2)(\beta P-c_1)}{2(1-v)(1-\alpha)+\alpha(3-2v)}}$, and $P_i = \frac{\beta P-c_1}{2} +$

$\frac{1}{2}\sqrt{\frac{\alpha(P-c_1-c_2)(\beta P-c_1)}{2(1-v)(1-\alpha)+\alpha(3-2v)}}$, the received e-waste by the formal and informal recyclers are as follows:

$$q_f = -\frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1)[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2}} + \frac{\alpha(3-2v)}{2(1-v)} + (1-\alpha) \qquad (3\text{-}6)$$

$$q_i = \frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1)[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2}} - \frac{\alpha}{2(1-v)} \qquad (3\text{-}7)$$

$$q_{if} = -\frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1)[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2}} + \frac{\alpha(3-2v)}{2(1-v)} \qquad (3\text{-}8)$$

Corollary 3-1. A high bargaining power of informal recyclers acts as an obstacle for the formalization activity.

Proof of Corollary 3-1.

$\frac{\partial q_f}{\partial \beta} < 0$, $\frac{\partial q_{if}}{\partial \beta} < 0$, $\frac{\partial q_i}{\partial \beta} > 0$. The partial differential results indicate that the e-waste recycled by formal recyclers decreases as the increasing bargaining power of informal recyclers.

In order to promote the formalization activity, it is important to comprehend and restrict the bargaining power of the informal recycler. On one hand, the government can regulate the recycling materials market directly by introducing recycled material label. Only the recycled materials with the label can be freely traded in the market. On the other hand, the development of alliances between the formal recycler and the market can be promoted from the government perspective. A recycled material label and a strong alliance may decrease the bargaining power of informal recyclers through influencing their sales convenience.

Corollary 3-2. Formalization extent of the informal collector decreases as the increasing additional cost of formal recyclers.

Proof of Corollary 3-2.

It can be derived that $\frac{\partial q_{if}}{\partial c_2} < 0,\ \frac{\partial q_f}{\partial c_2} < 0,\ \frac{\partial q_i}{\partial c_2} > 0.$

The additional cost mainly consists of environmental protection and waste treatment cost. In terms of policy, a cost sharing system can be a possible countermeasure. The government can undertake the additional cost directly or share the cost through subsidy or tax reduction. In terms of technology, more cost-efficient technologies should be developed and adopted by formal recycling activity. By perfecting the management system and adopting advanced technology, it is anticipated that a higher formalization extent of informal collectors can be achieved due to the decreased additional cost.

Corollary 3-3. A high sale price enlarges the payoff to informal collectors ($\frac{\partial P_f}{\partial \mathrm{P}} > 0$, $\frac{\partial P_i}{\partial \mathrm{P}} > 0$), while a high minimum recycling cost has the opposite influence ($\frac{\partial P_f}{\partial c_1} < 0, \frac{\partial P_i}{\partial c_1} < 0$). For the collectors, a high sale price and a low minimum recycling cost are preferred. However, the quantity of e-waste recycled by either formal or informal recyclers is uncertain.

Corollary 3-4. Increasing the e-waste collected by the informal collector (α) (increasing the reluctance of sending e-waste to formal recyclers *v*) will enlarge the payoff paid by both the formal and informal recyclers. And the change of payoff paid by the formal recycler is as twice as the one paid by the informal recycler.

Proof of Corollary 3-4.

It can be derived that

$\frac{\partial P_f}{\partial \alpha} > 0, \frac{\partial P_i}{\partial \alpha} > 0$, and $\frac{\partial P_f}{\partial \alpha} = 2\frac{\partial P_i}{\partial \alpha}$;

$\frac{\partial P_f}{\partial v} > 0$, $\frac{\partial P_i}{\partial v} > 0$, and $\frac{\partial P_f}{\partial v} = 2\frac{\partial P_i}{\partial v}$.

However, it is unclear whether $\frac{\partial q_{if}}{\partial \alpha}$, $\frac{\partial q_f}{\partial \alpha}$, $\frac{\partial q_i}{\partial \alpha}$, $\frac{\partial q_{if}}{\partial v}$, $\frac{\partial q_f}{\partial v}$ or $\frac{\partial q_i}{\partial v}$is bigger than zero or not.

Increasing the collected quantity of e-waste enlarges the market share of the informal collector. To attract informal collectors, the formal and informal recyclers have to compete with each other fiercely. Such competition will enlarge the economic burden of the formal recycler, and damage the sustainable development of formal reverse logistics. It is noteworthy that the quantity of e-waste recycled by the formal recycler is not yet clear. This result gives a hint to the formal collection and recycling industry, that is even though the formalization of informal collectors is a good choice, informal collectors should not be the only one in the market. Moderate competition, in other words, a certain number of formal collectors are necessary to reduce the economic burden.

To reduce the reluctance of sending e-waste to formal recyclers, publicization and education will play a big role. Most of the studies have pointed out the importance of publicization and education in waste management from the public awareness perspective (Qu et al., 2013; Sun et al., 2015; Cao et al., 2016b). In terms of the specific publicization and education content, it can specify the stabilized revenue and improved social identity for informal collectors if being formalized. In addition, it will be more convincing if the local or central government can actively and openly support and endorse the formalization.

3.5 Subsidy and penalty policy model

In order to promote the formalization of informal collectors, several policies are proposed and discussed. They are the penalty on informal collectors based on the quantity of e-waste sent to informal recyclers, penalty on informal recyclers based on the recycled quantity, subsidy to informal collectors based on the quantity of e-waste sent to formal recyclers, and subsidy to formal recyclers based on the recycled quantity.

Similar to section 3.4, we only focus on the condition when the informal collectors sending e-waste to formal recyclers.

The summarized optimal results are as follows:

$$P_f{}' = \sqrt{\frac{\alpha(P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic})(\beta P-c_1-X_{ic}-X_{ir})}{2(1-v)(1-\alpha)+\alpha(3-2v)}} - S_{ic} \quad (3\text{-}9)$$

And $P_i' = \frac{1}{2}\sqrt{\frac{\alpha\left(P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic}\right)(\beta P-c_1-X_{ic}-X_{ir})}{2(1-v)(1-\alpha)+\alpha(3-2v)}} + \frac{\beta P-c_1+X_{ic}-X_{ir}}{2}$ (3-10)

Meanwhile,

$$q_f{}' = -\frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1-X_{ic}-X_{ir})[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic}}} + \frac{\alpha(3-2v)}{2(1-v)} + (1-\alpha) \quad (3\text{-}11)$$

$$q_i{}' = \frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1-X_{ic}-X_{ir})[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic}}} - \frac{\alpha}{2(1-v)} \quad (3\text{-}12)$$

$$q_{if}{}' = -\frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1-X_{ic}-X_{ir})[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic}}} + \frac{\alpha(3-2v)}{2(1-v)} \quad (3\text{-}13)$$

Where the condition of $\sqrt{\frac{\alpha(P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic})(\beta P-c_1-X_{ic}-X_{ir})}{2(1-v)(1-\alpha)+\alpha(3-2v)}} > \frac{\beta P-c_1-X_{ic}-X_{ir}}{3-2v}$ should be satisfied.

In other words, $\beta' < \frac{\alpha(3-2v)^2(P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic})}{P[2(1-v)(1-\alpha)+\alpha(3-2v)]} + \frac{c_1+X_{ic}+X_{ir}}{P}$,

$$v' < \frac{3}{2} - \frac{(\beta P-c_1-X_{ic}-X_{ir})+}{4\alpha\left(P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic}\right)} - \frac{\sqrt{(\beta P-c_1-X_{ic}-X_{ir})^2-4\alpha(1-\alpha)(P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic})(\beta P-c_1-X_{ic}-X_{ir})}}{4\alpha\left(P-c_1-c_2+\frac{S_{fr}}{R}+S_{ic}\right)}$$

should be satisfied.

The total profits of the formal and informal recyclers are:

$$\pi_f' = \left(P - P_f{}' - c_1 - c_2 + \frac{S_{fr}}{R}\right) * q_f' \qquad (3\text{-}14)$$

$$\pi_i{}' = (\beta P - P_i{}' - c_1 - X_{ir}) * q_i{}' \qquad (3\text{-}15)$$

Note that the upper comma is used to distinguish the results of this section with section 3.4.

Corollary 3-5. Both subsidy and penalty policies are conducive to provide a low threshold for the achievement of formalization.

Comparing β' and β, v' and v, we can find that both the boundary of β' and v' are expanded ($\beta' \geq \beta$, $v' \geq v$). β' or β is the bargaining power of the informal recycler, v' or v is the reluctance of sending e-waste to formal recyclers. The expanded β' and v' indicate a lower threshold for the formalization of informal collectors. In developing countries, the environmental awareness of the whole society is low, the supervision system is in its infancy, and the education and publicization of formal channel are not yet mature. All of these may result in a high bargaining power of informal recyclers and a high reluctance of informal collectors. As a consequence, it becomes impossible to implement the formalization of informal collectors. However, the subsidy or penalty policies provide a lower threshold for the achievement of the formalization activity.

Corollary 3-6. Both the subsidy and penalty policies can promote the formalization of informal collectors. And there is no difference between the subsidy to informal collectors and formal recyclers (penalty on informal collectors or informal recyclers) regarding the change of recycling quantity.

Proof of Corollary 3-6.

$$\frac{\partial q_f{}'}{\partial S_{ic}} = \frac{\partial q_f{}'}{\partial(\frac{S_{fr}}{R})} > 0, \frac{\partial q_f{}'}{\partial X_{ic}} = \frac{\partial q_f{}'}{\partial X_{ir}} > 0;$$

$$\frac{\partial q_{if'}}{\partial S_{ic}} = \frac{\partial q_{if'}}{\partial(\frac{S_{fr}}{R})} > 0, \frac{\partial q_{if'}}{\partial X_{ic}} = \frac{\partial q_{if'}}{\partial X_{ir}} > 0;$$

$$\frac{\partial q_{i'}}{\partial S_{ic}} = \frac{\partial q_{i'}}{\partial(\frac{S_{fr}}{R})} < 0, \frac{\partial q_{i'}}{\partial X_{ic}} = \frac{\partial q_{i'}}{\partial X_{ir}} < 0.$$

Corollary 3-7. Subsidy (Penalty) policy increases (decreases) the payoff paid by informal (formal) recyclers. And subsidy to formal recycler increases the payoff paid by formal recyclers while the penalty on informal recycler decreases the payoff paid by informal recyclers. Moreover, the payoff paid by formal (informal) recyclers increases (decreases) rapidly when the subsidy (penalty) target is formal (informal) recyclers rather than informal collectors.

Proof of Corollary 3-7.

$$\frac{\partial P_{f'}}{\partial X_{ic}} = \frac{\partial P_{f'}}{\partial X_{ir}} < 0, \frac{\partial P_{f'}}{\partial(\frac{S_{fr}}{R})} > 0, \frac{\partial P_{f'}}{\partial(\frac{S_{fr}}{R})} > \frac{\partial P_{f'}}{\partial S_{ic}};$$

$$\frac{\partial P_{i'}}{\partial S_{ic}} = \frac{\partial P_{i'}}{\partial(\frac{S_{fr}}{R})} > 0, \frac{\partial P_{i'}}{\partial X_{ir}} < 0, \frac{\partial P_{i'}}{\partial X_{ir}} < \frac{\partial P_{i'}}{\partial X_{ic}}.$$

Corollary 3-8. Subsidy delay (represented as discount rate R) hinders the formalization of informal collectors.

Proof of Corollary 3-8.

After calculation, $\frac{\partial q_{if'}}{\partial \mathrm{R}} < 0$, $\frac{\partial q_{f'}}{\partial \mathrm{R}} < 0$, $\frac{\partial q_{i'}}{\partial \mathrm{R}} > 0$.

Taking China for example, the Chinese government has launched a subsidy policy for formal collection and recycling activities. However, a tedious process to apply and grant the subsidy has been pointed out (Cao et al. 2016b). If the formal channel plans to try to formalize informal collectors, a simplified and effective subsidy verification and grant system should be developed.

3.6 Numerical model

Regarding the collection of e-waste in China, informal collection and recycling activities are universal. In order to study the formalization extent for the context of China and visualize the effects of different policies, the following numerical data is employed based on the situation of China. It is reported that more than 80% of e-waste collected in China still depend on informal private traders ($\alpha = 0.8$) such as street peddles (Tang and Wang, 2014; Chi et al., 2014). Meanwhile, because of the lack of pressure from the public and the government perspective, the reluctance of sending e-waste to formal recyclers is relatively high ($\upsilon = 0.9$). The environmental protection and waste treatment cost have been argued occupy a huge proportion of the total recycling cost for formal recyclers ($c_2/c_1 = 0.75, c_1 = 0.2, c_2 = 0.15$). The sale price of the formal recycler is standardized as $P = 1$. Besides, considering the lack of regulation and supervision for the market of recycled materials, we consider a relatively high bargaining power of the informal recycler ($\beta = 0.9$). It can be found that these parameters make the condition satisfied in the benchmark model and policy model.

According to the benchmark model, it is calculated that $q_f = 0.359$, $q_{if} = 0.159$, $q_i = 0.641$, $P_f = 0.603$, $P_i = 0.652$, $\pi_f = 0.017$, and $\pi_i = 0.031$.

Only a small part of e-waste will be sent to formal recyclers from informal collectors ($q_{if} = 0.159$) if formalization of informal collectors is promoted, and the total profit of informal recycler is almost twice of the formal recycler.

Then, the effects of independent subsidy or penalty are analyzed respectively based on the given numerical data. We discussed how much the unit subsidy or penalty level is required respectively to promote the formalization to a certain level (Figure 3-2). The results show that if less than 0.6 e-waste recycled by formal recyclers is achieved from the current level (0.359 e-waste), a same unit subsidy or penalty level is required, in other words, the penalty and subsidy have the same efficiency. However, a higher subsidy level is required if more than 0.6 e-waste recycled by formal recyclers is achieved from the current situation (0.359 e-waste). This means that he penalty policy shows a better and more outstanding effectiveness on promoting formalization activity when the formalization extent is high. Besides, as the increased extent of formalization, the increasing trend of the subsidy is accelerated while the increasing trend of penalty slows down. This indicates the decremental effect of subsidy and the incremental effect of penalty on formalization extent. This phenomenon still holds even changing the value of each parameter (Figure3- 3). Moreover, considering the tedious process of subsidy for formal recyclers, the subsidy level is increased by R-fold (Figure 3-2). Apparently, a simplified subsidy process for the formal recyclers may be helpful.

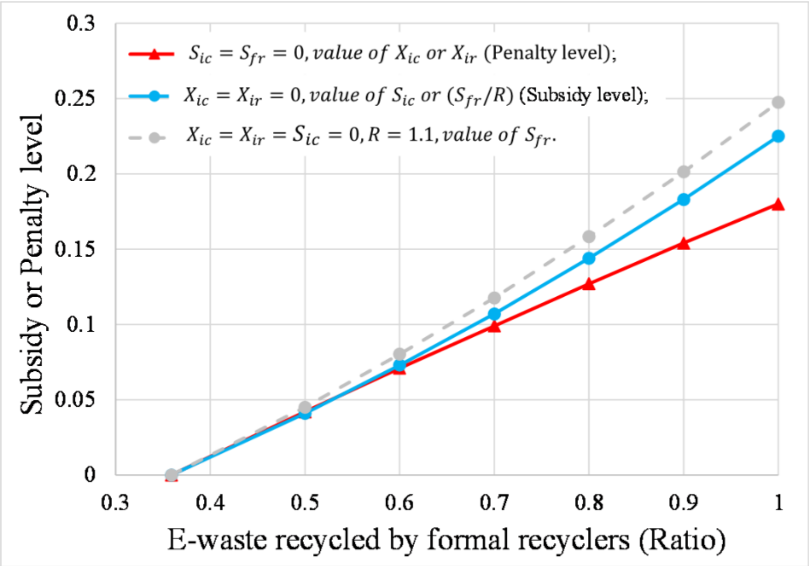

Figure 3-2 Corresponding subsidy or penalty level regarding different formalization extents

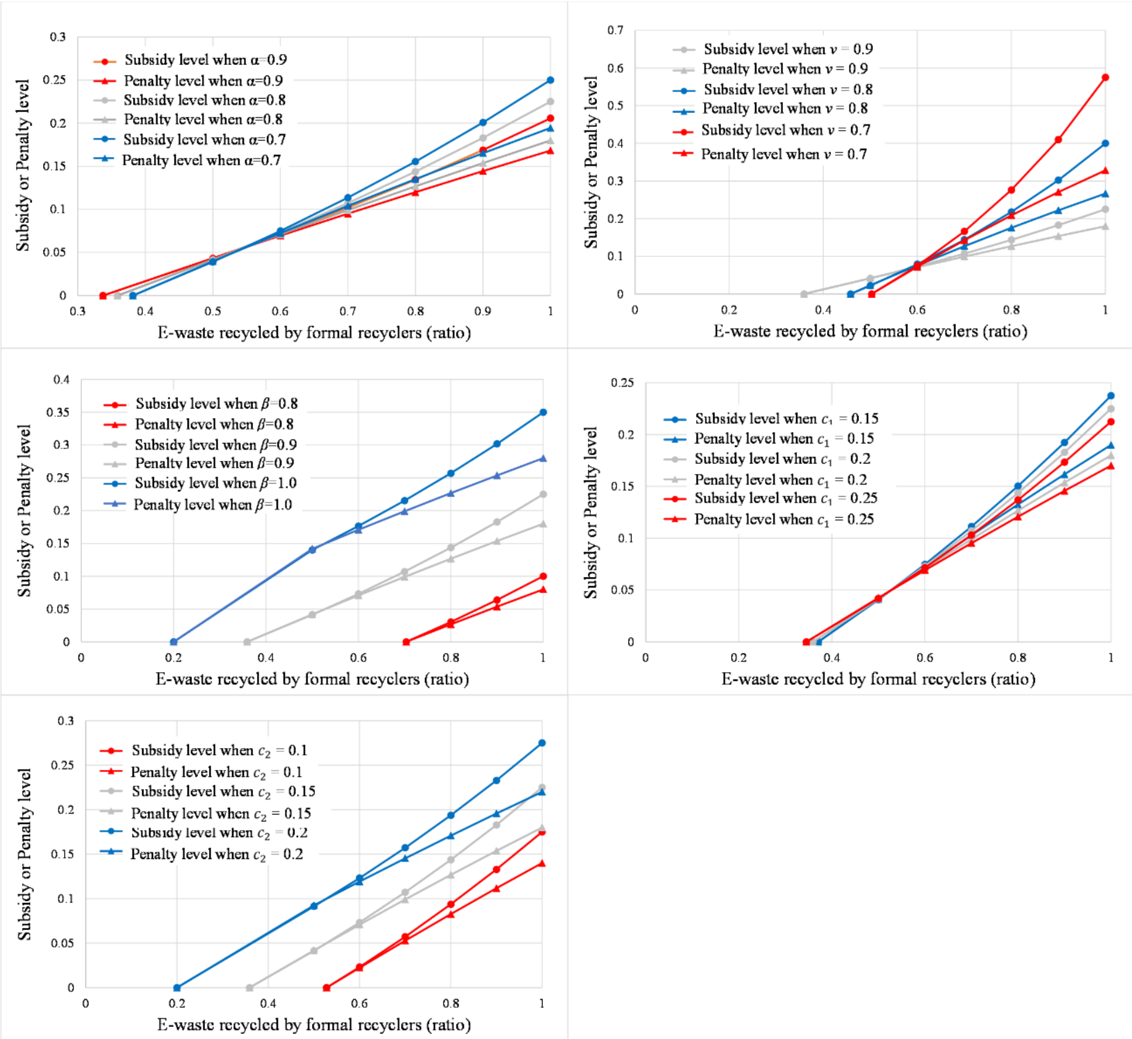

Figure 3-3 Sensitivity study of varying value of each parameter on subsidy or penalty level

In addition, the total profits of the formal and informal recyclers are calculated based on the given data $P = 1, v = 0.9, \beta = 0.9, \alpha = 0.8, c_1 = 0.2, c_2 = 0.15$ (Figure 3-4). The results show that the subsidy and penalty will increase (decrease) the total profit of the formal (informal) recycler. And the effect extent is almost the same regarding the total profit of the informal recycler. However, the subsidy will outperform the penalty in terms of the total profit of the formal recycler. Sensitivity studies regarding varied values of the above parameters show the same conclusion and further prove the robustness of the conclusions (Figure 3-5).

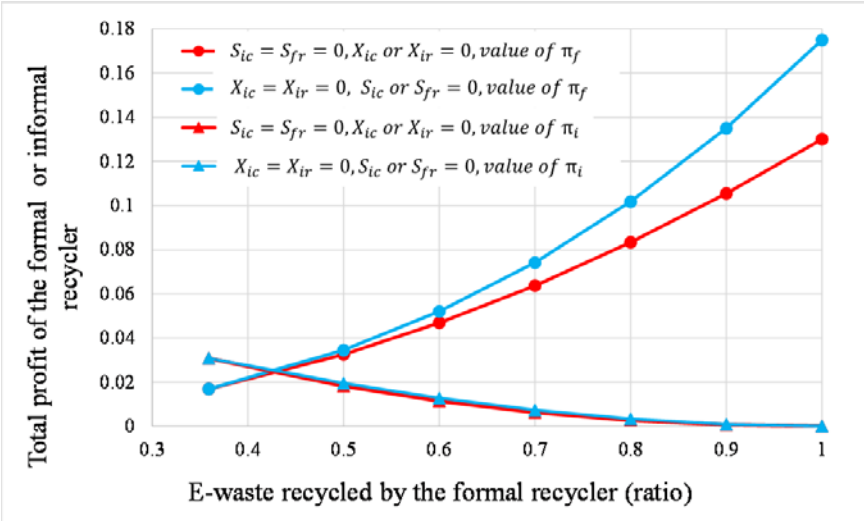

Figure 3-4 Total profit of formal recyclers or informal recyclers under different conditions

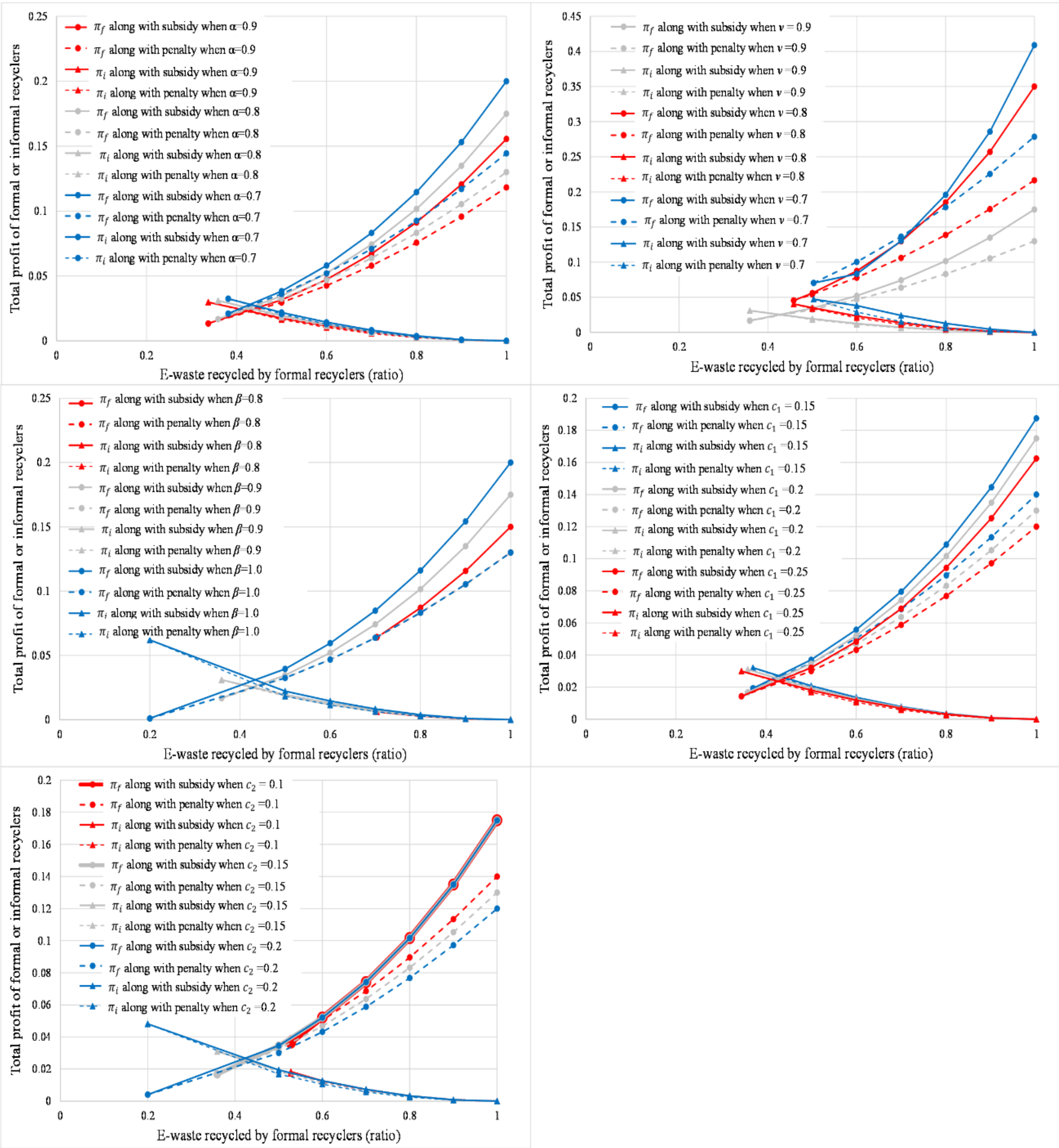

Figure 3-5 Sensitivity study regarding varying value of involving parameters

Considering the difficulty of implementation, the subsidy may be better than the penalty. More important, the subsidy can enlarge the total profit of the formal recycler, with which the enthusiasm of the formal recycler can be inspired and improved. However, it is noteworthy that the huge subsidy may bring a heavy financial burden on sustainable development of formal collection and recycling activities.

3.7 Conclusion

Informal collection and recycling of e-waste are prevailing in many developing countries where formal channel is in its infancy. And formalization of informal collectors has been concluded as beneficial for economical, environmental and social sustainability. Considering these, this study is conducted to quantitatively study the possibility of formalizing informal collectors and analyze the effects of different policies on promoting the formalization activity. It is concluded that formalization of informal collectors is influenced by several factors, including bargaining power, reluctance of informal collectors, and recycling cost of formal channel. This study also indicates the decremental effect of subsidy and the incremental effect of penalty on promoting formalization activity, and points out that the subsidy on informal collectors or formal recyclers (penalty on informal collectors or informal recyclers) presents no difference regarding the formalization extent.

Accordingly, it is expected that the formalization of informal collectors can be promoted by several possible countermeasures, including label the recycled material, build alliances between the formal recycler and the market, develop a cost-sharing system, and launch suitable subsidy or penalty policy. Through these countermeasures, the formalization of informal collectors can be promoted. This study is beneficial for the development of appropriate channels for e-waste collection and recycling, especially in developing countries where informal collectors are abundant.

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Chapter 4 Location planning of recycling centers: case study of WMPs

4.1 Introduction

In RSC, inadequate infrastructure has been highlighted as one prominent issue for the proper treatment of e-waste in China (Li et al., 2012; Polák and Drápalová, 2012; Yin et al., 2014). The problem is much more outstanding for waste mobile phones (WMPs) considering the less attention to them in contrast to focal attention to TVs, refrigerators, washing machines, air conditioners, and other large household appliances (Li et al., 2012; Song et al., 2012; Yu et al., 2010). Guo and Yan (2017) estimated that the annual WMPs will grow to 937.5 million units in China in 2025. WMPs contains a high content of gold, silver, iron, copper, tin and other natural resources. The huge waste quantities and the abundant resources contained make WMPs treatment necessary and challenge the inadequate infrastructures.

The development of adequate infrastructures for WMP treatment has already arisen the government's attention. Since March 1st, 2016, WMPs have been officially included in the new version of "Catalogue of Disposal of Waste Electrical and Electronic Products (2014 Edition)" in China (NDRC, 2015). WMPs, even the subsidy for their treatment has not yet decided, is becoming one of the six kinds subsidized e-waste in China. In order to promote proper treatment of e-waste and perfect the recycling system, the Chinese government has also proposed to establish recycling network according to the principle of rational layout, industrial clusters and ecological environmental protection (OSC, 2011; 2017). The upcoming government subsidy and the fundamental guidance policy will both promote and push the development and scientific planning of WMPs recycling infrastructures and recycling network system.

It is noteworthy that reliable data is one essential prerequisite and is helpful for establishing an economically strong recycling industry and efficiently expanding the recycling infrastructure (Linton and Yeomans, 2003; Saphores et al., 2009). In terms of WMPs, several estimation studies have been conducted in the context of China from a national perspective (Eugster et al., 2007; Yu et al., 2010; Liao and Zhang, 2012; Li et al., 2015a; Li et al., 2015b; Tan et al., 2017; Guo and Yan, 2017). Specifically, Liao and Zhang (2012), Li et al. (2015a), and Li et al. (2015b) respectively conducted a comparative study to estimate the WMPs in China and to compare the accuracy of different estimation models. Tan et al. (2017) and Guo and Yan (2017) both forecasted WMPs and further conducted substance flow analysis of WMPs in China. Among all the above-mentioned studies, only Li et al. (2015b) involved a static province-level estimation of WMPs for several provinces in China. The results of Li et al. (2015b) indicate the uneven distribution of WMPs in the different provinces of China. The complete spatial distribution information and the future trend of WMPs in different provinces are still unclear. There are 22 provinces, 4 direct-controlled municipalities, and 5 autonomous regions (all denoted as “province” in the following description) in mainland China (excluding Hongkong, Macao, and Taiwan). A complete and continuous province-level estimation and forecast of WMPs, rather than a static estimation, can uncover the change in WMPs in one area and will be helpful for comparatively studying the trend variations of WMPs in different areas. More importantly, it can provide the spatial distribution information of WMPs in China, which is the indispensable information for location planning of recycling centers for WMPs treatment.

With the spatial distribution information of WMPs at the provincial-level of China, a preliminary location planning of recycling centers is performed for WMPs treatment in China. Location planning issues are common in operations research and have been widely conducted through case studies previously, including the facility location plan of remanufacturing and recycling activities for e-waste and other products (Franke et al., 2006; Lu and Bostel, 2007; Queiruga et al., 2008; Dat et al., 2012; Golebiewski et al., 2013; Kilic et al., 2015; Demirel et al., 2016; Coelho and Mateus, 2017; John et al., 2018). In these studies, the influences of multi-products, capacity of facilities, cost differences among regions, and various uncertainties on the location planning result were well modeled and researched. Furthermore, locations were optimized with a focus from one-stage allocation to the entire reverse logistics in these studies. Based on these studies, a mathematical model for location planning of recycling centers in China is formulated. The model optimizes the location of WMP recycling centers through the spatial information of WMPs. The main target of location planning here is optimizing the location of recycling centers for WMPs treatment in China and providing recommendations on the development of recycling centers for both the government and recyclers.

In this end, the overall purposes of this study are to uncover the spatial distribution of WMPs through a province-level estimation of WMPs and to promote the scientific planning and rational layout of recycling centers in China. The remainder of this paper is organized as follows. The model utilized for the estimation and forecast of WMPs is explained, and the model for location planning of WMP recycling centers is constructed in Section 2. Section 3 presents the results and some discussions. Finally, conclusions are summarized in Section 4.

4.2 Methodology and Data

This study first uncovers the spatial distribution of WMPs in China through a province-level estimation study and then conducts a location planning study to optimize the locations of recycling centers based on the spatial information of WMPs in China. The overall flowchart of this study is shown in Figure 4-1.

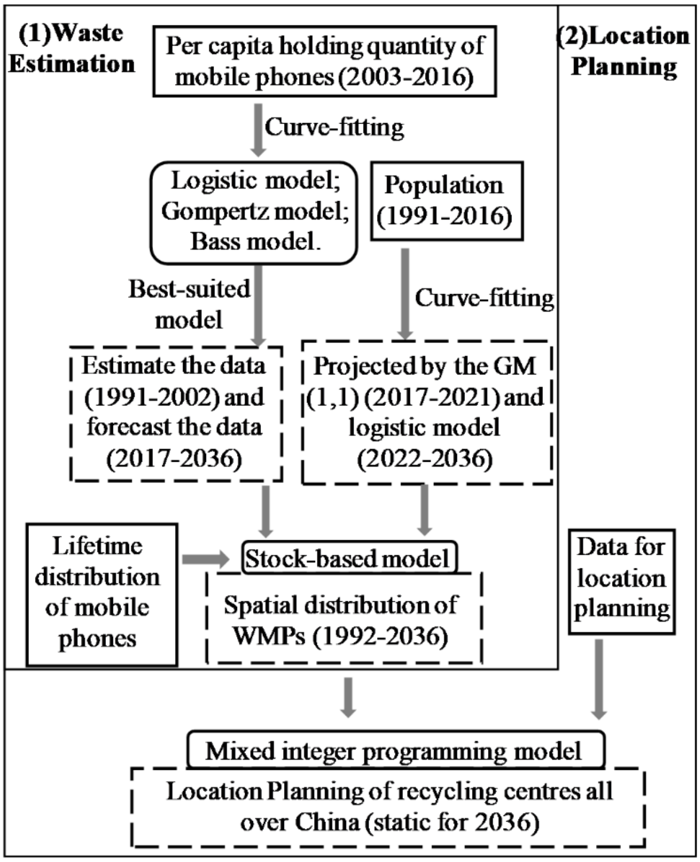

Figure 4-1 Overall flowchart of this study

4.2.1 Estimation and forecast of waste mobile phones

There are several methodologies for estimating and forecasting WMPs with all or several kinds of data among sales, stock, and lifetimes (Chancerel, 2010). On account of the deficient sales information of mobile phones at the provincial level of China, this study estimates and forecasts WMPs through the stock-based model. This model is based on the material flow analysis (MFA) methodology and has been applied to the forecast of household appliances, including TV sets and refrigerators, in China (Zhang et al., 2012). The model is expressed as follows:

$$F_t^{in} = (S_t - S_{t-1}) + F_t^{out} \quad (4\text{-}1)$$

$$F_t^{out} = \sum_{k=1}^{M} F_{t-k}^{in} \times f_k \quad (4\text{-}2)$$

wherein F_t^{in} and F_{t-k}^{in} are the inflows of mobile phones in years *t* and ($t - k$), respectively; F_t^{out} is the outflow of mobile phones (indicates WMPs) in year *t*; S_t and S_{t-1} are the in-use stock of mobile phones in year *t* and ($t - 1$), respectively; f_k is the lifetime distribution of mobile phones; and *M* is the maximum lifetime in the lifetime distribution.

Setting the initial issuing year of mobile phones in China as time $t = 0$, the initial inflows and outflows of mobile phones can be calculated as follows:

$$F_0^{in} = S_0, F_0^{out} = 0 \quad (4\text{-}3)$$

$$F_1^{out} = \sum_{k=1}^{M} F_0^{in} \times f_k = S_0 \times f_1 \quad (4\text{-}4)$$

$$F_1^{in} = S_1 - S_0 + S_0 \times f_1 \quad (4\text{-}5)$$

S_0 and S_1 are the in-use stock of mobile phones in the initial year and in the second year, respectively; f_1 is the probability of being WMPs after a year of utilization.

Accordingly, WMPs in each year can be estimated and forecasted through this iteration process.

The in-use stock of mobile phones is represented as mobile phone subscribers in this study. The in-use stock of mobile phones is the multiply of the population and per capita holding quantity of mobile phones.

The per capita holding quantity of mobile phones can be described as a sigmoid curve that converges to a saturation level. There are several models used for fitting the S-curve shape, and each of these models has its advantages and disadvantages (Walk, 2009; Kim, 2016; Wu and Chu, 2010). It has been indicated that the model with the best fitting results may lead to a more accurate forecast result (Bal et al., 2016). To select the best-suited model for forecasting the per capita holding quantity of mobile phones, the logistic, Gompertz, and Bass models are all applied, respectively, to fit the per capita holding quantity of mobile phones for each province. The logistic, Gompertz, and Bass models are expressed sequentially as follows:

$$y = \frac{\mathrm{a}}{1+\exp(-(\mathrm{b}+ct))} \qquad (4\text{-}6)$$

$$y = \mathrm{a} * \exp(-\mathrm{b} * \exp(-ct)) \qquad (4\text{-}7)$$

$$y = \mathrm{a} * \frac{1-\exp(-(\mathrm{b}+\mathrm{c})*t)}{1+(\mathrm{c}/\mathrm{b})*\exp(-(\mathrm{b}+\mathrm{c})*t)} \qquad (4\text{-}8)$$

Parameters y and t are the per capita holding quantity of mobile phones and time, respectively, “a” in all the three models represents the maximum per capita holding quantity of mobile phones, and “c” is the intrinsic growth rate in the logistic and Gompertz models. Meanwhile “b” and “c” are the innovation and imitation coefficient in the Bass model (Wu and Chu, 2010).

To select the best-suited model for each province, an ad hoc process is followed (Kim, 2016; Sultanov et al., 2016; Avila et al., 2018). First, validity is confirmed based on the confidence level (statistical significance at 99.9% in this study). Subsequently, the values of R-squared (coefficient of determination), root mean squared error (RMSE), and mean absolute percentage error (MAPE) are applied to help select the best-suited model among the three. A model with a higher R-squared, lower RMSE, and smaller MAPE (generally smaller than 20%) within the validity significance level represents superior performance (Hwang et al., 2009). The best-suited model is applied to reversely estimate (2002 to 1991) and forecast (2017 to 2036) the per capita holding quantity of mobile phones for each province.

Both the GM(1,1) and logistic model are applied to fit and forecast the population. Considering the high accuracy for short-term prediction, the GM(1,1) model (model details in Appendix D) is used to forecast the population from year 2017 to 2021. The population from year 2022 to 2036 is forecasted by the logistic model.

4.2.2 Location planning of recycling center

The objective of location planning is to minimize the whole cost of all the recycling centers that used to recycle all WMPs in China. The whole cost of one recycling center can be simply separated into construction cost, transportation cost, operation cost, and idle cost. The idle cost is the whole cost for a recycling center without conducting recycling activity, which is the minimum operating cost of the recycling center. The operation cost consisted of processing cost, environmental protection cost, and waste treatment cost refers to the whole additional costs due to recovery activity. The whole cost of all the recycling centers is the multiple of the number of recycling centers and the whole cost of one recycling center.

Given the finite capacity of a recycling center, several recycling centers are required to cover all the WMPs generated within China. Strategically, recycling centers can be randomly distributed to any province and gather WMPs all over China. Based on the spatial locations of WMPs, the location of recycling centers is optimized by focusing on one-stage allocation (WMPs to recycling centers). It is acceptable and preferred to a certain extent considering the lack of data and model simplification. Recycling activity is a process to recover less from more, and the transportation volume decreases sharply along the entire recycling process. The locations of recycling centers optimized by focusing on front-end allocation will greatly reduce the overall economic cost. Taking all of these into consideration, the model is expressed as follows:

i: Location of recycling center;

j: Place of WMPs;

Q: The total WMPs;

n_i: Number of recycling centers in location i;

q_j: Gross quantity of WMPs in location j;

C: Maximum capacity of one recycling center;

$Const_i$: Construction cost of one recycling center with a capacity C in i;

$Fixed_i$: Unit fixed cost;

a_{ij}: Unit transportation cost per meter per unit WMP from i to j, and $a_{ij} = a_{ji}$;

b_i: Unit operation cost per unit WMP in location i;

x_{ij}: Distance between location i and location j;

c_{ij}: The capacity spared to WMPs in place j from the recycling center in location i.

Minimize $\sum_{i=1}^{I}\sum_{j=1}^{J}(a_{ij}c_{ij}x_{ij} + b_ic_{ij} + n_iConst_i + n_iFixed_i)$ (4-9)

subject to

$\sum_{i=1}^{I} c_{ij} \geq q_j$ (4-10)

$\sum_{j=1}^{J} q_j = Q$ (4-11)

$\sum_{j=1}^{J} c_{ij} \leq n_iC$ (4-12)

$\mathrm{i} \in \mathrm{I}, \mathrm{j} \in \mathrm{J}; \mathrm{I}, \mathrm{J} = 1,2,3, \ldots, 31$ (4-13)

Constraint (4-10) stipulates that all the WMPs in specific location should be covered; constraint (4-11) indicates the relationship between the total WMPs and WMPs in specific location; constraint (4-12) stipulates that the capacity of each recycling center is not exceeded; the final constraint (4-13) restricts the locations of recycling centers and the locations of WMPs within the range of China.

4.2.3 Data

The mobile phone subscribers at province level are recorded from year 2003 to year 2016 (MIIT, 2003–2016). The population data are gained from the China Statistical Yearbooks (NBSC, 1992–2017). Beginning in the 1990s, the popularity of mobile phones began to spread because of sharp price cuts. The earliest record of a national-level mobile phone subscribership in China is for 1991 in which 47,500 people were subscribed to mobile phones, resulting in a negligible per capita holding quantity of mobile phones of 0.0000412 (MIIT, 2000). It is acceptable to set the year 1991 as the initial issue year of mobile phones in China in this study.

The authors launched an on-line questionnaire to investigate the lifetime of mobile phones in different provinces of China. This questionnaire is freely available on a Chinese website (https://wj.qq.com/s/2315789/c86e). Even though the questionnaire had been made available online for a while, only a few respondents answered it (Details of the questionnaire and the corresponding explanation are in Appendix E). In the following study, the national-level lifetime distribution of mobile phones in China surveyed in a previous study will be cited. The value of the shape parameter (β) and average lifespan (y_{av}) were estimated through Weibull distribution as 1.76 and 1.73, respectively, with an estimated coefficient of determination (R^2) at 0.996 (Guo and Yan, 2017). Then the lifetime distribution of mobile phones can be reversely derived with Weibull distribution function by the following equations:

$$f_t = F_t - F_{t-1} \quad (4\text{-}14)$$

$$F_t = 1 - \exp(-(t/\alpha)^{\beta}) \quad (4\text{-}15)$$

$$y_{av} = \alpha * \Gamma(1 + 1/\beta) \quad (4\text{-}16)$$

Where F_t and F_{t-1} are the accumulated WMPs in year *t* and *t-1* after t and *t-1* years' utilization, while f_t is the probability of WMPs in specific year *t* after *t* years' utilization. Γ represents the gamma function.

The lifetime distribution of mobile phones is shown as Figure 4-2.

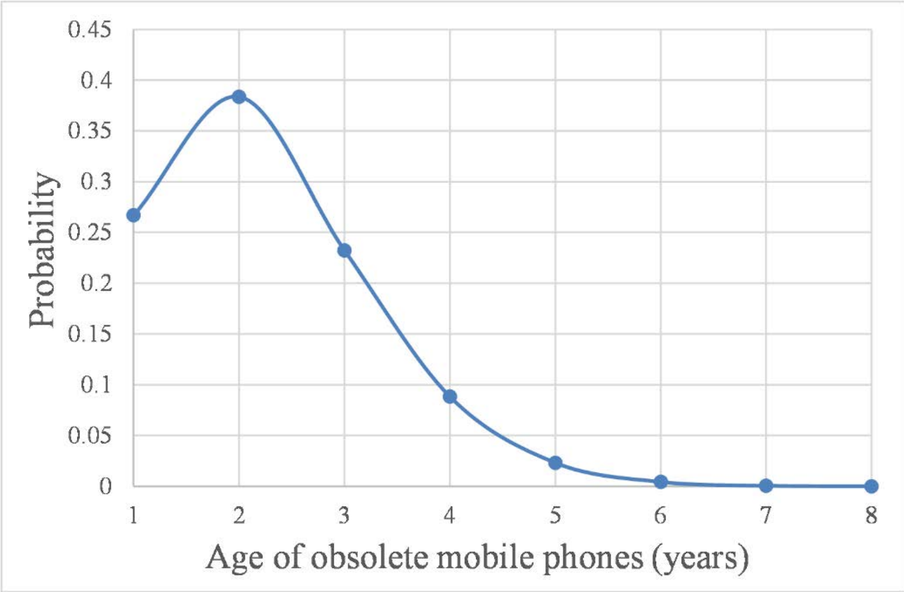

Figure 4-2 Lifetime distribution of Mobile phones in China

In the location planning study, distance measures are Euclidian, and the distance parameter x_{ij} is measured as the straight linear distance between the two capital cities of any two provinces in mainland China through Google Map. A total of 465 sets of distance data are measured and applied. This study employs a linear relationship between transportation cost and distance. The average capacity (*C*) of a typical treatment plant is approximate 5 million WMPs annually (Bian et al., 2016; Li, 2015).

On account of the lack of cost data, one precondition and four assumptions are considered to constraint the solution boundary to solve the location planning problem.

Precondition: The minimum idle capacity of recycling centers as a whole is preferred;

$$(\sum_{i=1}^{I} n_i - 1)C < Q \leq \sum_{i=1}^{I} n_i C \qquad (4\text{-}17)$$

$$n_i = 0,1,2,3, \ldots \qquad (4\text{-}18)$$

Assumption 1: Construction costs of one recycling center are the same in different places;

$$Const_1 = \cdots = Const_i = Const_j \qquad (4\text{-}19)$$

Assumption 2: Unit operation cost per unit WMP is constant in different places;

$$b_1 = \cdots = b_i = b_j \qquad (4\text{-}20)$$

Assumption 3: Unit fixed cost is the same for recycling centers in different areas;

$$Fixed_1 = \cdots = Fixed_i = Fixed_j \qquad (4\text{-}21)$$

Assumption 4: Unit transportation cost per meter per unit WMP is constant regardless of the departure and destination.

$$a_{12} = a_{13} = \cdots = a_{1j} = a_{21} = a_{23} = \cdots = a_{2j} = a_{ij} \qquad (4\text{-}22)$$

4.3 Results and Discussion

4.3.1 Curve-fitting of per capita holding quantity

The Rstudio software is applied to the curve-fitting of the per capita mobile phones of each province. Table 4-1 presents the fitting results for Sichuan province. The curve-fitting results for Sichuan show that the coefficients in both logistic and Bass model are significant at 99.9% confidence level. In addition, the logistic model presents a higher R-squared, lower RMSE and smaller MAPE. The logistic model is therefore selected as the best-suited model for the forecast of per capita holding quantity in Sichuan province. Similarly, the results in all the 31 provinces conclude that the logistic model is the best-suited one for all the 31 provinces in China.

Table 4-1 Curve-fitting results for Sichuan province from the three models

Parameter	Logistic			Gompertz			Bass		
	Coefficient	Std. error	P value	Coefficient	Std. error	P value	coefficient	Std. error	P value
a	1.0620 **	0.0540	6.38e-10	1.5404 **	0.2463	6.22e-05	1.0647 **	0.0561	9.37e-10
b	-5.9703 **	0.2658	1.53e-10	14.2200 *	3.3118	0.0013	0.0008 **	0.0002	0.0008
c	0.2877 **	0.0179	5.44e-09	0.1246 **	0.0188	3.65e-05	0.2849 **	0.0189	1.06e-08
R^2	0.9957			0.9922			0.9956		
RMSE	0.0033			0.0033			0.0035		
MAPE	0.0374			0.0557			0.0383		

'**', '*' Mark statistical significance at the 99.9%, and 99% confidence level.

The forecast results indicate that an increase per capita holding quantity of mobile phones in all the provinces from 2016 to 2036 and most provinces have a per capita holding quantity of mobile phones around 0.8-1.2 in 2036 (Table 4-2). This value is under or near the average level of developed countries (ITU, 2017). Only Beijing has a per capita holding quantity greater than 3, which is greater than the average level. The forecasted per capita holding quantity of mobile phones in Beijing is reasonable and acceptable. Beijing is one of the most economically advanced regions even in the world, while a positive relationship between economy and diffusion of mobile phones had been pointed out in several studies (Madden and Coble-Neal, 2004; Rouvinen, 2006; Lim et al., 2012). Besides, as a reference, the per capita holding quantity of mobile phones in Macao have already reached to 3.21 in year 2016 (ITU, 2017).

Table 4-2 Per capita mobile phones, population and recycling centers in 31 provinces of China

Province	Per capita mobile phones			Population (Million)			Quantity of recycling centers in 2036
	Real data	Forecast (Logistic)		Real data	Forecast		
	2016	2016	2036	2016	2016	2036	
Anhui	0.686	0.720	0.807	61.96	61.52	61.53	4
Beijing	1.840	1.803	3.553	21.73	22.43	39.99	12
Chongqing	0.913	0.939	1.513	30.48	29.43	28.83	4
Fujian	1.088	1.167	1.274	38.74	38.57	43.24	5
Guangdong	1.329	1.408	2.095	109.99	113.02	159.40	29
Gansu	0.804	0.827	0.898	26.10	26.25	26.28	2
Guangxi	0.758	0.787	0.987	48.38	47.65	47.67	4
Guizhou	0.843	0.862	0.972	35.55	36.65	36.66	3
Hainan	0.991	1.040	1.174	9.17	9.15	10.07	1
Hebei	0.833	0.860	0.954	74.70	74.39	84.26	7
Henan	0.818	0.851	1.078	95.32	94.81	94.84	9
Heilongjiang	0.882	0.930	1.636	37.99	38.31	38.33	6
Hubei	0.783	0.814	0.855	58.85	58.41	58.42	4
Hunan	0.709	0.738	0.815	68.22	66.96	69.84	5
Jilin	0.936	0.964	1.164	27.33	27.54	27.65	3
Jiangsu	1.018	1.076	1.242	79.99	80.56	89.35	10
Jiangxi	0.674	0.697	0.846	45.92	45.82	48.94	4
Liaoning	0.996	1.061	1.180	43.78	44.34	47.66	5
Neimenggu (inner Mongolia)	0.946	1.058	1.108	25.20	25.10	26.02	3
Ningxia	0.998	1.042	1.177	6.75	6.84	8.83	1
Qinghai	0.871	0.955	1.030	5.93	5.99	7.28	1
Shaanxi	0.962	0.986	1.067	38.13	37.91	38.22	4
Sichuan	0.842	0.869	1.061	82.62	82.57	82.58	8
Shandong	0.937	0.929	1.062	99.47	98.83	109.13	10
Shanghai	1.288	1.356	1.684	24.20	25.08	42.19	6
Shanxi	0.894	0.919	1.044	36.82	36.99	42.69	4
Tianjin	0.902	0.918	0.945	15.62	15.00	23.30	2
Xinjiang	0.830	0.900	0.990	23.98	23.78	29.31	3
Xizang (Tibet)	0.804	0.855	0.966	3.31	3.27	4.36	0
Yunnan	0.794	0.823	1.047	47.71	47.58	50.19	5

Zhejiang	1.326	1.384	1.744	55.90	56.49	70.03	11

4.3.2 WMPs and the spatial distribution

Combined with the projected population (Table 4-2), the WMPs in all 31 provinces of mainland China are estimated and forecasted from year 1992 to 2036 (Appendix F). The spatial distribution of WMPs in year 2016 is depicted in Figure 4-3. The distribution map indicates the largest amount of WMPs in Guangdong, followed by the Shandong and Jiangsu provinces. Meanwhile, the amount of WMPs is the smallest in the Xizang, Qinghai, and Ningxia provinces.

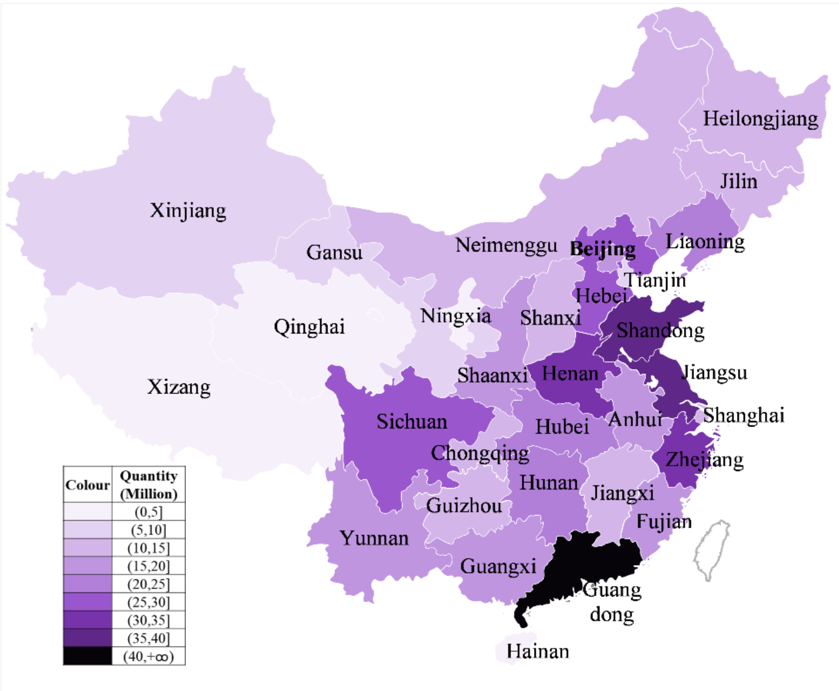

Figure 4-3 Spatial distribution of waste mobile phones in China in the year 2016

All 31 provinces show an increasing trend of WMPs from 2016 and 2036 (Figure 4-4). Considering the increase in WMPs all over China, more attention should be paid to the proper and appropriate treatment of WMPs in China. It is noteworthy that Guangdong and Beijing exhibit the largest trends. The results show that the WMPs in Guangdong and Beijing constitute approximately one quarter of all WMPs in China in 2036, while the proportion is only one-seventh in 2016. These two provinces should accelerate WMP recycling compared to other provinces, taking into account the unparalleled growth rate of WMPs.

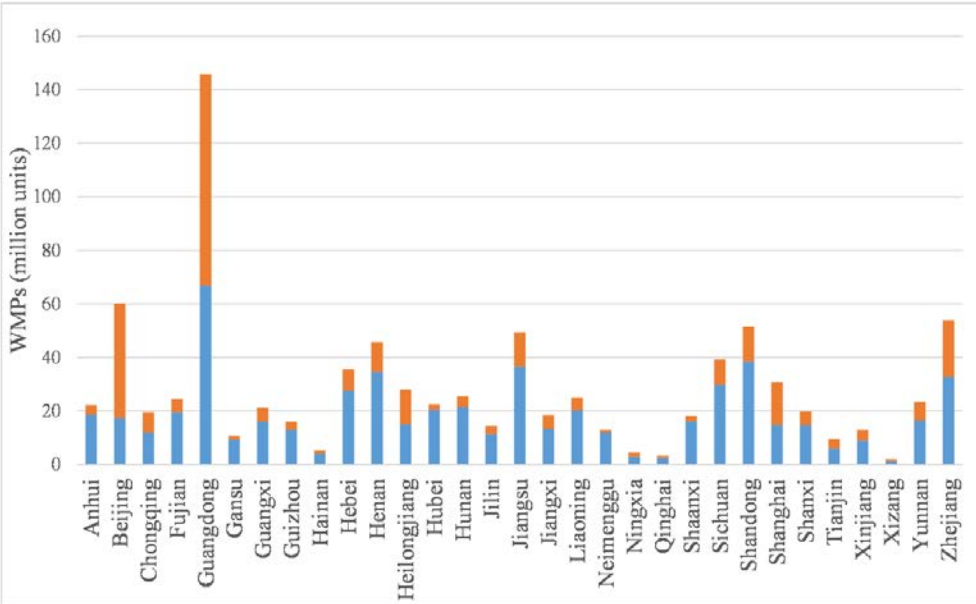

Figure 4-4 Comparison of WMPs in the year 2016 and 2036 (height of blue column represents WMPs in 2016 while the total height refers to WMPs in 2036)

4.3.3 Location planning results

As indicated by Bian et al. (2016) and Li (2015), the average capacity of a typical treatment plant is approximate 5 million WMPs annually. Combining the average capacity with the WMPs estimated from 1992-2036, the minimum recycling centers required to deal the annual WMPs can be calculated (Figure 4-5). It is calculated that the minimum required recycling centers is reaching 175 to cover all the WMPs in China in 2036. According to Yu (2016) and Xinhuanet (2017), only a few formal enterprises can practically handle the WMPs in China. A lot of recycling centers need to be developed in China from now on.

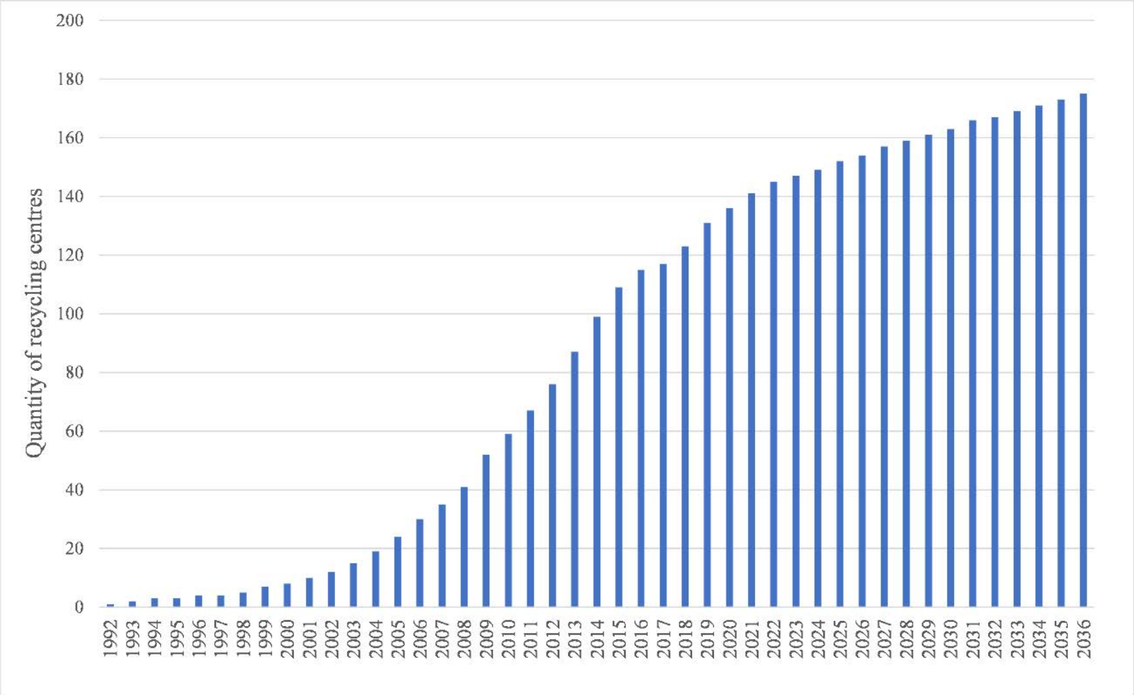

Figure 4-5 Minimum required quantity of recycling centers over years

The What'sBest software developed by Lindo Systems Inc. is employed and the Branch-and-Bound algorithm is applied to execute the mathematical calculation for location planning of recycling centers in China in 2036. The top three provinces in the number of recycling centers are Guangdong, Beijing and Zhejiang, with 29, 12, and 11 centers, respectively, while zero recycling center are planned to be established in Xizang, and only one recycling center is planned in Hainan, Ningxia, and Qinghai in 2036 (Table 4-2).

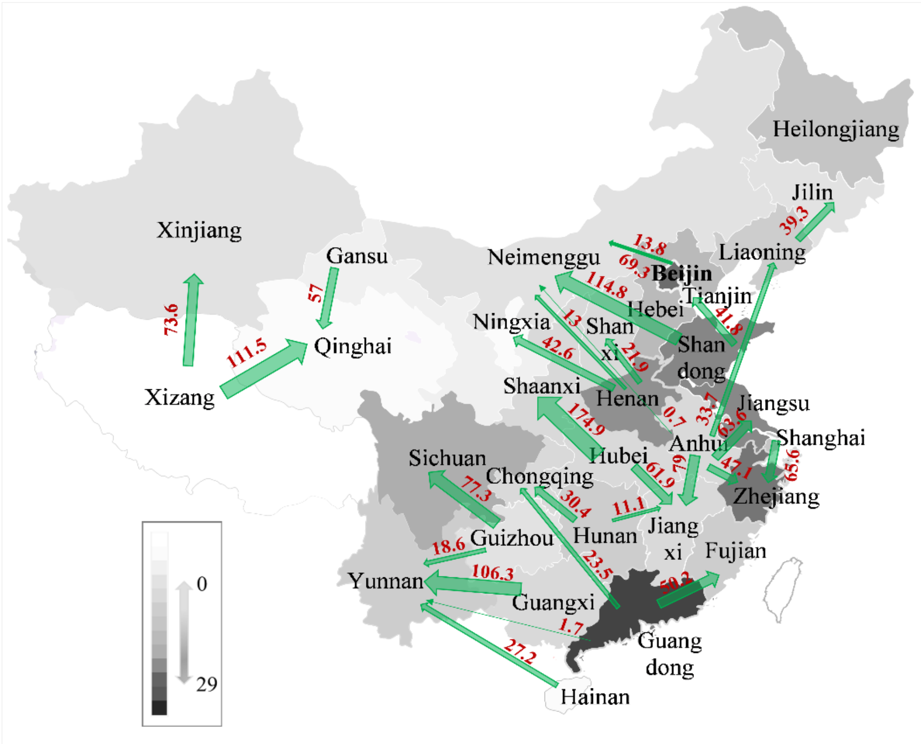

Figure 4-6 Optimization results of recycling centers and WMPs (Ten Thousand units) allocation in 2036

The allocated and transported quantity of WMPs as well as the destination of these WMPs are calculated and indicated (Figure 4-6). In Figure 4-6, the arrowhead indicates the destination of WMPs, and the figure on the arrow represents the WMPs flow between every set of two provinces. It is summarized that 15 provinces need to transport WMPs to other provinces, while 16 provinces need to receive them. Except for Heilongjiang, all the other 30 provinces need to cooperate with several other provinces to deal with WMPs. Among the 30 provinces, some provinces only have relationships with one province, e.g. Hainan only needs transport waste to Yunnan, or Sichuan only act as the destination of WMPs from Guizhou. Some provinces may cooperate with several provinces, e.g. Anhui needs to transport waste to Liaoning, Neimenggu, Zhejiang, Jiangxi and Jiangsu, while

Yunnan needs accept the waste from Hainan, Guizhou, Guangxi and Guangdong. In addition, Liaoning is the only province needing transport and accept waste simultaneously.

4.4 Conclusion

This study uncovered the spatial distribution of WMPs and optimized the locations of recycling centers in China. It is indicated that Guangdong, Shandong, and Jiangsu are the top three with the largest quantities of WMPs, while the Xizang, Qinghai, and Ningxia provinces are the three to have the fewest quantities in 2016. Furthermore, a remarkable increase in WMPs are predicted for Guangdong and Beijing from 2016 to 2036. The location planning study indicates that a total of 175 recycling centers are required to cover all WMPs in China in 2036. In the meantime, the location planning study indicates the concrete locations of recycling centers, and the transported quantity and destination of WMPs across provinces in 2036.

The overabundance of WMPs all over China imply the urgency of proper and appropriate recycling of WMPs. The disclosure of spatial distribution information can benefit the WMP recycling by providing necessary information for the central and local governments, as well as recyclers. For instance, concrete potential quantity of WMPs can indicate the size of the work opportunity for recyclers. In addition, considering the minimized economic cost, the optimized locations of recycling centers can promote the scientific planning and rational layout of recycling centers, which will benefit the development of recycling centers in China.

There are some deficiencies in this study. In terms of the estimation of WMPs, the same lifetime distribution of mobile phones is used for all provinces. However, the lifetime distribution may vary across provinces. It should also be pointed out that the actual number of WMPs may increase as the decreasing lifetime of mobile phones worldwide. There are some assumptions in the location planning model. Once the data is complete, some of these assumptions can be removed, which will lead to a more practical result. The uncertain collection rate should also be incorporated to analyze the influence on the location planning of WMP recycling centers in China.

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Chapter 5 Managerial implications on the optimization and governance of RSC

RSC matters a lot for the proper and appropriate treatment of e-waste since it links the generation of e-waste in the upstream and the proper treatment in the downstream. In order to promote the proper and appropriate treatment of e-waste, the whole study focuses on the optimization and governance of RSC. This study mainly focuses on the channel structure and infrastructure layout of formal RSC. Through the whole study, the key findings are summarized.

1) Formal recyclers should positively implement collection efforts in order to improve the collected quantity and the profit of the formal channel even they outsource collection activities to independent collectors, wherein the collection efforts comprised of publicizing and disseminating the necessity of e-waste recycling can promote the participation of consumers;

2) There exists the conflict of interests when deciding the optimal formal channel structure (Figure 5-1). In details, for the formal recycler (the highest collected quantity and profit), the formal channel structure in Model A always outperforms others, and Model C is always the worst; For consumers (the highest collection price), it concludes that Model B won't be the optimal while Model C won't be the worst choice of consumers; For the government (from the aspect of minimizing the profit of informal RSCs with the lowest subsidy level), the optimal channel structure varies and depends on specific conditions;

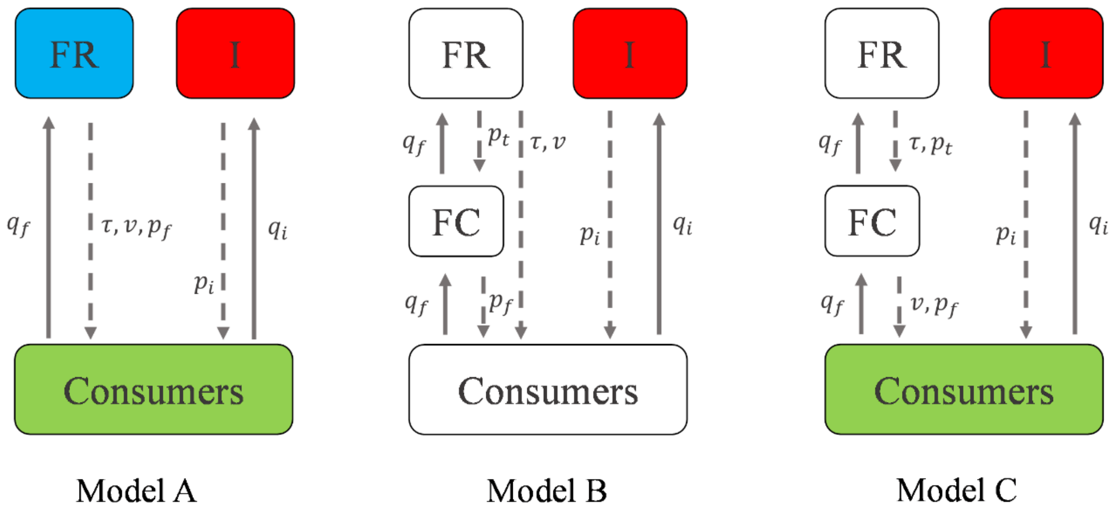

Figure 5-1 Optimal formal channel from different perspectives (Blue and Green mean the possible highest benefits for FR and Consumers respectively, Red indicates the possible scenarios that minimizing informal RSC with the lowest subsidy)

3) The corresponding optimal subsidy for each of the three reverse channel structures is indicated from the aspect of minimizing the informal channel's profit;

4) Both the subsidy and penalty policies can promote the formalization of informal collectors. And there is no difference between the subsidy to informal collectors and formal recyclers (penalty on informal collectors or informal recyclers) regarding the change of recycling quantity;

5) There exists the decremental effect of subsidy and the incremental effect of penalty on promoting formalization activity;

6) There are different effectiveness between the Penalty and Subsidy. And the former one shows a better and more outstanding effectiveness when the formalization extent is high.

7) A simplified and effective subsidy verification and grant system (high responsiveness of the subsidy system) should be developed to promote the formalization of informal collectors;

8) Subsidy can improve the profit of the formal recycler, while subsidy and penalty policies almost have the same influence on the profit of the informal recycler;

9) Formalization of informal collectors also can be promoted through following countermeasures: labeling the recycled material, building alliances between the formal recycler and the market, developing a cost-sharing system, and so on;

10) Among Logistic, Gompertz and Bass models, the Logistic model outperforms others in fitting the per capita holding quantity of mobile phones in provincial level of China;

11) The WMPs in all 31 provinces of mainland China are estimated and forecasted from year 1992 to 2036. The largest amount of WMPs are in Guangdong, followed by the Shandong and Jiangsu provinces, while the amount of WMPs is the smallest in the Xizang, Qinghai, and Ningxia provinces in 2016;

12) All 31 provinces show an increasing trend of WMPs from 2016 and 2036. It is noteworthy that Guangdong and Beijing exhibit the largest trends;

13) A broadly increasing trend of WMPs from western to eastern China (almost similar to the economic development);

14) The minimum required amount of recycling centers is reaching 175 to cover all the WMPs in China in 2036. The top three provinces in terms of the number of recycling centers are Guangdong, Beijing and Zhejiang, with 29, 12, and 11 centers, respectively, while zero recycling center are planned to be established in Xizang, and only one recycling center is planned in Hainan, Ningxia, and Qinghai in 2036;

15) According to the location planning analysis, this study also indicates the cross-boundary transportation quantities of WMPs among 31 provinces of mainland China.

These findings indicate the optimal channel structure and infrastructure layout of formal RSC, and conclude the optimal subsidy and compare the effectiveness of different policies. Based on these findings, we derive some important managerial implications for the government and the recycler in formal RSC.

For the government, the first implication is that the design and implementation of any policies should be prudent. On the one hand, the study concludes that the subsidy currently implemented in China may benefit the informal RSC and the effectiveness of different policies varies on promoting the formalization of informal collectors. These indicate that the government should fully consider the adverse influence or the effectiveness of different policies before launching a specific policy. On the other hand, it is noteworthy that a varied difference between the effectiveness of subsidy and penalty policies along with different formalization extent, which indicating that the government should pay attention to the dynamic influence of the policy since its influence may change along with time. In other words, the government should prudently adjust the policy as time goes in order to keep its effectiveness. Secondly, the supervision system of a specific policy should be efficient. Specifically, the government should try its best to simplify the subsidy system and improve its responsiveness. Thirdly, the location planning study indicates that all the 30 provinces except Heilongjiang should cooperate with at least one another provinces in WMPs treatment to achieve the minimum treatment cost. Therefore, it’s a better choice for the government to promote the co-construction of recycling centers and cooperation on WMPs treatment across provinces in China.

There are also three major implications for formal recyclers. Firstly, through comparing the three formal channel structure, it is shown that the highest profit and largest collection rate can be always gained when the formal recycler collect e-waste directly. Therefore, it's the best choice of the formal recycler to establish its own collection channel or to centralize other independent collection channels. Secondly, the formal recycler should positively implement activities to promote consumers' participation even the collection activity is outsourced to an independent collector. This is because that both the profit and collection rate are higher for the formal recycler. Lastly, we optimize the locations of recycling centers given the objective of minimizing the overall treatment cost. Considering the minimized cost, the formal recycler is suggested to establish its recycling centers following the planned locations.

Chapter 6 Conclusion

E-waste is one fast-growing stream of waste and has attracted increasing interests worldwide. E-waste contains various precious and hazardous metals, which make it have a dual economic and environmental influence. Because of the adverse environmental influence, the proper and appropriate treatment of e-waste become essential and urgent. The problem is more prominent for the context of China taking into account that China generates both the highest e-waste in Asia and in the world. This study summarizes that there are a bunch of issues still lying in the proper treatment of e-waste in China currently, including the low consumers' participation, the abundant informal collection and recycling activities, the low recycling rate, the low attention to small e-waste, and the lacking infrastructures etc.

To tackle the adverse environmental influence and enhance the resources conservation, this study focuses on the development of formal RSC and its optimization and governance, in order to promote the proper and appropriate treatment of e-waste. The study pays major attention to the prominent problems practically encountered in collection and recycling activities of formal RSC in China. Wherein the prominent problems are summarized as the suitable collection strategy, channel structure, channel coordination, green technology investment and facility locations. Based on the knowledge of operations research, management science and microeconomics, these prominent issues are theoretically modelled and analyzed for both the recycler in formal RSC and the government. Besides, a series of numerical simulation are conducted according to the context of China. Finally, we provide some managerial implications to both the recycler in formal RSC and the government, wherein the implications derived from this study and are concluded as beneficial for the development of formal RSC.

This study firstly focuses on the competitive formal and informal RSCs. By modelling the influence of collection efforts, green technology investment and the government subsidy, this study establishes three game theoretic models that corresponding respectively to three different dual-channel structures. These models are used to analyze the optimal collection strategy and channel structure of formal RSC under the competitive formal and informal RSCs, and indicate the optimal government subsidies. Then, this study considers the coordination of formal and informal RSCs for its benefits on e-waste treatment. A game theory model is built to analyze how to effectively promote the formalization of informal collectors. Based on the model, we discuss and compare the influences of four different policies (two subsidies and two penalties). Finally, the study pays attention to the development and rational layout of recycling centers in formal RSC. This study establishes several forecasting models to estimate and forecast the provincial WMPs of mainland China and develops a mixed-integer programming model for location planning of corresponding recycling infrastructures.

Based on the theoretical models and related numerical analysis, several key findings are concluded and provided for decision-making. The study firstly analyzes the optimal formal channel structures from the perspectives of formal recycler, consumer and government respectively. It is concluded that there exists the conflict of interests when deciding the optimal formal channel structure. The results further indicate that formal recyclers should positively implement collection efforts in order to improve the collected quantity and the profit of the formal channel even they outsource collection activities to independent collectors. Besides, the optimal subsidies are calculated for different formal channel structures from the aspect of minimizing the profit of informal RSC. Thirdly, the study concludes that both the subsidy and penalty policies can promote the formalization of informal collectors. And there is no difference between the subsidy to informal collectors and formal recyclers (penalty on informal collectors or informal recyclers) regarding the change of recycling quantity. It is noteworthy that there exist the decremental effect of subsidy and the incremental effect of penalty on promoting formalization activity. Lastly, the study estimates the WMPs in all 31 provinces of mainland China from year 1992 to 2036. Through the location planning study, it indicates the concrete locations of recycling centers and the WMPs flows across provinces, and concludes that a total of 175 recycling centers are required for WMPs treatment in China in 2036.

Accordingly, this study indicates major managerial implications for both the government and the recycler in formal RSC. For the government, the first implication is that the design and implementation of any policies should be prudent. On the one hand, the government should fully consider the effectiveness of different policies and even their adverse influence before launching a specific policy. On the other hand, the government should pay attention to the dynamic influence of the policy since its influence may change along with time. The government should prudently adjust the policy as time goes in order to keep its effectiveness. Secondly, the supervision system of a specific policy should be efficient. Specifically, the government should try its best to simplify the subsidy system and improve its responsiveness. Thirdly, the government should promote the co-construction of recycling centers and cooperation on WMPs treatment across provinces in China. There are also three major implications for formal recyclers. Firstly, it's the best choice of the formal recycler to establish its own collection channel or to centralize other independent collection channels. Secondly, the formal recycler should positively implement activities to promote consumers' participation even the collection activity is outsourced to an independent collector. Lastly, considering the minimized cost, the formal recycler is suggested to establish its recycling centers following the planned locations.

Throughout the study, we mainly focus on the optimization and governance of RSC for e-waste treatment. The benefits of this study on the development and optimization of RSC can be summarized as follows. Firstly, the whole study can help maximize the economic profit of formal RSC and benefit the environment. Secondly, the study can help promote the collection rate of formal RSC through the optimized formal channel structure and the efficiently coordinated formal and informal RSCs. Thirdly, because of the optimized locations of recycling centers, the study can contribute to the rational layout of recycling centers in formal RSC.

Appendix A.

Notations:

i, *j*, *k:* Provinces in mainland China (integer; 1, 2, …, 31 in this study), EEE category (integer; 1, 2, …, 6 in this study), material category (integer);

a, *b*, *c:* Unit price of a kind material (dollars/tonne), unit TMR of a kind material (tonne/tonne), material weight per unit EEE (tonne);

Q: quantity of a kind of electronic product;

W: quantity of a kind of e-waste;

S: Per 100 households electronic products;

Pop: Population;

q: Average family size (person/household);

T: Average lifetime of a kind electronic product (year);

G: Weight of a kind material in all electronic product (tonne);

(a) Unit proportion:

$Unit\ Price_1 : Unit\ Price_2 : \cdots : Unit\ Price_i$;

$Unit\ TMR_1 : Unit\ TMR_2 : \cdots : Unit\ TMR_i$;

(b) Proportion according to the overall quantity in 2018 in China:

$Price_1 : Price_2 : \cdots : Price_i$;

$TMR_1 : TMR_2 : \cdots : TMR_i$;

Unit price of one kind e-waste:

$$Unit\ Price_i = \sum_{k=1}^{K} a_k c_{ik} \qquad \text{(A-1)}$$

Unit TMR of one kind e-waste:

$$Unit\ TMR_i = \sum_{k=1}^{K} b_k c_{ik} \qquad \text{(A-2)}$$

Price Magnitude of e-waste according to the overall quantity in 2018 in China:

$$Price_i = \sum_{k=1}^{K} (W_{ij} * Unit\ Price_i) \qquad \text{(A-3)}$$

TMR Magnitude of e-waste according to the overall quantity in 2018 in China:

$$TMR_i = \sum_{k=1}^{K} (W_{ij} * Unit\ TMR_i) \qquad \text{(A-4)}$$

In order to estimate the quantity of potential e-waste, the consumption and use approach is employed for each local province. This approach has been applied to estimate e-waste in many studies (Polak and Drapalova, 2012; Li et al. 2015).

$$W_{ij} = \frac{Q_{ij}}{T_{ij}} \qquad \text{(A-5)}$$

T_{ij} is the lifetime of a kind of electronic product *j* in local province *i*. Q_{ij} is the possession quantity of a kind of electronic product *j* in local province *i*, which is calculated as equation (A-6):

$$Q_{ij} = \frac{S_{ij}}{100 * q_i} * Pop_i \qquad \text{(A-6)}$$

The per 100 households electronic products, population and average family size for the six major kinds of electronic products in 31 provinces are derived from China Statistical Yearbooks (NBS, 2018). Average lifetime of washing machine, refrigerator, TV (LCD), air conditioner, desk PC, smartphone are 10, 14, 16, 6, 4 and 2 years in this study respectively (Guo et al., 2017; Habuer et al., 2014; Li et al., 2015; Cucchiella et al., 2015). Main material compositions are compiled from Habuer et al. (2014), Cucchiella et al. (2015), Jiang et al. (2016) and Guo et al. (2017). The price of each kind of material are cited from the London Metal Exchange (LME, 2019). The TMR of each metal calculated by the National Institute for Materials Science of Japan (Katagiri et al., 2009).

Table A-1 Main material compositions of electronic products (g/unit) and the corresponding price (TMR) of metals

	Plastics	**Fe**	**Al**	**Cu**	**Au**	**Ag**	**Pd**	**Pb**	**Sn**	**Zn**	**Ni**	**Co**
Washing machine	14120	20744.6	800.68	1287.6	0.012	0.035		1.496	6.188	1.632		0.011
Refrigerator	24035	26185.775	719.400	1916.750	0.012	0.012		5.775	22.825	4.675		0.033
TVs (LCD)	5678.4	9530.639	1110.387	189.129	0.318	0.249	0.253	1.424	58.425	42.595	0.671	0.004
Air conditioner	8850	22977	4659.315	9001.250	0.020	0.078		7.830	25.650	6.615		0.039
Desk PCs	3542.460	7236.611	624.311	405.917	0.647	2.236	0.187	27.137	21.253	3.217	0.006	
Smart phone	60	8.000	2.900	14.000	0.038	0.224	0.015	0.600	1.000	1.000	1.500	6.300
TMR (tonne/tonne)	/	8	48	360	1100000	4800	810000	28	81	36	260	600
Price (US dollars/tonne)	/	256	1735.5	5820	47727714.15	565048.55	56938889.7	2202	16825	2500	16200	35500

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Appendix B.

As defined in this study, $0 \leq s, \tau_0 \leq 1$, $0 < k \leq 1$, $0 < m \leq 1$, $0 < \lambda < 1$, $0 < \alpha_i < 1$. Besides, since τ, v, p_f, p_i, p_t, q_f, q_i, π_{fc}, π_{fr}, π_f and π_i are non-negative in all the three models, $s + \tau_0 - (1 - \alpha_i) > 0$ and $4 - m^2 - (k(1+\lambda))^2 > 0$ always hold.

Proof of Proposition 2-1. $\frac{\partial \tau^A}{\partial s} > 0$, $\frac{\partial \tau^B}{\partial s} > 0$, $\frac{\partial \tau^C}{\partial s} > 0$, $\frac{\partial v^A}{\partial s} > 0$, $\frac{\partial v^B}{\partial s} > 0$, $\frac{\partial v^C}{\partial s} > 0$. As the increase of the government's subsidy, both collection efforts and green technology investment increase in the three models. Hence it can be concluded that the government's subsidy promotes collection efforts and green technology investment.

Proof of Proposition 2-2. (1) $\frac{\partial q_f{}^A}{\partial s} > 0$, $\frac{\partial q_f{}^B}{\partial s} > 0$, $\frac{\partial q_f{}^C}{\partial s} > 0$. Formal collection quantity (q_f) can be improved by the government's subsidy (s) in all the three models;

(2) $\frac{\partial q_i{}^A}{\partial s} = \frac{k^2(1+\lambda)-1}{4-m^2-(k(1+\lambda))^2}$, $\frac{\partial q_i{}^B}{\partial s} = \frac{k^2(1+\lambda)-1}{6-m^2-(k(1+\lambda))^2}$. When $k^2(1+\lambda) > 1$, the increase of s improves $q_i{}^A$ and $q_i{}^B$, when $k^2(1+\lambda) < 1$, the increase of s lowers $q_i{}^A$ and $q_i{}^B$;

(5) $\frac{\partial q_i{}^C}{\partial s} = \frac{\lambda k^2 - 1}{6-2\lambda k^2(1+\lambda)-m^2} < 0$. The subsidy ($s$) has a negative influence on $q_i{}^C$.

Proof of Proposition 2-3. (1) $\frac{\partial p_f{}^A}{\partial s} = \frac{2-(k(1+\lambda))^2}{4-m^2-(k(1+\lambda))^2}$, $\frac{\partial p_f{}^B}{\partial s} = \frac{2-(k(1+\lambda))^2}{6-m^2-(k(1+\lambda))^2}$. Since $4 - m^2 - (k(1+\lambda))^2 > 0$ and $6 - m^2 - (k(1+\lambda))^2 > 0$, therefore when $k(1+\lambda) < \sqrt{2}$, $p_f{}^A$ and $p_f{}^B$ increase as s increases, when $k(1+\lambda) > \sqrt{2}$, $p_f{}^A$ and $p_f{}^B$ decrease as s increases;

(2) $\frac{\partial p_t{}^B}{\partial s} = \frac{3-(k(1+\lambda))^2}{6-m^2-(k(1+\lambda))^2}$. When $k(1+\lambda) < \sqrt{3}$, the increase of s leads an increase in $p_t{}^B$, when $k(1+\lambda) > \sqrt{3}$, the increase of s leads a decrease in $p_t{}^B$;

(3) $\frac{\partial p_i{}^A}{\partial s} = \frac{1-k^2(1+\lambda)}{4-m^2-(k(1+\lambda))^2}$, $\frac{\partial p_i{}^B}{\partial s} = \frac{1-k^2(1+\lambda)}{6-m^2-(k(1+\lambda))^2}$. When $k^2(1+\lambda) > 1$, the increase of s lowers $p_i{}^A$ and $p_i{}^B$, when $k^2(1+\lambda) < 1$, the increase of s improves $p_i{}^A$ and $p_i{}^B$;

(4) $\frac{\partial p_f{}^C}{\partial s} = \frac{2-\lambda k^2(1+\lambda)}{6-2\lambda k^2(1+\lambda)-m^2} > 0$, $\frac{\partial p_t{}^C}{\partial s} = \frac{3-\lambda k^2(1+\lambda)}{6-2\lambda k^2(1+\lambda)-m^2} > 0$, $\frac{\partial p_i{}^C}{\partial s} = \frac{1-\lambda k^2}{6-2\lambda k^2(1+\lambda)-m^2} > 0$.

The subsidy (s) has a positive influence on $p_t{}^C$, $p_f{}^C$, and $p_i{}^C$.

Proof of Proposition 2-4. (1) $\frac{\partial \pi_f{}^A}{\partial s} > 0$, $\frac{\partial \pi_f{}^B}{\partial s} > 0$, $\frac{\partial \pi_{fr}{}^B}{\partial s} > 0$, $\frac{\partial \pi_{fc}{}^B}{\partial s} > 0$, $\frac{\partial \pi_f{}^C}{\partial s} > 0$, $\frac{\partial \pi_{fr}{}^C}{\partial s} > 0$ and $\frac{\partial \pi_{fc}{}^C}{\partial s} > 0$. When government increases subsidy, it obviously promotes the optimal profits of the whole formal channel.

(2) $\frac{\partial \pi_i{}^A}{\partial s} = \frac{2\left(k^2(1+\lambda)-1\right)^2(s+\tau_0-1)+2\left(k^2(1+\lambda)-1\right)(3-m^2-\lambda k^2(1+\lambda))\alpha_i}{(4-m^2-\left(k(1+\lambda)\right)^2)^2} = \frac{2\left(k^2(1+\lambda)-1\right)[\left(k^2(1+\lambda)-1\right)(s+\tau_0-1)+\left(3-m^2-\lambda k^2(1+\lambda)\right)\alpha_i]}{(4-m^2-\left(k(1+\lambda)\right)^2)^2} = \frac{2\left(k^2(1+\lambda)-1\right)}{4-m^2-\left(k(1+\lambda)\right)^2} q_i{}^A$, similarly, $\frac{\partial \pi_i{}^B}{\partial s} = \frac{2\left(k^2(1+\lambda)-1\right)}{6-m^2-(k(1+\lambda))^2} q_i{}^B$ and $\frac{\partial \pi_i{}^C}{\partial s} = \frac{2\left(\lambda k^2-1\right)}{6-2\lambda k^2(1+\lambda)-m^2} q_i{}^C$.

When $k^2(1+\lambda) > 1$, $\frac{\partial \pi_i{}^A}{\partial s} = \frac{2\left(k^2(1+\lambda)-1\right)}{4-m^2-\left(k(1+\lambda)\right)^2} q_i{}^A \geq 0$ and $\frac{\partial \pi_i{}^B}{\partial s} = \frac{2\left(k^2(1+\lambda)-1\right)}{6-m^2-(k(1+\lambda))^2} q_i{}^B \geq 0$ since $q_i{}^A \geq 0$ and $q_i{}^B \geq 0$ always hold. Hence s increases, $\pi_i{}^A$ and $\pi_i{}^B$ increase, When $k^2(1+\lambda) < 1$, s increases, $\pi_i{}^A$ and $\pi_i{}^B$ decrease. Since $\lambda k^2 - 1 < 0$ always hold, $\frac{\partial \pi_i{}^C}{\partial s} = \frac{2\left(\lambda k^2-1\right)}{6-2\lambda k^2(1+\lambda)-m^2} q_i{}^C \leq 0$ always holds since $q_i{}^C \geq 0$. Therefore $\pi_i{}^C$ decreases as the increase of s.

Proof of Proposition 2-5. (1) Proof of the influence of k

$\frac{\partial \tau^A}{\partial k} > 0$, $\frac{\partial \tau^B}{\partial k} > 0$, $\frac{\partial \tau^C}{\partial k} > 0$, $\frac{\partial v^A}{\partial k} > 0$, $\frac{\partial v^B}{\partial k} > 0$, $\frac{\partial v^C}{\partial k} > 0$, $\frac{\partial q_f{}^A}{\partial k} > 0$, $\frac{\partial q_f{}^B}{\partial k} > 0$, $\frac{\partial q_f{}^C}{\partial k} > 0$, $\frac{\partial \pi_f{}^A}{\partial k} > 0$, $\frac{\partial \pi_f{}^B}{\partial k} > 0$, $\frac{\partial \pi_{fr}{}^B}{\partial k} > 0$, $\frac{\partial \pi_{fc}{}^B}{\partial k} > 0$, $\frac{\partial \pi_f{}^C}{\partial k} > 0$, $\frac{\partial \pi_{fr}{}^C}{\partial k} > 0$.

$\frac{\partial \pi_{fc}{}^{C}}{\partial k} = \frac{4(s+\tau_0-(1-\alpha_i))^2}{(2(6-2\lambda k^2(1+\lambda)-m^2)^2)^2}[-(16-4(\lambda k)^2)(\lambda k^3(1+\lambda)^2)-(1-(\lambda k)^2)8\lambda k(1+\lambda)(6-m^2)-(\lambda k)^2(6-m^2)^2] < 0$

Then it calculates that $\frac{\partial p_f{}^{A}}{\partial k} = 2k(1+\lambda)^2\frac{(m^2-2)(s+\tau_0-(1-\alpha_i))}{(4-m^2-(k(1+\lambda))^2)^2} < 0$, $\frac{\partial p_t{}^{B}}{\partial k} = 2k(1+\lambda)^2\frac{(m^2-3)(s+\tau_0-(1-\alpha_i))}{(6-m^2-(k(1+\lambda))^2)^2} < 0$, $\frac{\partial p_f{}^{B}}{\partial k} = 2k(1+\lambda)^2\frac{(m^2-4)(s+\tau_0-(1-\alpha_i))}{(6-m^2-(k(1+\lambda))^2)^2} < 0$, $\frac{\partial p_f{}^{C}}{\partial k} = 2\lambda k(1+\lambda)\frac{(m^2-2)(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} < 0$, however, $\frac{\partial p_t{}^{C}}{\partial k} = 2\lambda k(1+\lambda)\frac{m^2(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} > 0$.

$\frac{\partial q_i{}^{A}}{\partial k} = 2k(1+\lambda)\frac{(3-m^2-\lambda)(s+\tau_0-(1-\alpha_i))}{(4-m^2-(k(1+\lambda))^2)^2} > 0$, $\frac{\partial q_i{}^{B}}{\partial k} = 2k(1+\lambda)\frac{(5-m^2-\lambda)(s+\tau_0-(1-\alpha_i))}{(6-m^2-(k(1+\lambda))^2)^2} > 0$, $\frac{\partial q_i{}^{C}}{\partial k} = 2\lambda k\frac{(4-m^2-2\lambda)(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} > 0$.

$\frac{\partial p_i{}^{A}}{\partial k} = -2k(1+\lambda)\frac{(3-m^2-\lambda)(s+\tau_0-(1-\alpha_i))}{(4-m^2-(k(1+\lambda))^2)^2} < 0$, $\frac{\partial p_i{}^{B}}{\partial k} = -2k(1+\lambda)\frac{(5-m^2-\lambda)(s+\tau_0-(1-\alpha_i))}{(6-m^2-(k(1+\lambda))^2)^2} < 0$, $\frac{\partial p_i{}^{C}}{\partial k} = -2\lambda k\frac{(4-m^2-2\lambda)(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} < 0$.

$\pi_i = (1-p_i)q_i$, since q_i increases and p_i decreases as the increase of k. Therefore, k has a positive influence on π_i.

In summary, k has a positive influence on τ, v, q_f, q_i, π_{fr}, π_f, π_i and has a negative influence on p_f, p_i in all the three models. However, k has a positive influence on $p_t{}^{C}$, $\pi_{fc}{}^{B}$ and a negative influence on $p_t{}^{B}$, $\pi_{fc}{}^{C}$.

(2) Proof of the influence of λ

$\frac{\partial \tau^A}{\partial \lambda} > 0$, $\frac{\partial \tau^B}{\partial \lambda} > 0$, $\frac{\partial \tau^C}{\partial \lambda} > 0$, $\frac{\partial v^A}{\partial \lambda} > 0$, $\frac{\partial v^B}{\partial \lambda} > 0$, $\frac{\partial v^C}{\partial \lambda} > 0$, $\frac{\partial {q_f}^A}{\partial \lambda} > 0$, $\frac{\partial {q_f}^B}{\partial \lambda} > 0$, $\frac{\partial {q_f}^C}{\partial \lambda} > 0$, $\frac{\partial {p_f}^A}{\partial \lambda} < 0$, $\frac{\partial {p_f}^B}{\partial \lambda} < 0$, $\frac{\partial {p_t}^B}{\partial \lambda} < 0$, $\frac{\partial {p_f}^C}{\partial \lambda} < 0$, $\frac{\partial {p_t}^C}{\partial \lambda} > 0$, $\frac{\partial {\pi_f}^A}{\partial \lambda} > 0$, $\frac{\partial {\pi_f}^B}{\partial \lambda} > 0$, $\frac{\partial {\pi_{fr}}^B}{\partial \lambda} > 0$, $\frac{\partial {\pi_{fc}}^B}{\partial \lambda} > 0$, $\frac{\partial {\pi_{fc}}^C}{\partial \lambda} < 0$, $\frac{\partial {\pi_f}^C}{\partial \lambda} > 0$, $\frac{\partial {\pi_{fr}}^C}{\partial \lambda} > 0$.

$\frac{\partial {q_i}^A}{\partial \lambda} = k^2 \frac{(2-m^2-2\lambda+k^2(1+\lambda)^2)(s+\tau_0-(1-\alpha_i))}{(4-m^2-\left(k(1+\lambda)\right)^2)^2}$, when $2-m^2-2\lambda+k^2(1+\lambda)^2 > 0$, the increase of λ improves ${q_i}^A$, otherwise, the opposite stands; $\frac{\partial {q_i}^B}{\partial \lambda} = k^2 \frac{(4-m^2-2\lambda+k^2(1+\lambda)^2)(s+\tau_0-(1-\alpha_i))}{(6-m^2-\left(k(1+\lambda)\right)^2)^2} > 0$, $\frac{\partial {q_i}^C}{\partial \lambda} = k^2 \frac{(4-m^2-4\lambda+2k^2\lambda^2)(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2}$, when $4-m^2-4\lambda+2k^2\lambda^2 > 0$ the increase of λ improves ${q_i}^C$, otherwise, the opposite stands.

$\frac{\partial {p_i}^A}{\partial \lambda} = -k^2 \frac{(2-m^2-2\lambda+k^2(1+\lambda)^2)(s+\tau_0-(1-\alpha_i))}{(4-m^2-\left(k(1+\lambda)\right)^2)^2}$, when $2-m^2-2\lambda+k^2(1+\lambda)^2 < 0$, the increase of λ improves ${p_i}^A$, otherwise, the opposite stands; $\frac{\partial {p_i}^B}{\partial \lambda} = -k^2 \frac{(4-m^2-2\lambda+k^2(1+\lambda)^2)(s+\tau_0-(1-\alpha_i))}{(6-m^2-\left(k(1+\lambda)\right)^2)^2} < 0$, $\frac{\partial {p_i}^C}{\partial \lambda} = -k^2 \frac{(4-m^2-4\lambda+2k^2\lambda^2)(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2}$, when $4-m^2-4\lambda+2k^2\lambda^2 < 0$ the increase of λ improves ${p_i}^C$, otherwise, the opposite stands.

$\pi_i = (1-p_i)q_i$, when $2-m^2-2\lambda+k^2(1+\lambda)^2 > 0$, the increase of λ improves ${\pi_i}^A$, otherwise, the opposite stands; when $4-m^2-4\lambda+2k^2\lambda^2 > 0$ the increase of λ improves ${\pi_i}^C$, otherwise, the opposite stands; the increase of λ improves ${\pi_i}^B$.

In summary, λ and k have the same kind influence on τ, v, q_f, p_f, p_t, π_{fc}, π_{fr}, π_f, however, when $2-m^2-2\lambda+k^2(1+\lambda)^2 > 0$, the increase of λ improves ${q_i}^A$, ${\pi_i}^A$ and lowers ${p_i}^A$, otherwise, the opposite stands; when $4-m^2-4\lambda+2k^2\lambda^2 > 0$ the increase of λ improves ${q_i}^C$, ${\pi_i}^C$ and lowers ${p_i}^C$, otherwise, the opposite stands; the increase of λ improves ${q_i}^B$, ${\pi_i}^B$ and lowers ${p_i}^B$.

(3) It can be easily found that τ_0 and s have the same slopes for all the equilibrium results, which leading to the same kind influence of τ_0 and s.

Proof of the influence of m

$\frac{\partial \tau^A}{\partial m} > 0$, $\frac{\partial \tau^B}{\partial m} > 0$, $\frac{\partial \tau^C}{\partial m} > 0$, $\frac{\partial v^A}{\partial m} > 0$, $\frac{\partial v^B}{\partial m} > 0$, $\frac{\partial v^C}{\partial m} > 0$, $\frac{\partial {q_f}^A}{\partial m} > 0$, $\frac{\partial {q_f}^B}{\partial m} > 0$, $\frac{\partial {q_f}^C}{\partial m} > 0$, $\frac{\partial {\pi_f}^A}{\partial m} > 0$, $\frac{\partial {\pi_f}^B}{\partial m} > 0$, $\frac{\partial {\pi_{fr}}^B}{\partial m} > 0$, $\frac{\partial {\pi_{fc}}^B}{\partial m} > 0$, $\frac{\partial {\pi_f}^C}{\partial m} > 0$, $\frac{\partial {\pi_{fr}}^C}{\partial m} > 0$.

$\frac{\partial {p_f}^A}{\partial m} = 2m\frac{(2-k^2(1+\lambda)^2)(s+\tau_0-(1-\alpha_i))}{(4-m^2-\left(k(1+\lambda)\right)^2)^2}$, $\frac{\partial {p_f}^B}{\partial m} = 2m\frac{(2-k^2(1+\lambda)^2)(s+\tau_0-(1-\alpha_i))}{(6-m^2-\left(k(1+\lambda)\right)^2)^2}$. when $k(1+\lambda) < \sqrt{2}$, m can promote ${p_f}^A$ and ${p_f}^B$, while the influence is the opposite when $k(1+\lambda) > \sqrt{2}$.

$\frac{\partial {p_t}^B}{\partial m} = 2m\frac{(3-k^2(1+\lambda)^2)(s+\tau_0+1-\alpha_i)}{(6-m^2-\left(k(1+\lambda)\right)^2)^2}$, when $k(1+\lambda) < \sqrt{3}$, m can promote ${p_t}^B$, while the influence is the opposite when $k(1+\lambda) > \sqrt{3}$.

$\frac{\partial {p_t}^C}{\partial m} = 2m\frac{(3-\lambda k^2(1+\lambda))(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} > 0$ and $\frac{\partial {p_f}^C}{\partial m} = 2m\frac{(2-\lambda k^2(1+\lambda))(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} > 0$, m has a positive influence on ${p_t}^C$ and ${p_f}^C$.

$\frac{\partial {q_i}^A}{\partial m} = 2m\frac{(k^2(1+\lambda)-1)(s+\tau_0-(1-\alpha_i))}{(4-m^2-\left(k(1+\lambda)\right)^2)^2}$, $\frac{\partial {q_i}^B}{\partial m} = 2m\frac{(k^2(1+\lambda)-1)(s+\tau_0-(1-\alpha_i))}{(6-m^2-\left(k(1+\lambda)\right)^2)^2}$, $\frac{\partial {p_i}^A}{\partial m} = -2m\frac{(k^2(1+\lambda)-1)(s+\tau_0-(1-\alpha_i))}{(4-m^2-\left(k(1+\lambda)\right)^2)^2}$, $\frac{\partial {p_i}^B}{\partial m} = -2m\frac{(k^2(1+\lambda)-1)(s+\tau_0-(1-\alpha_i))}{(6-m^2-\left(k(1+\lambda)\right)^2)^2}$. when $k^2(1+\lambda) > 1$, m can promote ${q_i}^A$ and ${q_i}^B$, decrease ${p_i}^A$ and ${p_i}^B$, while the influence is the opposite when $k^2(1+\lambda) < 1$.

$\frac{\partial q_i{}^C}{\partial m} = 2m\frac{(\lambda k^2-1)(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} < 0$. m has a negative influence on $q_i{}^C$.

$\frac{\partial p_i{}^C}{\partial m} = -2m\frac{(\lambda k^2-1)(s+\tau_0-(1-\alpha_i))}{(6-2\lambda k^2(1+\lambda)-m^2)^2} > 0$. m has a positive influence on $p_i{}^C$.

$\pi_i = (1-p_i)q_i$, since the trends of q_i and p_i are the opposite as the change of m. Therefore, when $k^2(1+\lambda) > 1$, m can promote $\pi_i{}^A$, while the influence is the opposite when $k^2(1+\lambda) < 1$. when $k^2(1+\lambda) > 1$, m can promote $\pi_i{}^B$, while the influence is the opposite when $k^2(1+\lambda) < 1$. m has a negative influence on $\pi_i{}^C$.

It can be found that m has the same kind influence with s.

Proof of Proposition 2-6. $\frac{\partial \tau^A}{\partial \alpha_i} > 0$, $\frac{\partial \tau^B}{\partial \alpha_i} > 0$, $\frac{\partial \tau^C}{\partial \alpha_i} > 0$, $\frac{\partial v^A}{\partial \alpha_i} > 0$, $\frac{\partial v^B}{\partial \alpha_i} > 0$, $\frac{\partial v^C}{\partial \alpha_i} > 0$, $\frac{\partial q_f{}^A}{\partial \alpha_i} > 0$, $\frac{\partial q_f{}^B}{\partial \alpha_i} > 0$, $\frac{\partial q_f{}^C}{\partial \alpha_i} > 0$, $\frac{\partial \pi_f{}^A}{\partial \alpha_i} > 0$, $\frac{\partial \pi_f{}^B}{\partial \alpha_i} > 0$, $\frac{\partial \pi_{fr}{}^B}{\partial \alpha_i} > 0$, $\frac{\partial \pi_{fc}{}^B}{\partial \alpha_i} > 0$, $\frac{\partial \pi_f{}^C}{\partial \alpha_i} > 0$, $\frac{\partial \pi_{fr}{}^C}{\partial \alpha_i} > 0$, $\frac{\partial \pi_{fc}{}^C}{\partial \alpha_i} > 0$;

$\frac{\partial p_t{}^B}{\partial \alpha_i} < 0$, $\frac{\partial p_t{}^C}{\partial \alpha_i} < 0$,$\frac{\partial p_f{}^A}{\partial \alpha_i} < 0$, $\frac{\partial p_f{}^B}{\partial \alpha_i} < 0$, $\frac{\partial p_f{}^C}{\partial \alpha_i} < 0$, $\frac{\partial p_i{}^A}{\partial \alpha_i} < 0$, $\frac{\partial p_i{}^B}{\partial \alpha_i} < 0$, $\frac{\partial p_i{}^C}{\partial \alpha_i} < 0$, $\frac{\partial q_i{}^A}{\partial \alpha_i} > 0$, $\frac{\partial q_i{}^B}{\partial \alpha_i} > 0$, $\frac{\partial q_i{}^C}{\partial \alpha_i} > 0$.

$\pi_i = (1-p_i)q_i$, since q_i increases and p_i decreases as the increase of α_i. Therefore, α_i has a positive influence on π_i.

In summary, α_i has a positive influence on the collection efforts (v), green technology investment (τ), formal and informal collection quantity (q_f, q_i), formal and informal channel's profit ($\pi_{fc}, \pi_{fr}, \pi_f, \pi_i$). While it has a negative influence on the formal and informal payoffs (p_f, p_i), transferring price (p_t) in all the three models.

Proof of Proposition 2-7. (1) Using the difference of different equilibrium results, it can compare the difference among the three models. It calculates that $\tau^A > \tau^B > \tau^C$, $v^A > v^B > v^C$, ${q_f}^A > {q_f}^B > {q_f}^C$, ${\pi_{fr}}^B > {\pi_{fr}}^C$, ${\pi_{fc}}^B > {\pi_{fc}}^C$, ${\pi_f}^A > {\pi_f}^B = {\pi_{fr}}^B + {\pi_{fc}}^B > {\pi_f}^C = {\pi_{fr}}^C + {\pi_{fc}}^C$.

(2) ${p_t}^B - {p_t}^C = \frac{-\left(3+3\lambda-m^2-\lambda(k(1+\lambda))^2\right)k^2(1+\lambda)(s+\tau_0-(1-\alpha_i))+(3-m^2)}{(6-m^2-(k(1+\lambda))^2)(6-2\lambda k^2(1+\lambda)-m^2)}$, since $3+3\lambda-m^2-\lambda(k(1+\lambda))^2 = (1-m^2) + (2+3\lambda-\lambda(k(1+\lambda))^2) > 0$, therefore ${p_t}^B < {p_t}^C$.

${p_f}^B - {p_f}^C = \frac{k^2(1+\lambda)(\lambda k^2(1+\lambda)^2+m^2-4-2\lambda)(s+\tau_0-(1-\alpha_i))}{(6-m^2-(k(1+\lambda))^2)(6-2\lambda k^2(1+\lambda)-m^2)}$, Since $\lambda k^2(1+\lambda)^2+m^2-4-2\lambda = (m^2-1)+(-3-2\lambda+\lambda k^2(1+\lambda)^2) < 0$, therefore ${p_f}^B < {p_f}^C$ always holds; ${p_f}^A - {p_f}^B = \frac{\left(-4+2(k(1+\lambda))^2\right)(s+\tau_0+1-\alpha_i)}{(4-m^2-(k(1+\lambda))^2)(6-m^2-(k(1+\lambda))^2)}$, when $k(1+\lambda) > \sqrt{2}$, ${p_f}^A > {p_f}^B$, otherwise, ${p_f}^A < {p_f}^B$; ${p_f}^A - {p_f}^C = \frac{\left(4+k^2(1+\lambda)(\lambda k^2(1+\lambda)^2+m^2-4(1+\lambda))\right)(s+\tau_0-(1-\alpha_i))}{(4-m^2-(k(1+\lambda))^2)(6-2\lambda k^2(1+\lambda)-m^2)}$, when $4+k^2(1+\lambda)(\lambda k^2(1+\lambda)^2+m^2-4(1+\lambda)) > 0$, ${p_f}^A > {p_f}^C$, otherwise, ${p_f}^A < {p_f}^C$.

${q_i}^B - {q_i}^C = \frac{k^2(5-m^2+\lambda^2-\lambda k^2(1+\lambda)^2)(s+\tau_0-(1-\alpha_i))}{(6-m^2-(k(1+\lambda))^2)(6-2\lambda k^2(1+\lambda)-m^2)}$, $5-m^2+\lambda^2-\lambda k^2(1+\lambda)^2 = 4-m^2-(k(1+\lambda))^2+1+k^2(1+\lambda)^2+\lambda^2-\lambda k^2(1+\lambda)^2 = 4-m^2-(k(1+\lambda))^2+1+\lambda^2+k^2(1+\lambda)^2(1-\lambda)$, since $4-m^2-(k(1+\lambda))^2 > 0$ always holds in this study, $5-m^2+\lambda^2-\lambda k^2(1+\lambda)^2 > 0$ always holds. Therefore, ${q_i}^B > {q_i}^C$ always holds; ${q_i}^A - {q_i}^B = \frac{2(1-k^2(1+\lambda))(s+\tau_0+1-\alpha_i)}{(4-m^2-(k(1+\lambda))^2)(6-m^2-(k(1+\lambda))^2)}$, when $k^2(1+\lambda) < 1$, ${q_i}^A > {q_i}^B$, otherwise, ${q_i}^A < {q_i}^B$; ${q_i}^A - {q_i}^C = \frac{(-2-\lambda k^4(1+\lambda)^2+k^2(5-m^2+2\lambda+\lambda^2))(s+\tau_0-(1-\alpha_i))}{(6-m^2-(k(1+\lambda))^2)(6-2\lambda k^2(1+\lambda)-m^2)}$, when $-2-\lambda k^4(1+\lambda)^2+k^2(5-m^2+2\lambda+\lambda^2) > 0$, ${q_i}^A > {q_i}^C$, otherwise, ${q_i}^A < {q_i}^C$.

${p_i}^B - {p_i}^C = \frac{k^2\left(-(5-m^2+\lambda^2-\lambda k^2(1+\lambda)^2)\right)\left(s+\tau_0-(1-\alpha_i)\right)}{(6-m^2-\left(k(1+\lambda)\right)^2)(6-2\lambda k^2(1+\lambda)-m^2)}$, since $5 - m^2 + \lambda^2 - \lambda k^2(1+\lambda)^2 > 0$, therefore, ${p_i}^B < {p_i}^C$ always holds; ${p_i}^A - {p_i}^B = \frac{-2(1-k^2(1+\lambda))(s+\tau_0+1-\alpha_i)}{(4-m^2-\left(k(1+\lambda)\right)^2)(6-m^2-\left(k(1+\lambda)\right)^2)}$, when $k^2(1+\lambda) < 1$, ${p_i}^A < {p_i}^B$, otherwise, ${p_i}^A > {p_i}^B$; ${p_i}^A - {p_i}^C = \frac{-\left(-2-\lambda k^4(1+\lambda)^2+k^2(5-m^2+2\lambda+\lambda^2)\left(s+\tau_0-(1-\alpha_i)\right)\right)}{(6-m^2-\left(k(1+\lambda)\right)^2)(6-2\lambda k^2(1+\lambda)-m^2)}$, when $-2 - \lambda k^4(1+\lambda)^2 + k^2(5 - m^2 + 2\lambda + \lambda^2) > 0$, ${p_i}^A < {p_i}^C$, otherwise, ${p_i}^A > {p_i}^C$.

$\pi_i = (1 - p_i)q_i$, since ${q_i}^B > {q_i}^C$ and ${p_i}^B < {p_i}^C$, therefore ${\pi_i}^B > {\pi_i}^C$ always holds; likewise, it can be calculated that when $k^2(1+\lambda) < 1$, ${\pi_i}^A > {\pi_i}^B$, otherwise, ${\pi_i}^A < {\pi_i}^B$; when $-2 - \lambda k^4(1+\lambda)^2 + k^2(5 - m^2 + 2\lambda + \lambda^2 > 0$, ${\pi_i}^A > {\pi_i}^C$, otherwise, ${\pi_i}^A < {\pi_i}^C$.

In summary, ${p_t}^B < {p_t}^C$, ${p_f}^B < {p_f}^C$, ${q_i}^B > {q_i}^C$, ${p_i}^B < {p_i}^C$, ${\pi_i}^B > {\pi_i}^C$ always hold; when $k(1+\lambda) > \sqrt{2}$, ${p_f}^A > {p_f}^B$, otherwise, ${p_f}^A < {p_f}^B$; when $4 + k^2(1+\lambda)(\lambda k^2(1+\lambda)^2 + m^2 - 4(1+\lambda)) > 0$, ${p_f}^A > {p_f}^C$, otherwise, ${p_f}^A < {p_f}^C$; when $k^2(1+\lambda) < 1$, ${q_i}^A > {q_i}^B$, ${p_i}^A < {p_i}^B$, ${\pi_i}^A > {\pi_i}^B$, otherwise, ${q_i}^A < {q_i}^B$, ${p_i}^A > {p_i}^B$, ${\pi_i}^A < {\pi_i}^B$, when $-2 - \lambda k^4(1+\lambda)^2 + k^2(5 - m^2 + 2\lambda + \lambda^2) > 0$, ${q_i}^A > {q_i}^C$, ${p_i}^A < {p_i}^C$, ${\pi_i}^A > {\pi_i}^C$, otherwise, ${q_i}^A < {q_i}^C$, ${p_i}^A > {p_i}^C$, ${\pi_i}^A < {\pi_i}^C$.

Proof of Proposition 2-8. According to the equilibrium results of the informal channel's profit in the three models, it calculates that $\begin{cases} \frac{\partial^2 {\pi_i}^A}{\partial s^2} > 0 \\ \frac{\partial^2 {\pi_i}^B}{\partial s^2} > 0 \\ \frac{\partial^2 {\pi_i}^C}{\partial s^2} > 0 \end{cases}$. These second-order partial derivatives indicate that the π_i in all the three models are the convex functions with respect to s. Hence, there exists s to minimize the π_i.

Set $\begin{cases} \frac{\partial \pi_i{}^A}{\partial s} = \frac{2\left(k^2(1+\lambda)-1\right)^2(s+\tau_0-1)+2\left(k^2(1+\lambda)-1\right)(3-m^2-\lambda k^2(1+\lambda))\alpha_i}{(4-m^2-\left(k(1+\lambda)\right)^2)^2} = 0 \\ \frac{\partial \pi_i{}^B}{\partial s} = \frac{2\left(k^2(1+\lambda)-1\right)^2(s+\tau_0-1)+2\left(k^2(1+\lambda)-1\right)\left(5-m^2-\lambda k^2(1+\lambda)\right)\alpha_i}{(6-m^2-(k(1+\lambda))^2)^2} = 0 \\ \frac{\partial \pi_i{}^C}{\partial s} = \frac{2\left(\lambda k^2-1\right)^2(s+\tau_0-1)+2\left(\lambda k^2-1\right)(5-\lambda k^2(1+2\lambda)-m^2)\alpha_i}{(6-2\lambda k^2(1+\lambda)-m^2)^2} = 0 \end{cases}$, the optimal unit subsidies to minimize the informal channel's profit can be calculated for the three models.

$s^{*A} = \frac{1-k^2(1+\lambda)+(3-m^2-\lambda k^2(1+\lambda))\alpha_i}{1-k^2(1+\lambda)} - \tau_0$, $s^{*B} = \frac{1-k^2(1+\lambda)+(5-m^2-\lambda k^2(1+\lambda))\alpha_i}{1-k^2(1+\lambda)} - \tau_0$ and $s^{*C} = \frac{1-\lambda k^2+\left(5-\lambda k^2(1+2\lambda)-m^2\right)\alpha_i}{1-\lambda k^2} - \tau_0$.

Proof of Corollary 2-4.

$s^{*A} - s^{*B} = \frac{1-k^2(1+\lambda)+\left(3-m^2-\lambda k^2(1+\lambda)\right)\alpha_i}{1-k^2(1+\lambda)} - \tau_0 - \left(\frac{1-k^2(1+\lambda)+\left(5-m^2-\lambda k^2(1+\lambda)\right)\alpha_i}{1-k^2(1+\lambda)} - \tau_0\right) = \frac{-2\alpha_i}{1-k^2(1+\lambda)}$, when $k^2(1+\lambda) < 1$, $s^{*A} < s^{*B}$, when $k^2(1+\lambda) > 1$, $s^{*A} > s^{*B}$.

$s^{*B} - s^{*C} = \frac{1-k^2(1+\lambda)+\left(5-m^2-\lambda k^2(1+\lambda)\right)\alpha_i}{1-k^2(1+\lambda)} - \tau_0 - \left(\frac{1-\lambda k^2+\left(5-\lambda k^2(1+2\lambda)-m^2\right)\alpha_i}{1-\lambda k^2} - \tau_0\right) = \frac{(5-m^2-\lambda k^2(1+\lambda)^2+\lambda^2)k^2\alpha_i}{(1-k^2(1+\lambda))(1-\lambda k^2)}$, since $1-\lambda k^2 > 0$ and $5-m^2-\lambda k^2(1+\lambda)^2+\lambda^2 > 0$, when $k^2(1+\lambda) < 1$, $s^{*C} < s^{*B}$, when $k^2(1+\lambda) > 1$, $s^{*C} > s^{*B}$.

In summary, when $k^2(1+\lambda) > 1$, $s^{*A} > s^{*B}$, $s^{*C} > s^{*B}$.

When $k^2(1+\lambda) < 1$, comparing s^{*A} and s^{*C}.

$s^{*A} - s^{*C} = \frac{1-k^2(1+\lambda)+\left(3-m^2-\lambda k^2(1+\lambda)\right)\alpha_i}{1-k^2(1+\lambda)} - \tau_0 - \left(\frac{1-\lambda k^2+\left(5-\lambda k^2(1+2\lambda)-m^2\right)\alpha_i}{1-\lambda k^2} - \tau_0\right) = \frac{\left(\left(5+2\lambda+\lambda^2-m^2-\lambda k^2(1+\lambda)^2\right)k^2-2\right)\alpha_i}{(1-k^2(1+\lambda))(1-\lambda k^2)}$, the value difference of s^{*A} and s^{*C} $k^2(1+\lambda) < 1$ is considered. When $((5+2\lambda+\lambda^2-m^2-\lambda k^2(1+\lambda)^2)k^2-2) > 0$, $s^{*A} > s^{*C}$, when $(5+2\lambda+\lambda^2-m^2-\lambda k^2(1+\lambda)^2)k^2-2 < 0$, $s^{*A} < s^{*C}$.

Appendix C.

Proof of Proposition 3-1:

Based on the backward deduction rule, the optimal solutions of the informal recycler are initially analyzed. Set $\frac{\partial \pi_i}{\partial P_i} = 0$, Then, $P_i = \frac{\beta P - c_1 + P_f}{2}$.

Substituting P_i in the profit function of the formal recycler, we gain:

$$\max \pi_f(P_f) = \left(P - P_f - c_1 - c_2\right)\left[\frac{(3-2v)\alpha P_f - \alpha(\beta P - c_1)}{2P_f(1-v)} + (1-\alpha)\right] = f(x) \quad \text{(C-1)}$$

$$s.t. P_i = \frac{\beta P - c_1 + P_f}{2} < (2-v)P_f, \text{ and set } \mathrm{g(x)} = \beta P - c_1 - (3-2v)P_f < 0 \quad \text{(C-2)}$$

The Karush-Kuhn-Tucker (KKT) conditions of the above constrained optimization problem is shown as follows:

$$\begin{cases} \nabla f(x) + \lambda \nabla \mathrm{g(x)} = 0 \\ \lambda \mathrm{g(x)} = 0 \\ \lambda \geq 0 \end{cases} \quad \text{(C-3)}$$

After arrangement,

$$\begin{cases} \frac{-\alpha(3-2v)(P_f)^2 + \alpha(P - c_1 - c_2)(\beta P - c_1)}{2(1-v)(P_f)^2} - (1-\alpha) + \lambda(3-2v) = 0 \\ \lambda\left[\beta P - c_1 - (3-2v)P_f\right] = 0 \\ \lambda \geq 0 \end{cases} \quad \text{(C-4)}$$

① When λ=0,

$P_f = \sqrt{\frac{\alpha(P-c_1-c_2)(\beta P-c_1)}{2(1-v)(1-\alpha)+\alpha(3-2v)}}$ and $P_i = \frac{\beta P - c_1 + P_f}{2} = \frac{\beta P - c_1}{2} + \frac{1}{2}\sqrt{\frac{\alpha(P-c_1-c_2)(\beta P-c_1)}{2(1-v)(1-\alpha)+\alpha(3-2v)}}$.

Since g(x)<0, $\sqrt{\frac{\alpha(P-c_1-c_2)(\beta P-c_1)}{2(1-v)(1-\alpha)+\alpha(3-2v)}} > \frac{\beta P - c_1}{3-2v}$ is the condition should be met for above P_f and P_i.

Accordingly, $\beta < \frac{\alpha(3-2v)^2(P-c_1-c_2)}{P[2(1-v)(1-\alpha)+\alpha(3-2v)]} + \frac{c_1}{P}$, $v < \frac{3}{2} - \frac{(\beta P-c_1)+\sqrt{(\beta P-c_1)^2-4\alpha(1-\alpha)(P-c_1-c_2)(\beta P-c_1)}}{4\alpha(P-c_1-c_2)}$ should be satisfied.

② When $\lambda \neq 0$,

$P_f = \frac{\beta P-c_1}{3-2v}$.

Under this optimal condition, the informal collector will never send any collected WEEE to the formal recycler ($q_f = \alpha\frac{(2-v)P_f-P_i}{P_f(1-v)} + (1-\alpha) = 1-\alpha$, $q_{if} = 0$). We do not go to the details considering the goal of this study.

In the following study, we will focus on the condition of ①, where $\sqrt{\frac{\alpha(P-c_1-c_2)(\beta P-c_1)}{2(1-v)(1-\alpha)+\alpha(3-2v)}} > \frac{\beta P-c_1}{3-2v}$, under which the following quantity can be derived:

$$q_f = -\frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1)[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2}} + \frac{\alpha(3-2v)}{2(1-v)} + (1-\alpha) \qquad \text{(C-5)}$$

$$q_i = \frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1)[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2}} - \frac{\alpha}{2(1-v)} \qquad \text{(C-6)}$$

$$q_{if} = -\frac{1}{2(1-v)}\sqrt{\frac{\alpha(\beta P-c_1)[2(1-v)(1-\alpha)+\alpha(3-2v)]}{P-c_1-c_2}} + \frac{\alpha(3-2v)}{2(1-v)} \qquad \text{(C-7)}$$

Appendix D.

GM (1, 1) model

$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), x^{(0)}(3), \dots , x^{(0)}(n)\right)$, where n is the number of observations.

Define the series $X^{(1)}$ in the following way:

$X^{(1)} = \left(x^{(1)}(1), x^{(1)}(2), x^{(1)}(3), \dots , x^{(1)}(n)\right)$.

Where $x^{(1)}(1) = x^{(0)}(1)$, $x^{(1)}(2) = x^{(0)}(1) + x^{(0)}(2)$, … , $x^{(1)}(k) = \sum_{m=1}^{k} x^{(0)}(m)$

The GM (1, 1) model is defined by a first order differential equation:

$$\frac{dx^{(1)}(k)}{dk} + ax^{(1)}(k) = b$$

The solution can be obtained using the least-squares method:

$$[\hat{a}, \hat{b}]^T = (B^T B)^{-1} B^T x_n$$

Where $B = \begin{bmatrix} -0.5(x^{(1)}(1) + x^{(1)}(2)) & 1 \\ -0.5(x^{(1)}(2) + x^{(1)}(3)) & 1 \\ \vdots & \vdots \\ -0.5(x^{(1)}(n-1) + x^{(1)}(n)) & 1 \end{bmatrix}$

$x_n = [x^{(0)}(2), x^{(0)}(3), \dots , x^{(0)}(n)]$

Discrete solution of differential equation:

$\hat{x}^{(1)}(k) = \left(x^{(0)}(1) - \frac{\hat{b}}{\hat{a}}\right) e^{-\hat{a}(k-1)} + \frac{\hat{b}}{\hat{a}}$

Then the predicated series is calculated following the formula:

$x_{forecast}(1) = x^{(0)}(1)$,

$x_{forecast}(k) = \hat{x}^{(1)}(k) - \hat{x}^{(1)}(k-1)$, where $k = 2, 3, \dots, n$.

Appendix E.

Questionnaire and related information

In this study, we planned to investigate the lifetime distribution of mobile phones for every province (31 provinces in China). Considering the vast land area and limited finance, the online questionnaire survey is employed regardless of conducting direct interview. The questionnaire was put online through a professional questionnaire website named Tencent questionnaire (https://wj.qq.com/s/2315789/c86e), which is one of the biggest questionnaire websites in China. This questionnaire website provides basic questionnaire templates and can help develop the final questionnaire. The website itself is a platform to publish the developed questionnaire. Besides, the developed questionnaire can be shared through the social software in China, such QQ, Wechat. It deserves to emphasize that both the two mentioned social softwares and the Tencent questionnaire are all belong to the Tencent company, which is one of the biggest Internet companies in China. Besides professionally developing and easily publishing the questionnaire, the Tencent questionnaire also provides analysis tool to help preliminarily analyze the collected data. Meanwhile, all the collected data can be directly exported to SPSS and other analysis software.

We drafted the questionnaire and then shared with several Wechat friends to pre-validate the feasibility of the questionnaire. The feedback includes the answer time and the easy-understanding extent of the questionnaire. The questionnaire is easy to understand and averagely less than three minutes were taken to fulfill the questionnaire. Then we optimized and published the questionnaire on May 10, 2018. After then, we checked the questionnaire results twice every month and conducted the final check on January 2, 2019.

Based on the population in each of the 31 provinces, sample size for each province is calculated as around 385, resulting in at least a sum of 11935 respondents (The sample size is calculated under given the confidence level as 95%, the margin of error as 5). The collected data is not applied in this study considering the much lower responses. The reasons of fail to collect many responses required to build the lifespan model are preliminarily analyzed and summarized as follows:

Firstly, large size and dispersion of the sample as a consequence of too many specified locations in the survey. We planned to survey the lifetime distribution of mobile phones for every province. This requires huge respondents from all the 31 provinces and a certain amount of data from each province. However, the Internet population and the Internet-access frequency are different across provinces in China, which hinder the collection of enough data from each province;

Besides, may be the questionnaire method. Only the Online questionnaire is employed considering the finance problem. However, the low participation ratio of online questionnaire has been pointed out previously (Guo and Yan, 2017). Even though Snowball sampling may benefit the online questionnaire (online from friends to friends), however, regardless of the biases (Baltar and Brunet, 2012; Brace-Govan, 2004), it is impossible for the authors to get access to enough people from every province of China;

In addition, lack of temptation. Only small gifts are designed and prepared for each respondent, which is insufficient to induce enough people to participate in the survey. A certain temptation has been pointed out as necessary for gathering enough respondents (Schewe and Cournoyer, 1976; Yu et al., 2017).

In this study, we cited the lifetime distribution of mobile phones from the survey of Guo and Yan (2017). In their study, online and direct interviews questionnaire are jointly conducted from December 2014 to April 2015. The online survey targets are the entire country, whereas the direct interview is conducted at the city of Guangzhou, Changsha, Ganzhou. They compared the average lifetime of mobile phones in their study (1.73) with the results of Li et al. (2015) (1.9) to confirm their results. The average lifetime in these two studies are rather close, which makes it reasonable and acceptable.

Table E-1 Survey of mobile phone consumption habits in China

Survey of mobile phone consumption habits in China (excluding Hong Kong, Macao and Taiwan)		
Part one:		
01	Gender?	Male or Female
02	Age?	20≤; 20< ≤25; 25< ≤30; 30< ≤40; 40<
03	Monthly salary (or living expense in case no salary)?	1000≤; 1000< ≤2000; 2000< ≤3000; 3000< ≤5000; 5000< ≤8000; 8000< ≤10000; 10000< ≤20000; 20000<; secret
Part two:		
04	Province of respondent?	List of the 31 provinces in the mainland of China.
Part three:		
05	Number of mobile phone (including useless one)?	0; 1; 2; 3; 4≤
06	Utilization lifetime of the previous mobile phone (year)?	≤0.5; 0.5< ≤1; 1< ≤1.5; 1.5< ≤2; 2< ≤2.5; 2.5< ≤3; 3< ≤3.5; 3.5< ≤4; 4< ≤4.5; 4.5< ≤5; 5< ≤5.5; 5.5< ≤6; 6.5< ≤7; 7< ≤7.5; 7.5< ≤8; 8<
07	Utilization time of the latest mobile phone (year)?	≤0.5; 0.5< ≤1; 1< ≤1.5; 1.5< ≤2; 2< ≤2.5; 2.5< ≤3; 3< ≤3.5; 3.5< ≤4; 4< ≤4.5; 4.5< ≤5; 5< ≤5.5; 5.5< ≤6; 6.5< ≤7; 7< ≤7.5; 7.5< ≤8; 8<

08	Expectation utilization lifetime of the latest mobile phone (year)?	≤0.5; 0.5< ≤1; 1< ≤1.5; 1.5< ≤2; 2< ≤2.5; 2.5< ≤3; 3< ≤3.5; 3.5< ≤4; 4< ≤4.5; 4.5< ≤5; 5< ≤5.5; 5.5< ≤6; 6.5< ≤7; 7< ≤7.5; 7.5< ≤8; 8<
09	Is the latest mobile phone a new one or secondhand product?	New or secondhand
10	Purchase price of mobile phone?	≤1000; 1000< ≤2000; 2000< ≤3000; 3000< ≤4000; 4000<

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Appendix F.

Table F-1 Waste mobile phones in 31 provinces of China, from 1992 to 2036 (million units)

	Anhui	Beijing	Chongqing	Fujian	Guangdong	Gansu	Guangxi	Guizhou	Hainan
1992	0.02	0.53	0.20	0.04	1.77	0.00	0.06	0.01	0.00
1993	0.04	0.98	0.38	0.09	3.31	0.01	0.12	0.01	0.01
1994	0.06	1.10	0.46	0.13	3.85	0.01	0.16	0.02	0.01
1995	0.09	1.22	0.54	0.17	4.40	0.02	0.21	0.03	0.02
1996	0.12	1.46	0.65	0.24	5.14	0.03	0.28	0.04	0.03
1997	0.17	1.69	0.78	0.33	5.99	0.04	0.37	0.06	0.04
1998	0.25	1.87	0.94	0.45	6.92	0.06	0.48	0.09	0.06
1999	0.35	2.06	1.12	0.61	7.97	0.09	0.62	0.13	0.08
2000	0.49	2.30	1.33	0.83	9.19	0.14	0.81	0.19	0.11
2001	0.67	2.71	1.59	1.16	11.71	0.21	1.01	0.27	0.15
2002	0.95	3.11	1.88	1.57	13.23	0.30	1.33	0.40	0.21
2003	1.34	3.50	2.22	2.10	14.38	0.44	1.75	0.60	0.29
2004	2.23	4.09	2.18	3.10	15.24	0.83	2.02	1.03	0.45
2005	3.18	4.95	2.66	4.18	17.73	1.22	2.76	1.49	0.63
2006	3.91	5.83	3.49	4.99	23.08	1.49	3.72	1.92	0.75
2007	4.65	6.49	4.15	5.79	27.94	1.79	4.54	2.28	0.88
2008	5.45	6.86	4.70	6.78	31.39	2.33	5.31	2.84	1.10
2009	6.79	7.13	5.35	9.00	35.52	3.28	6.46	4.25	1.52
2010	8.00	7.43	5.76	10.92	37.24	4.17	7.45	5.41	1.86
2011	9.75	7.90	6.28	11.86	39.18	5.15	8.58	6.47	2.21
2012	12.36	9.45	7.06	13.40	42.86	6.20	9.88	7.86	2.62
2013	14.60	11.67	8.00	15.70	47.43	7.08	11.07	9.16	3.00
2014	16.47	13.36	9.31	18.09	55.45	7.86	12.85	10.36	3.42
2015	17.85	15.17	10.73	19.35	63.36	8.73	14.70	11.77	3.80
2016	18.68	17.36	11.81	19.40	66.81	9.23	15.93	12.85	4.08
2017	19.01	18.10	12.36	19.03	66.24	9.37	16.39	13.34	4.12
2018	19.91	19.15	12.92	20.09	72.61	9.88	17.32	14.13	4.35
2019	20.80	21.07	13.68	21.29	80.89	10.36	18.38	14.85	4.63
2020	21.23	23.03	14.44	21.81	86.46	10.55	19.08	15.18	4.79
2021	21.52	25.04	15.14	22.20	91.71	10.69	19.63	15.39	4.91
2022	21.74	27.14	15.77	22.57	97.06	10.80	20.10	15.56	5.02
2023	21.88	29.07	16.37	22.64	99.98	10.63	20.14	15.70	4.98
2024	21.97	31.10	16.90	22.71	103.06	10.49	20.18	15.79	4.94
2025	22.05	33.33	17.34	22.92	107.38	10.51	20.39	15.84	4.99
2026	22.10	35.62	17.73	23.11	111.63	10.54	20.56	15.88	5.03
2027	22.15	37.95	18.06	23.28	115.66	10.55	20.68	15.91	5.07

2028	22.17	40.32	18.35	23.44	119.53	10.56	20.78	15.92	5.10
2029	22.20	42.72	18.59	23.59	123.26	10.56	20.85	15.94	5.12
2030	22.21	45.15	18.80	23.74	126.85	10.56	20.91	15.94	5.15
2031	22.22	47.61	18.97	23.87	130.30	10.57	20.95	15.95	5.17
2032	22.23	50.09	19.11	24.01	133.62	10.57	20.99	15.95	5.20
2033	22.23	52.58	19.23	24.13	136.81	10.57	21.01	15.96	5.22
2034	22.24	55.09	19.32	24.26	139.90	10.57	21.04	15.96	5.24
2035	22.24	57.61	19.40	24.38	142.88	10.57	21.05	15.96	5.25
2036	22.24	60.14	19.46	24.50	145.75	10.57	21.06	15.96	5.27

Continuing

Hebei	Henan	Heilongjiang	Hubei	Hunan	Jilin	Jiangsu	Jiangxi	Liaoning	Neimenggu	Ningxia
0.07	0.10	0.27	0.02	0.03	0.09	0.14	0.04	0.06	0.01	0.006
0.14	0.20	0.51	0.04	0.07	0.17	0.29	0.08	0.13	0.02	0.013
0.20	0.27	0.61	0.06	0.10	0.22	0.39	0.11	0.18	0.02	0.02
0.27	0.35	0.71	0.09	0.14	0.28	0.51	0.15	0.24	0.04	0.03
0.37	0.46	0.85	0.13	0.19	0.36	0.67	0.19	0.32	0.05	0.03
0.50	0.61	1.01	0.19	0.27	0.46	0.89	0.26	0.43	0.08	0.05
0.68	0.81	1.20	0.27	0.37	0.58	1.17	0.34	0.58	0.12	0.06
0.92	1.07	1.42	0.40	0.52	0.74	1.54	0.45	0.78	0.18	0.09
1.24	1.40	1.68	0.59	0.72	0.93	2.02	0.60	1.04	0.27	0.12
1.68	1.82	1.95	0.86	0.98	1.18	2.67	0.77	1.39	0.39	0.16
2.23	2.40	2.30	1.23	1.35	1.47	3.47	0.99	1.84	0.57	0.21
2.95	3.15	2.73	1.76	1.86	1.82	4.44	1.30	2.40	0.83	0.28
3.80	3.54	3.21	2.61	2.68	2.18	6.36	1.82	3.57	1.42	0.35
5.30	4.66	3.81	3.79	3.68	2.74	8.41	2.33	4.79	2.08	0.53
6.66	6.18	4.46	5.00	4.59	3.27	9.92	2.93	5.34	2.61	0.71
8.06	7.96	5.01	6.19	5.54	3.98	11.34	3.59	6.00	3.09	0.83
9.93	10.27	5.64	7.47	6.68	4.88	12.75	4.23	7.16	3.76	0.97
12.84	13.78	6.67	9.57	8.73	5.78	15.75	5.18	9.45	5.40	1.27
14.80	16.23	7.47	11.62	10.53	6.34	18.36	6.08	11.35	6.39	1.48
16.75	18.03	8.22	13.70	12.42	6.99	21.62	7.06	12.89	7.12	1.68
19.04	20.19	9.15	15.52	14.54	7.82	26.04	8.39	14.49	8.54	1.94
21.77	22.67	10.37	17.79	16.69	8.87	29.99	10.12	16.27	10.12	2.32
24.34	25.90	11.75	19.71	18.99	9.93	33.24	11.54	18.42	11.21	2.66
26.30	31.01	13.45	20.24	20.57	10.64	35.67	12.56	19.77	11.89	2.84
27.58	34.64	14.96	20.51	21.45	11.33	36.54	13.25	20.23	11.81	2.96
27.91	35.19	15.22	20.67	21.72	11.55	36.51	13.70	19.85	11.04	3.02
28.95	37.10	16.42	21.20	22.33	12.11	38.86	14.62	20.81	11.57	3.21
30.18	39.61	18.11	21.72	23.08	12.82	41.33	15.53	22.03	12.34	3.41
30.93	41.20	19.34	21.91	23.54	13.23	42.57	16.10	22.53	12.53	3.53
31.52	42.42	20.44	22.03	23.87	13.55	43.52	16.57	22.87	12.63	3.62
32.04	43.45	21.50	22.12	24.13	13.82	44.37	16.97	23.18	12.74	3.71
32.39	43.70	22.21	22.22	24.34	13.82	44.91	17.12	23.43	12.66	3.79

32.70	43.91	22.89	22.28	24.51	13.82	45.38	17.24	23.64	12.60	3.86
33.03	44.35	23.65	22.31	24.64	13.94	45.89	17.44	23.82	12.64	3.93
33.34	44.72	24.35	22.33	24.75	14.05	46.35	17.62	23.98	12.68	3.99
33.62	44.99	24.96	22.34	24.85	14.13	46.75	17.76	24.12	12.71	4.05
33.88	45.19	25.49	22.35	24.93	14.19	47.11	17.88	24.25	12.73	4.11
34.13	45.35	25.97	22.36	25.00	14.24	47.45	17.99	24.37	12.76	4.17
34.36	45.47	26.38	22.36	25.07	14.28	47.76	18.08	24.48	12.78	4.23
34.60	45.56	26.73	22.36	25.14	14.31	48.05	18.16	24.58	12.80	4.29
34.82	45.63	27.04	22.36	25.19	14.34	48.33	18.24	24.68	12.82	4.35
35.04	45.68	27.30	22.37	25.25	14.36	48.60	18.31	24.78	12.84	4.40
35.26	45.72	27.53	22.37	25.31	14.37	48.86	18.37	24.87	12.85	4.46
35.48	45.75	27.72	22.37	25.36	14.39	49.12	18.43	24.96	12.87	4.52
35.69	45.78	27.89	22.37	25.41	14.40	49.36	18.48	25.06	12.88	4.57

Continuing

Qing hai	Shaan xi	Sichu an	Shand ong	Shang hai	Shan xi	Tianji n	Xinjia ng	Xizan g	Yunn an	Zhejia ng
0.002	0.02	0.08	0.10	0.52	0.04	0.02	0.02	0.001	0.05	0.39
0.004	0.04	0.16	0.21	0.97	0.08	0.04	0.03	0.001	0.11	0.75
0.006	0.06	0.21	0.29	1.13	0.10	0.06	0.04	0.002	0.14	0.93
0.009	0.08	0.28	0.38	1.29	0.14	0.08	0.06	0.003	0.19	1.13
0.013	0.11	0.37	0.51	1.48	0.19	0.11	0.08	0.004	0.25	1.39
0.02	0.16	0.50	0.69	1.70	0.26	0.16	0.12	0.005	0.32	1.71
0.03	0.23	0.68	0.92	1.95	0.35	0.21	0.16	0.008	0.42	2.12
0.04	0.33	0.91	1.24	2.23	0.47	0.29	0.23	0.011	0.55	2.60
0.06	0.46	1.21	1.66	2.53	0.62	0.40	0.31	0.02	0.72	3.17
0.08	0.65	1.57	2.24	3.08	0.85	0.55	0.45	0.02	0.95	3.94
0.12	0.92	2.10	2.97	3.52	1.12	0.74	0.61	0.03	1.22	4.78
0.17	1.29	2.80	3.90	3.87	1.47	0.97	0.81	0.05	1.57	5.71
0.30	1.90	3.71	5.18	4.18	1.85	1.32	1.22	0.09	2.12	6.65
0.43	2.69	5.12	6.78	4.84	2.55	1.69	1.79	0.14	2.72	8.43
0.52	3.43	6.59	8.33	5.71	3.29	1.95	2.14	0.18	3.27	10.30
0.59	4.10	7.62	10.17	6.48	3.90	2.21	2.38	0.20	3.96	11.77
0.73	5.10	8.74	12.61	7.14	4.54	2.61	2.87	0.26	4.79	13.37
0.98	7.43	11.08	17.63	7.98	6.45	3.39	3.91	0.34	6.33	16.09
1.13	8.89	13.04	20.91	8.53	7.89	3.89	4.72	0.39	7.64	18.06
1.29	9.97	15.62	23.02	9.21	8.62	4.29	5.09	0.51	8.72	19.84
1.65	11.28	18.58	26.15	10.27	9.68	4.81	5.81	0.66	9.99	22.71
2.02	12.83	21.66	30.10	11.64	10.87	5.49	7.16	0.83	11.41	25.75
2.28	14.40	24.63	33.07	13.08	12.27	5.98	8.56	0.97	13.01	28.77
2.40	15.57	27.66	35.89	14.13	13.72	6.04	9.12	1.13	15.05	31.23
2.41	16.14	29.82	38.33	14.71	14.61	5.96	9.00	1.17	16.52	32.78
2.35	16.36	30.89	40.72	14.34	14.79	6.15	8.90	1.17	16.96	33.24
2.51	17.04	32.56	42.47	15.29	15.44	6.40	9.64	1.26	18.16	35.57

2.69	17.68	34.22	43.73	16.77	16.23	6.59	10.38	1.35	19.55	38.28
2.76	18.00	35.29	44.93	17.71	16.72	6.79	10.73	1.40	20.47	40.03
2.80	18.23	36.11	45.95	18.58	17.12	7.00	11.03	1.44	21.22	41.56
2.85	18.42	36.75	46.80	19.47	17.47	7.20	11.31	1.48	21.89	43.00
2.89	18.21	37.47	47.29	20.16	17.67	7.27	11.29	1.51	21.85	43.92
2.93	18.04	38.02	47.71	20.87	17.86	7.36	11.30	1.54	21.83	44.79
2.97	18.09	38.33	48.20	21.69	18.08	7.54	11.46	1.57	22.13	45.83
3.00	18.14	38.55	48.64	22.52	18.28	7.72	11.62	1.59	22.39	46.79
3.03	18.17	38.73	49.02	23.33	18.46	7.89	11.77	1.62	22.60	47.68
3.06	18.19	38.86	49.37	24.14	18.63	8.07	11.90	1.65	22.76	48.50
3.10	18.20	38.96	49.69	24.94	18.79	8.25	12.04	1.67	22.90	49.28
3.13	18.22	39.04	49.99	25.75	18.95	8.44	12.16	1.70	23.02	50.02
3.16	18.22	39.10	50.28	26.56	19.09	8.62	12.28	1.72	23.12	50.72
3.19	18.23	39.14	50.55	27.37	19.24	8.81	12.40	1.75	23.21	51.39
3.22	18.24	39.17	50.81	28.18	19.38	9.00	12.52	1.77	23.29	52.04
3.25	18.24	39.19	51.07	29.00	19.51	9.19	12.63	1.80	23.35	52.66
3.28	18.25	39.21	51.32	29.83	19.65	9.39	12.74	1.82	23.41	53.28
3.32	18.25	39.23	51.57	30.66	19.78	9.58	12.85	1.85	23.46	53.87