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DISSERTATION

DEVELOPMENT OF INTEGRATED E-WASTE MANAGEMENT SYSTEM BASED ON RESOURCE-SAVING IN CHINA

Speciality 073 - Management
(Field of study 07 – Management and administration)

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The dissertation contains the results of own research. The use of ideas, results and texts of other authors have references to the relevant source

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In terms of volume and environmental impact on the planet, electronic waste (e-waste) has become the fastest growing waste stream in the world. However, the officially recorded collection and recycling rate is only 17.4%, so recycling activities have not kept pace with the global growth of e-waste. The distribution and environmental impact of e-waste varies across regions of the globe. In developed countries, there is usually infrastructure for e-waste recycling, but in low- and middle-income countries the infrastructure for managing e-waste is still underdeveloped or non-existent, and therefore e-waste is mainly managed by the informal sector. In such cases, e-waste is usually disposed of in poor conditions, posing a serious threat to human health and causing serious environmental pollution in the areas where it is collected and disposed of. E-waste has a complex composition, containing both hazardous and valuable substances, and is known as urban mine. It contains several precious, critical and other non-critical metals that can be used as secondary materials if recycled. Unfortunately, specialized technologies are rarely used and a large amount of e-waste is disposed of outside the formal treatment system. Rough technologies are very ineffective in recovering resources, as recycling in this case is usually concentrated on a few high-value elements, with low recovery rates, while most other metals are discarded and inevitably lost.

Governments around the world are formulating national e-waste regulations and legislation to cope with the increase in end-of-life electrical and electronic products. In most countries, current e-waste legislation includes bans on the import and export of e-waste, recycling requirements for specific types of e-waste and extended producer responsibility. The EU has a long history of e-waste legislation. The EU Waste Electric and Electronic Equipment Directive, which has been in force since early 2003, is a comprehensive e-waste management law that governs the collection, recycling and resource recovery process. Another directive, the Restriction of Hazardous Substances Directive, aimed at modifying product design and packaging to restrict the use of six toxic materials in the manufacturing process. China has enacted laws banning the import of hazardous e-waste, and in addition, the Chinese government has passed the “Measures for the Prevention and Control of Pollution from Electronic Information Products” and the “Regulations on the Collection and Disposal of Waste Electrical and Electronic Equipment”. China has established a fund for the disposal of waste electrical and electronic equipment (WEEE) to finance the recovery and treatment of e-waste.

China's e-waste recycling system is very poorly organized and consists of both the formal and informal sectors, with the informal sector dominating until 2003. In 2009, China introduced the "old for new" household appliance replacement policy, which encourages consumers to participate in the recycling of end-of-life household appliances through formal channels. In 2012, the Chinese government implemented the WEEE recycling fund management scheme and provided fixed subsidies to certified e-waste treatment plants based on the actual amount of e-waste dismantled. Afterwards, the subsidy policy for the disposal fund of discarded electrical and electronic products was improved. In 2020, China implemented the “Program on Improving the Recycling and Disposal System for Waste Household Appliances and Promoting the Renewal of Household Appliance Consumption", and took many specific actions to support household appliance manufacturers, sales and recycling enterprises in establishing diversified recycling channels. There are six main ways of handling e-waste in China. Peddlers collect about 60% of recyclable e-waste. Approximately 20% of recyclable e-waste is collected by distributors or retailers, mainly through "old for new" policy. Only 10% of recyclable e-waste is collected by specialized collectors. A small amount of e-waste is recycled in the second-hand market. Smaller sized e-waste products are always discarded at home or sometimes in municipal solid waste.

Circular economy (CE) is the good point of sustainability because it provides a set of practices that can generate more sustainable operations, making organizational sustainability possible. In an ideal CE, all generated waste would be reused as raw materials in the production process. The implementation of the CE is mainly due to the lack of information, which makes digital transformation an ideal enabler of the CE. The rapid development of digital technologies (DTs) has facilitated the waste management process in CE, and the application of smart technologies provides new opportunities for more effective e-waste management. This study provides a comprehensive understanding of the current research status on intelligent e-waste management in China through a systematic literature review and content analysis. Based on this, advanced DTs used in the e-waste management are discussed. With the rapid development of Internet and the popularity of e-commerce, Internet-based e-waste collection provides consumers with a simple and formal channel to dispose of their e-waste, overcoming the limitations of traditional e-waste collection. E-waste management based on the Internet of Things (IoT) and cloud platforms has created a smarter way of managing and disposing of waste, with IoT technology collecting information about the content and location of trash cans from monitors on the lids and transmitting the information to the e-waste collection team through a centralized server. Artificial intelligence (AI) technology has the potential to revolutionize e-waste management by improving efficiency, accuracy and sustainability. After collected, e-waste can be sorted using AI algorithms, making it easier to recover valuable elements, reducing the demand for original resources. AI technology can also be used to create decision support systems for managing e-waste that can recommend the most appropriate recycling practices, disposal options, and resource recovery technologies based on data analytics and machine learning algorithms.

Many companies in China are applying the IoT, big data, cloud computing and AI to develop smart e-waste collection and recycling systems, and this study introduces the latest progress of smart e-waste collection and classification measures in China, which have been implemented and scaled up through local businesses and entrepreneurial initiatives as an alternative to informal methods. The results highlight the potential of smart technologies in e-waste management.

The recycling of waste electronic products involves national legislation, payment mechanisms, definition of responsibilities of relevant recycling and treatment entities, and government supervision. China's e-waste management is relatively backward, and developed countries' e-waste management system and practical experience can provide us with learning and reference. This study analyzed the e-waste recycling and treatment systems of the Netherlands, Belgium, Sweden, Germany and Switzerland, the countries in Europe where e-waste management legislation and practice were carried out earlier, and the extended producer responsibility system has become a recognized principle. It also introduced the Japanese government's home appliance law and recycling system, and the U.S. state laws and regulations on the recycling and treatment of waste electronic products as well as professional waste electronic product recycling and treatment companies.

The recycling of e-waste can adopt an integrated strategy, which can be divided into three types: vertically integrated recycling mode with manufacturers as the center, vertically integrated recycling mode centered on third-party recycling and treatment, and horizontally integrated mode with joint recycling and treatment as the core, and analyzed the advantages of each mode. The characteristics of the market for refurbished/remanufactured electrical and electronic products after the recovery of e-waste and how to improve the utilization rate of used electrical and electronic products and reduce the cost of refurbishment/remanufacturing were investigated.

Literature studies shows that DTs have positively influenced the shift from a linear to a CE model and have facilitated the implementation of circular strategies by enterprises. However, how should enterprises apply various DTs of Industry 4.0 throughout the whole product lifecycle to implement CE-related strategies. This study presents a conceptual framework for exploring DTs in CE operations from the perspective of product lifecycle. The rapid development of DTs such as IoT, Cyber-Physical Systems, Cloud Computing, AI, Big Data Analytics, and Digital Twins has mobilized automation and data exchange in the smart manufacturing and production processes to reduce overconsumption and production errors, improve efficiency, and thus drive sustainable development. This study investigates the relationship between CE and DTs to identify the role of DTs in supporting CE implementation.

Various business model innovation approaches have been proposed to support CE. DTs can achieve circular goals through interrelated monitoring, control, optimization, and automation functions. DTs applied to service-oriented product-service systems (PSS) can help to innovate circular business models, fully utilize idle resources, and provide high-quality personalized services. Shifting business thinking from linear economy to CE faces many challenges, requiring appropriate management of sustainable production and consumption patterns, closed-loop supply chains and PSS. This study provides useful insights into the digitization of circular business models, helping to understand the role and functionality of DTs in circular business with whole lifecycle management, especially in the design and recovery phases.

In addition, we studied how various Industry 4.0 DTs, such as IoT, Big Data, and Cloud Computing, can be utilized to enable the transition to CE. The goal of Industry 4.0 is to use DTs to improve the manufacturing of high-quality products at the lowest cost. Industry 4.0 offers alternatives for sustainable production and consumption, minimizing energy loss, resource consumption and environmental degradation. Industry 4.0 provides a new perspective on how the manufacturing industry can utilize new technologies to create value with maximum output and minimum resource utilization. Based on the literature analysis, six DTs have been identified as primarily Industry 4.0 technologies relevant to CE: cyber-physical systems, IoT, AI, Big Data Analytics, Additive Manufacturing, and Simulation. DTs play an important role in environmental sustainable operation decision making, and the synergies and sustainability of Industry 4.0 will further contribute to a sustainable society.

To measure the impact of DTs on CE development, we defined CE performance objectives. We adopted three CE performance objectives: using fewer materials and resources by improving resource efficiency, extending product lifespan, and closing the loop. we clarified how DTs promote CE performance objectives in terms of the three stages of the product lifecycle: product design, product use, and product recovery. In the initial stage of the product lifecycle, that is, the design stage, DTs help realize the circular design of the product, such as detachable and recyclable components, to achieve the third CE performance objective, that is, to close the loop. In addition, product design to increase lifespan helps achieve the second CE performance objective, that is, to slow down resource flows. In the middle of the product lifecycle, that is, the use stage, the application of DTs makes the product "smart"; thus, value is no longer generated from the design and production stages, but from the use stage. IoT technology can monitor and track product activities, collect usage data, and combine with cloud computing, big data analytics, and AI to provide technical support for product use, guide users on optimizing the product use, extend product lifetime, and accomplish the CE second performance objective, which is to slow down resource consumption. Based on the usage data, the product design can be improved to satisfy the CE first performance objective, enhance the efficiency of raw materials, and reduce the flow of resources. DTs also facilitate preventive or predictive maintenance; thus, products can maintain a longer service life. At the end stage of product lifecycle, the loop can be closed by streaming the product into a second lifecycle or by efficient recycling through efficient reverse logistics systems. However, in the final stage of the product life cycle, CE activities are closely related to the design in the initial stage of the product life cycle. Increasing the investment in DTs in the product design stage is necessary to create conditions for the product to close the loop in the end stage.

Circular business models, such as access-based product-service system (AB-PSS), have been enabled by DTs. In recent years, bike-sharing systems have flourished in smart cities. As a typical example, intelligent transportation systems can effectively improve the mobility and safety while reducing the impact on the environment. Bike-sharing service is based on the company's time-sharing rental model, which provides many public bicycles to the public in public places. To illustrate the impact of DTs on CE, we studied the case of shared bicycles service. In the case of shared bicycles, DTs enables improvements in CE. DTs combined with the AB-PSS business model can improve resource efficiency, extend product life, and close the loop on resource flows. By examining how DTs affect CE performance objectives, the conceptual framework developed provides further insights into the role of DTs as a CE enabler in terms of the product lifecycle. Our findings provide a practical reference for researchers and managers to utilize the potential of DTs to support CE transformation.

This study systematically researches the construction of the evaluation index system of urban CE and the selection of evaluation indicators, and proposes a set of methods for constructing the evaluation index system of urban CE, and applies them to practical case of Chinese cities. When designing the evaluation index system for urban CE, it is necessary to follow the principles: scientific principle, systematic principle, dynamic principle, comparability principle, operability principle and territorial principle. The methodology applied in the evaluation of urban CE includes 4 steps. First, a critical literature review was conducted based on PRISMA to identify the theoretical basis for the contribution of digital technology to smart city CE and to establish an evaluation framework for urban CE. A reasonable conceptual framework was selected as the basis for establishing the indicators, and effective indicators were identified in the Chinese context. Second, the raw data of the indicators are standardized. Third, analytic hierarchy process method was used to calculate the weight values of the indicators within the framework. Finally, the formula was utilized to calculate the evaluation index of urban CE. The index system is divided into three levels: the guideline layer, the elementary layer and the indicator layer, and the guideline layer is divided into the economic subsystem, the social subsystem and the environmental subsystem, which are comprehensively measured and examined as a whole. The elementary layer is based on five levels: economic strength, economic efficiency, reduced use of resources, reuse and resource recovery, and ecological environment. Through investigation and research, a total of 17 quantitative indicators were selected for the indicator level, each with practical and meaningful data support.

The use of advanced technology to improve urban management in smart cities has become an important trend for future urban development, and urban CE is regarded as an important way to realize sustainable urban development. This study established an urban CE evaluation index system, including the selection and standardization of evaluation indexes, calculates the weights through the analytic hierarchy process method, and finally calculates the CE evaluation indexes of prefecture-level cities in China. This study empirically examines the relationship, mediating effect, and timing mechanism of smart city policies on environmental pollution reduction and urban CE development based on the panel data of 253 prefecture-level cities in China from 2003 to 2017 by using difference in difference method. The results of the empirical analysis show that (a) smart city construction has a significant relationship with environmental pollution emission reduction and urban CE development; (b) the implementation of smart city policies can increase the contribution to urban CE development through technological innovation; and (c) This study further proves that with the support of technological innovation, smart cities have a long-lasting impact on the development of CE. Moreover, when we conducted robustness testing, the conclusion remained valid. Further examining the results of the study on the difference-in-difference method of smart cities on environmental pollution and CE, the study finds that smart city policies promote environmental pollution reduction and urban CE development through technological innovation. This study provides insights for urban policy makers and managers to implement urban transformation for smart city and CE development.

This dissertation promotes e-waste management in Xinxiang city from the perspective of digital technology. It explores the construction of an advanced, efficient, and intelligent recycling management program for e-waste in Xinxiang city, and tries to guide practice through case studies. This study proposes an intelligent recycling system for e-waste based on IoT technology. On the one hand, for large volume waste home appliance, reservation and quotation can be made in advance through online methods such as websites, smartphone application, and WeChat applet, and door-to-door pickup of large e-waste can be realized for residents. On the other hand, for small waste appliances, IoT smart recycling bins set up in communities and major commercial areas are used as recycling carriers. By setting up an infrared full container alarm system in the smart recycling bins at each recycling outlet, real-time analysis of back-office data is used to plan optimized logistics and recycling routes.

In addition, after the delivery of waste appliances is completed, the value of the delivered waste will be exchanged through the back-end settlement system at the first time, thus incentivizing more residents to participate in the formal recycling of waste appliances. IoT technology is the key to building an intelligent recycling system for waste household appliances. Key DTs such as radio frequency identification tags, warehouse management barcodes, logistics tracking technology, data sharing and data backtracking provide an intelligent platform for urban e-waste management.

This study explores the construction of an intelligent logistics and recycling system for the recycling of e-waste in Xinxiang city, which consists of four parts: e-waste logistics and recycling network coverage, e-waste logistics and recycling process tracking, e-waste logistics and recycling routes intelligent recommendation, and e-waste inventory management. The e-waste logistics and recycling network will be combined with the intelligent recycling bins based on IoT to build a three-tier logistics and recycling system with "points, stations and centers" as the core. By setting up community collection points (collection booths or mobile collection vehicles), regional collection stations (collection stores) and regional collection centers (processing and utilization centers), a new intelligent integrated recycling system with reasonable layout and comprehensive coverage will be formed.

The tracking of the recycling process of the reverse logistics of used and end-of-life household appliances will utilize the logistics tracking technology, adopting the fusion of multiple tracking technologies to realize the heterogeneous sharing and chain query of waste household appliance reverse logistics recycling data. Through the wireless communication network and technology, comprehensive road traffic information is obtained, global positioning system /GIS control center is used to obtain the road traffic condition and the state of logistics vehicles on the recycling logistics network, the whole process of vehicles is tracked, the comprehensive control of the recycling logistics state is realized. The visualization management platform is established to visualize the utilization plan of the recycling vehicles, the optimization of the transportation scheme and the dynamic control of the vehicles and goods within the platform. Based on logistics and recycling information data management, it establishes the inventory management of waste household appliances, collects all the data in the work of inventory processing, and realizes the inventory decision-making support.

A questionnaire survey was conducted among the citizens of Xinxiang city, and statistical analysis methods were used to determine the relationship between the variables. It was found that residents' willingness to recycle e-waste will directly affect residents' e-waste recycling behavior. Residents' willingness to recycle e-waste is influenced by the internal environment, thereby adjusting residents' e-waste recycling behavior. Residents' willingness to recycle e-waste is affected by the external environment, thereby regulating residents' e-waste recycling behavior. The incentives for residents to recycle e-waste will adjust residents' willingness to promote the sustainable development of e-waste recycling. Addressing barriers to e-waste recycling will adjust residents' willingness to recycle e-waste, intervene in residents' behavior, and promote the sustainable development of e-waste recycling.

Adopting relevant incentives to solve the problems caused by e-waste recycling barriers will increase residents' willingness to recycle e-waste, thereby intervening in residents' behavior and promoting the sustainable development of e-waste recycling.

We combined the incentive system with the smart e-waste collection system to construct a set of incentives suitable for China's smart e-waste recycling system, which is conducive to improving the e-waste recycling rate and has applicability. Existing smart e-waste collection systems use a single economic incentive method. It faces fierce competition from unauthorized informal recyclers, resulting in a small number of users and inability to fully utilize its advantages. In the reverse logistics of e-waste recycling, consumers are the starting point of product recycling. By analyzing the characteristics and determinants of Chinese users' recycling behavior, this study selects appropriate incentives for a smart e-waste collection system to meet Chinese consumers' perceptions of WEEE. The incentive system is based on economic incentives, including currency, reward points, and tax incentives, and combines negative incentives, mainly fines. Rewards and punishments are employed simultaneously to achieve long-term and sustainable incentive effects. The incentive system is based on the convenient infrastructure of the smart e-waste collection system, and its financial model must be shared by multiple stakeholders from the government, smart e-waste systems, and manufacturers.

Keywords: electronic waste, circular economy, sustainable development, sustainability, waste management, recycling, Industry 4.0, smart e-waste collection, circular business model, product-service system, product circularity, recycling behavior, digital technologies, Internet of Things, social responsibility, China, innovation technology, energy consumption, environmental management, development.

АНОТАЦІЯ

Хан Яфень. Розвиток інтегрованої системи управління електронними відходами на основі ресурсозбереження в Китаї. – Кваліфікаційна наукова робота на правах рукопису.

Дисертація на здобуття наукового ступеня доктора філософії за спеціальністю 073 – Менеджмент. – Сумський національний аграрний університет, Суми, 2023.

Відходи електричного та електронного обладнання (з англ. "waste electrical and electronic equipment") є одним із швидко зростаючих потоків відходів у світі, який характеризується багатокомпонентним складом і наявністю небезпечних речовин. Офіційно зареєстрований рівень збирання та переробки цих відходів у світі становить лише 17,4%. Необхідність мінімізації негативного впливу електронних відходів на довкілля та наявність цінних компонентів обумовлюють необхідність впровадження прогресивних систем їх роздільного збирання та переробки на засадах ресурсозбереження із застосуванням digital-технологій. Аналіз останніх аналітичних звітів свідчить, що у розвинутих країнах існує інфраструктура для збирання та переробки електронних відходів, в той час як у країнах з низьким і середнім рівнем доходу така інфраструктура або взагалі відсутня, або недостатньо розвинена, в результаті чого набуває розвитку неформальний сектор переробки, для якого відсутні будь-які норми і стандарти.

В процесі дослідження встановлено, що країни усього світу створюють дієву нормативну базу у сфері поводження з електронними відходів на засадах сталості, яка включає низку законів, національні плани і програми. Так, Європейський Союз має довгу історію розвитку законодавства щодо поводження з електронними відходами. Директива ЄС "Про вироби електричного та електронного обладнання та його відходи", яка набула чинності на початку 2003 року, є комплексним законодавчим документом,

який регулює процеси збирання, переробки та відновлення ресурсів. Директива ЄС "Про обмеження використання небезпечних речовин у електричному та електронному обладнанні" (з англ. "Restriction of Hazardous Substances in Electrical and Electronic Equipment") спрямована на зміну дизайну виробу та упаковки задля обмеження використання шести небезпечних речовин у виробничому процесі. Китай, у свою чергу, також прийняв низку нормативних актів, серед яких основними є "Заходи щодо запобігання та контролю забруднення електронними виробами" та "Положення про збір та утилізацію відходів електричного та електронного обладнання". В цілому, раціональне поводження з відпрацьованими електронними виробами потребує удосконалення національного законодавства, розроблення механізмів покриття витрат, визначення обов’язків відповідних організацій зі збирання та переробки відходів. У роботі було проаналізовано нормативне забезпечення у сфері поводження з електронними відходами у Нідерландах, Бельгії, Швеції, Німеччині та Швейцарії, закон Японії "Про побутову техніку та систему переробки", закони та норми США щодо поводження з цими відходами. За результатами дослідження встановлено, що система управління електронними відходами в Китаї є недосконалою у порівнянні з прогресивними країнами світу.

Виявлено, що на сьогодні концептуальною основою рециклінгу відпрацьованих виробів є модель циркулярної економіки. Огляд літератури показав, що цифрові технології сприяють прискоренню переходу від лінійної моделі економіки до циркулярної. Було встановлено шість типів digital-технологій Industry 4.0, що мають відношення до циркулярної моделі економіки, зокрема: кіберфізична система (з англ. "Cyber-Physical Systems"), Інтернет речей (з англ. "Internet of Things"), технології штучного інтелекту (з англ. "Artificial Intelligence Technologies"), аналітика великих даних (з англ. "Big Data Analytics"), адитивне виробництво (з англ. "Additive Manufacturing") і технології симуляцій (з англ. "Simulation"). Було доведено, що цифрові технології відіграють важливу роль у прийнятті рішень щодо екологічно безпечної економічної діяльності, у тому числі у сфері поводження з відходами, а синергія та стійкість Industry 4.0 сприятиме подальшому розвитку сталого суспільства.

За результатами дослідження автором розроблено концептуальну основу циркулярної моделі економіки на основі застосування digital-технологій, впроваджених на усіх етапах життєвого циклу продукту. Мова йде про застосування різних digital-технологій Industry 4.0, охоплюючи увесь життєвий цикл продукту задля прискорення переходу до циркулярної моделі. На початковій стадії життєвого циклу, тобто на стадії проектування, цифрові технології можуть сприяти реалізації дизайну виробу відповідно до циркулярних стратегій. Стосовно стадії використання, застосування відповідних технологій (а саме хмарних технологій, аналітики великих даних і штучного інтелекту) робить внесок у моніторинг даного процесу задля подовження терміну служби продукту. Завершальна стадія життєвого циклу продукту тісно пов’язана з його проектуванням на початковій стадії. Виходячи з цього, зроблено висновок, що збільшення інвестицій у застосування digital-технологій на стадії проектування продукту є необхідним для створення передумов для замикання матеріальної петлі на кінцевій стадії.

Запропоновано систему індикаторів оцінки рівня розвитку циркулярної моделі на рівні міста. На відміну від існуючих, викладена система базується на 17 індикаторах, диференційованих за трьома вимірами «економіка-ресурси-довкілля» з п'ятьма відповідними показниками оцінки, у тому числі: (i) економічна спроможність, (ii) економічна ефективність, (iii) скорочення ресурсів, (iv) зменшення забруднення та (v) повторне використання та рециклінг. При розробленні системи індикаторів оцінки для циркулярної економіки міста необхідно дотримуватись наступних принципів: наукового обґрунтування, системного підходу, динамічності, сумісності, оперативності та територіальної приналежності. Науково-методичний підхід, застосований в оцінці рівня циркулярної економіки, включає чотири кроки. По-перше, на основі застосування PRISMA-методу було проведено огляд літератури, щоб сформувати методологічну основу для дослідження внеску цифрових технологій у створення smart-міста та для формування системи індикаторів оцінки циркулярної економіки міста. По-друге, було стандартизовано вихідні дані виявлених індикаторів. По-третє, для розрахунку вагових значень індикаторів було використано метод аналітичного ієрархічного процесу. На останньому кроці була використана формула для обчислення системи індикаторів оцінки циркулярної економіки міста. Система індикаторів була поділена на три рівні та після цього обрано 17 кількісних показників в якості індикаторів.

У роботі викладено результати емпіричного дослідження взаємозв’язку застосування smart-технологій зі зменшенням забруднення навколишнього середовища і розвитком циркулярної економіки міста на основі даних 253 міст на рівні префектур у Китаї з 2003 по 2017 роки. Результати дослідження показують, що створення smart-міста має значний зв’язок зі скороченням викидів забруднюючих речовин та розвитком економіки замкнутого циклу міста. Реалізація політики smart-міста може сприяти розвитку циркулярної економіки за рахунок технологічних інновацій. У ході виконання дослідження було доведено, що завдяки підтримці технологічних інновацій smart-міста мають тривалий вплив на розвиток економіки замкнутого циклу. У роботі викладено практичні рекомендації для органів місцевої влади та менеджерів щодо економічного розвитку міста на засадах smart-технологій та принципів циркулярної моделі.

За результатами дослідження автором запропоновано науково-методичний підхід щодо формування системи управління електронними відходами відповідно до принципів моделі циркулярної економіки на основі впровадження digital-технологій та smart-систем поводження з ними. Даний підхід сприятиме сталому управлінню електронними відходами в місті Сіньсян. Встановлюючи інфрачервону систему сигналізації повного контейнера для smart-контейнерів на кожному пункті збирання, було запропоновано використовувати "back-office" даних в реальному часі для планування і оптимізації маршрутів збирання. В результаті вартість збирання відходів буде зменшуватись, стимулюючи споживачів використовувати офіційні канали повернення відпрацьованих виробів.

В роботі запропоновано smart-систему збирання та переробки електронних відходів у місті Сіньсян, яка базується на створенні трирівневої системи логістики, що включає громадські пункти збирання, регіональні станції та центри збирання. Обґрунтовано доцільність об'єднання мережі збирання електронних відходів зі smart-контейнерами на основі застосування технологій Інтернету речей, щоб побудувати трирівневу систему логістики та подальшої переробки електронних відходів. Встановлюючи пункти збору (стаціонарні кабіни або пересувні засоби), регіональні пункти збору (склади збору) і регіональні центри збору (центри обробки та утилізації) буде сформовано нову інтелектуальну інтегровану систему переробки зі smart-плануванням і повним територіальним покриттям.

В дисертації приведено результати опитування жителів міста Сіньсян для виявлення факторів впливу на їх поведінку щодо належного поводження з відпрацьованими виробами. За результатами цього дослідження було встановлено, що бажання мешканців позбуватися електронних відходів належним чином безпосередньо впливатиме на відповідну поведінку. Саме створення системи стимулів для мешканців буде сприяти раціональній поведінці, а отже і розвитку системи поводження з електронними відходами.

З метою формування раціональної поведінки споживачів, у роботі викладено перелік науково обґрунтованих економічних стимулів, які відповідають вимогам smart-системи поводження з електронними відходами відповідно до встановлених законодавчих вимог в Китаї. Це заохочує споживачів до використання платформ smart-переробки електронних відходів. Запропоновано об'єднати систему заохочення зі smart-системою збирання електронних відходів. Існуючі smart-системи їх збирання використовують єдиний метод економічного стимулювання, який стикається із жорсткою конкуренцією з боку неавторизованих неофіційних переробників, що призводить до невеликої кількості залучених користувачів. У зворотній логістиці споживачі є відправною точкою переробки продукту. Аналізуючи характеристики та детермінанти поведінки китайських споживачів щодо переробки, дане дослідження пропонує відповідні стимули для smart-систем збирання електронних відходів. Запропонована система стимулювання ґрунтується на економічних стимулах, зокрема грошова винагорода, податкові пільги, штрафи, що призведе до досягнення довгострокових і стійких економічних та соціальних ефектів.

Ключові слова: електронні відходи, циркулярна економіка, сталий розвиток, стійкість, управління відходами, рециклінг, Індустрія 4.0, smart-система збирання електронних відходів, бізнес-модель, система "продукт-послуга", циркулярність продукту, поведінка споживача, digital-технології, Інтернет речей, соціальна відповідальність, інноваційні технології, енергоспоживання, екологічний менеджмент, розвиток, Китай.

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LIST OF ABBREVIATIONS

E-waste – Electronic waste

EEE – Electrical and electronic equipment

WEEE – Waste electrical and electronic equipment

EU – European Union

DTs – digital technologies

CE – circular economy

PSS – product-service systems

AB-PSS – access-based product-service systems

AI – Artificial Intelligence

ICT – Information and communication technology

IoT – Internet of Things

EPR – Extended Producer Responsibility

IT – Information technology

RFID – Radio frequency identification

GPS – Global positioning system

AHP – Analytic Hierarchy Process

DID method – Difference in difference method

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INTRODUCTION

Relevance of the topic. With the rapid development of science and technology, people use more and more electronic products in their daily life, and the intelligent electronic products are updated rapidly. People replace them frequently, resulting in many electronic waste products. The recycling of waste electronic products has become a new recycling field. Waste electronic products which are rich in many precious mineral resources have high reuse value, if we can fully excavate and make good use of these resources. It is realistic to solve the problem of resource shortages and environmental disruption encountered in China's current economic development. The recycling of waste electronic products in China is still not standardized, most of the waste electronic products have not been recycled rationally, which has brought serious consequences to the environment and society. Developing circular economy (CE), it is imperative to realize resource recycling and alleviate the negative impact of waste electronic products on society and environment. However, the recycling of waste electronic products in China is not ideal, which needs further study.

The recycling of waste electronic products not only saves a lot of resources and energy, but also brings social and economic benefits for manufacturers and processors, avoids environmental pollution, and protects people’s health. Therefore, the research on the recycling of waste electronic products is particularly important for the establishment of a CE society.

A CE is fundamentally different from a linear economy. A linear economy traditionally follows the “take-make-dispose” step by step plan which means that raw materials are collected, then transformed into products that are used until they are finally discarded as waste. Value is created in this economic system by producing and selling as many products as possible. CE comes as an alternative to the method of the linear economy, which works in a far smoother and more sustainable way. The focus of CE is to maintain the added value of material while minimizing waste, and concentrated on the usage of products as resources. Looking at the whole lifecycle of a product, Cradle to grave is the standard lifecycle mode in the linear economy. In contrast, the CE adheres to Cradle-to-Cradle (C2C) design, which seeks to reuse all materials and eliminate waste.

The concept and research of CE has aroused great interest among scholars and practitioners. The 3R principles (reduce, reuse, recycle) are widely acknowledged as the foundation of CE. The reduction principle is aimed at the input side, and its purpose is to minimize resources consumption without affecting the production process, to achieve the purpose of saving resources, reducing the pressure on natural resources, and improving production efficiency. The reuse principle focuses on the production process, which means to find new ways to use things that otherwise would have been thrown out. Reuse the all or part of waste directly or after repair, renovation, and remanufacturing through clean production technology, and at the same time improves the production process to maximize the use of input resources. Manufacturers are required to extend the product life longer, to prevent products from becoming waste prematurely, and resist disposable goods. The principle of recycling is mainly aimed at the output side. Its purpose is to turn something old and useless into something new and useful, realize the closed-loop of material flow, transform waste into renewable resources and further reduce the original exploitation and utilization of natural resources. R strategies have been conceptualized in different ways. 10R principles of CE include refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recovery, which are not equally important in CE implementation.

The CE is the optimal point of sustainability, because it provides a set of practices that can produce more sustainable operations, making sustainability possible in organizations. Intelligent methods were used in electronic waste (e-waste) management in the construction of smart cities. The e-waste collection and management in smart cities is shifting from peddler collection and manual sorting procedures to sustainable systems based on various smart technologies. It has great potential to develop more sustainable business practices to manage e-waste from a closed-loop lifecycle perspective. All this determined the choice of the topic, purpose, and objectives of the study.

Connection of work with scientific programs, plans, topics.

The subject of this study is consistent with the basic principles of “The 2030 Agenda for Sustainable Development” (Resolution 70/1 of UN General Assembly), the “European Green Deal” (Announcement of the European Commission in 2019), the “Sustainable Development Strategy of Ukraine until 2030” (draft No. 9015 of 07.08.2018), and “China's National Plan on the Implementation of the 2030 Agenda for Sustainable Development” (Announcement of the Chinese government in 2019).

The dissertation was carried out following the topic of scientific research of the Erasmus+ Programme of the European Union within the project "Towards circular economy thinking & ideation in Ukraine according to the EU action plan" (grant number 620966-EPP-1-2020), in which the author investigated the foreign experience of management of CE-related e-waste management system.

The purpose of the study is to develop of an integrated e-waste management system based on resource-saving in China to achieve the dual effects of environment and economy through the collection, recycling, and remanufacturing of waste electronic products.

The purpose requires addressing the following objectives:

- To explore progressive recycling mode of waste electronic products, making use of new technology to carry out recycling innovation strategy to provide new decision-making ideas for regular recycling enterprises to improve the recycling amount of e-waste;

- To summarize the recycling mode suitable for China's national conditions, not limited to the implement extended producer responsibility (EPR) system;

- To propose countermeasures to control e-waste pollution and realize e-waste management for smart city construction, drawing on the advanced management experience of e-waste in developed countries;

- To develop a scientific and methodical approach to format a closed-loop intelligent management system of e-waste based on information and digital technologies (DTs);

- To develop an evaluation index system to assess management performance of urban CE, and apply it to practical case of Chinese cities;

- To conduct a case study on the status of e-waste management and the citizens' attitudes and behaviors to recycle e-waste in Chinese city to determine the ideal shape of an effective urban e-waste management;

- To propose the incentive system to construct a set of incentives suitable for China's smart e-waste recycling system.

The object of the study is the e-waste management in line with the circular economy principles in China.

The subject of the study is the collection and recycling processes of e-waste management driven by digital technologies.

Research methods. The methodological foundation of the thesis work is the basic provisions of economic theory and management theory, which becomes the basis for studying e-waste management system. In accordance with the defined tasks, a wide list of research methods were adopted in the study: bibliometric analyses to identify the current status and recycle mode in the e-waste management; system analysis and generalization methods to analysis of the concept and characteristics of reverse logistics of e-waste; structural-logical analysis to develop the preconditions and principles of formation of the system of management of e-waste in accordance with the requirements of the circular model; causal and consequential connections - to clarify the essence of DTs in smart city construction and urban CE development; statistical analysis to identify the trends of e-waste management with the development of science and technology; surveys and interviews to test scientific hypotheses which are factors and obstruction of waste electronic products recycling management; comparison analysis to investigate the incentive mechanism and Countermeasures of waste electrical and electronic products management system.

The information base of the study was the legislative and normative acts of the People's Republic of China, the official materials of the CNR Statistics Committee and the provinces, scientific articles by Ukrainian and Chinese, reports, analytical documents, Internet resources and author calculations.

The scientific novelty of the obtained results is based on CE theory and in accordance with the legally established requirements in the field of e-waste management in China, we utilized new digital technologies to implement innovative CE-related recycling strategies, and developed the integrated e-waste management system for China based on resource-saving. The scientific essence could be concluded as follows:

First obtained：

- The scientific and methodological approach to form a system for urban e-waste management and to facilitate the implementation of the CE model based on the application of digital technologies and an intelligent recycling system towards the formalization of e-waste recycling has been proposed.

Improved:

- The conceptual framework for a digitally enabled circular economy in the context of the product life cycle has been developed. Unlike the existing ones, it involves the various Industry 4.0 DTs covering all stages of the product life cycle to accelerate the CE transition.

- The evaluation index system for assessing the level of CE development at the city level has been proposed. As opposed to the existing ones, it is based on 17 indicators differentiated by three "economy-resources-environment" dimensions with five relevant evaluation metrics, including (i) economic strength, (ii) economic efficiency, (iii) resource reduction, (iv) pollution reduction, and (v) reuse and recycling.

- An intelligent logistics and recycling system for e-waste management based on advanced digital technologies in city Xinxiang has been developed and designed, which is based on the setting up a three-tier logistics and recycling system with community collection points, regional collection stations and regional collection centers as its core, and as opposed to available one, it forms a new type of intelligent and comprehensive recycling system with reasonable layout and comprehensive coverage.

Further developed:

- The academic researches on smart e-waste recycling in China and cutting-edge smart e-waste recycling solutions from commercial and emerging technology companies have been structured based on the extensive literature review which allowed identifying key challenges and providing countermeasures for future smart e-waste management.

- The insights in the form of practical recommendations for urban policymakers and managers have been outlined to implement urban transformation towards smart cities and CE by using wide range of technology innovations towards environmental pollution prevention and saving the value of materials and products in the economic system as long as possible.

- A set of scientifically justified economic incentives eligible for smart e-waste recycling system in line with the legally established requirements in this field in China has been proposed, which encourages consumers engagement to using the smart e-waste recycling platform.

The scientific and practical significance of the dissertation lies in improving e-waste management in cities, providing insights for city policymakers and managers to implement urban transformation to the development of urban smartness and CE, and providing a practical reference for researchers and managers to capitalize the potential of DTs to support CE transition.

Applicant's personal contribution. The scientific provisions, methods and techniques, experiments, statistical treatments, and analysis of results of the dissertation are obtained by the author and reflected in published works. Interpret and summarize the results, draw the dissertation's conclusions, and make practical recommendations under the supervisor's guidance.

Approbation of the results of the dissertation. The main provisions and results of the research were presented and received general scientific approval at the annual scientific reports and conferences of faculty and graduate students at Sumy National Agrarian University (Sumy, Ukraine, 2019-2022); The main results of the dissertation were published at 6 national and international scientific conferences ([6-10] in the list of publications given in the annotation); International Scientific Conference “2nd Congress on Intelligent Systems” (CIS2021), (04-05.09.2021, Bengaluru, India); VII International Scientific-Practical Conference “Modern Management: Trends, Problems and Prospects for Development” (14.04.2021, Dnipro, Ukraine); International Scientific Conference “Answers on Nowadays Economic and Environmental Challenges in a Vision of Scientists”, (25-26.06.2019, Odessa, Ukraine); the scientific and practical conference “Economic development in the context of integration into the European research and innovation area”, (23-24.06.2023,Vinnytsia, Ukraine); IV International scientific and theoretical conference “science of XXI century: development, main theories and achievements”, (30.06.2023, Helsinki, Finland); X International scientific and practical conference “science and technology: problems, prospects and innovations”, (6-8.07.2023, Osaka, Japan).

Publication of obtained results. The main provisions of the dissertation are published in 9 scientific publications, including subsections in 1 book; 2 articles in scientific professional publications of Ukraine, which are included in international scient metric databases, 2 articles in a foreign publication indexed by the Scopus and Web of Science databases, the rest are conference proceedings.

Scope and structure of the dissertation. The dissertation consists of an introduction, three sections, conclusions, a list of references, and appendices. The total volume of work is 323 pages, in particular: 269 pages of the main text, 51 tables, 37 figures, and 3 appendices, a list of references that includes 260 items.

SECTION 1. THEORETICAL FOUNDATION OF THE FORMATION OF AN ELECTRONIC WASTE MANAGEMENT SYSTEM

1.1 Thorough analysis of the global electronic waste accumulation and assessment of circular economy potential

Electrical and Electronic Equipment (EEE) includes a wide range of products with circuity or electrical components with a power or battery supply. EEE is widely used in everyday household and business use, but it is also increasingly used in transport, health, security systems, and generators of energy. EEE consumption is closely correlated with generalized worldwide economic growth (Baldé et al., 2017). EEE has grown essential in modern life and is raising living standards, but is also counterproductive to improving living standards due to the high resource requirements of its production and use. The amount of EEE is increasing because of higher levels of disposable incomes, increasing urbanization and mobility, and further industrialization in some regions of the world. The total weight of annual global EEE consumption rises by 2.5 (Baldé et al., 2017) million metric tons (Mt) on average (excluding solar panels). EEE is discarded after use without the intent of reuse by its owner, creating a waste stream that contains valuable and hazardous materials. This waste stream is referred to as E-waste, also known as electronic waste, or Waste Electrical and Electronic Equipment (WEEE).

EEE comprises of a large variety of products. For statistical purposes, it is divided into 54 different product-centric categories which are grouped into six general categories corresponding closely to their waste management characteristics (Forti et al., 2018). The six main categories are shown as Table 1.1.

Table 1.1 – Six main categories of WEEE

Category	Contents
1.Temperature exchange equipment	Fridges, freezers, air conditioners, and heat pumps
2. Screens and monitors	Liquid crystal displays and light-emitting diode televisions and monitors, laptops, and tablets
3. Lamps	Fluorescent lamps, high intensity discharge lamps, and light-emitting diode lamps
4. Large equipment	Dishwashers, washing machines, ovens and central heating systems, large printing systems, and photovoltaic panels
5. Small equipment	Microwaves, grills and toasters, personal care products, speakers, cameras, audio sets and headphones, as well as toys, household tools, and medical and monitoring systems
6. Small information technology (IT) and telecommunication equipment	Desktop personal computers, printers, mobile phones, cordless phones, keyboards, routers, and consoles

Source: prepared by the author based on (Forti et al., 2018)

Global e-waste generated by year and per capita are shown in Figure 1.1. E-waste has become the fastest-growing waste stream in the world in terms of volume and its environmental impact on the planet. The Global E-Waste Monitor 2020 (Forti et al., 2020) reported that the global production of e-waste in 2019 reached an astonishingly high mark of 53.6 million tons, an average of 7.3 kg per capita. It is estimated that the amount of e-waste generated will exceed 74Mt in 2030. Thus, the global quantity of e-waste is increasing at an alarming rate of almost 2 Mt per year. In 2019, the formal documented collection and recycling was 9.3 Mt, and only 17.4 % of e-waste was officially collected and recycled (Forti et al., 2020). Compared with the year of 2014, the formal documented collection and recycling grew 1.8Mt. However, the total e-waste generation increased by 9.2Mt. This illustrates that recycling activities are not keeping pace with the global growth of e-waste. The corresponding quantities and proportions of the six main categories of global e-waste in 2019 are shown in Figure 1.2. Among the e-waste categories measured by weight, small equipment ranked first, accounting for the largest proportion of 32% (Forti et al., 2020).

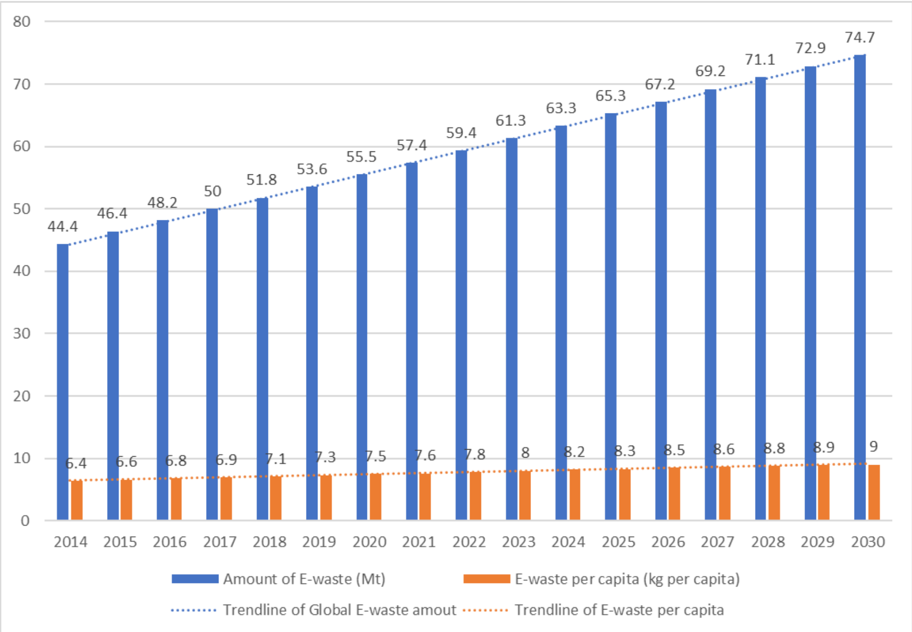

Figure 1.1 – Global e-waste generated by year (statistics data from 2014 - 2019; forecast data from 2020 - 2030)

Source: prepared by the author based on the Global E-waste Monitor 2020

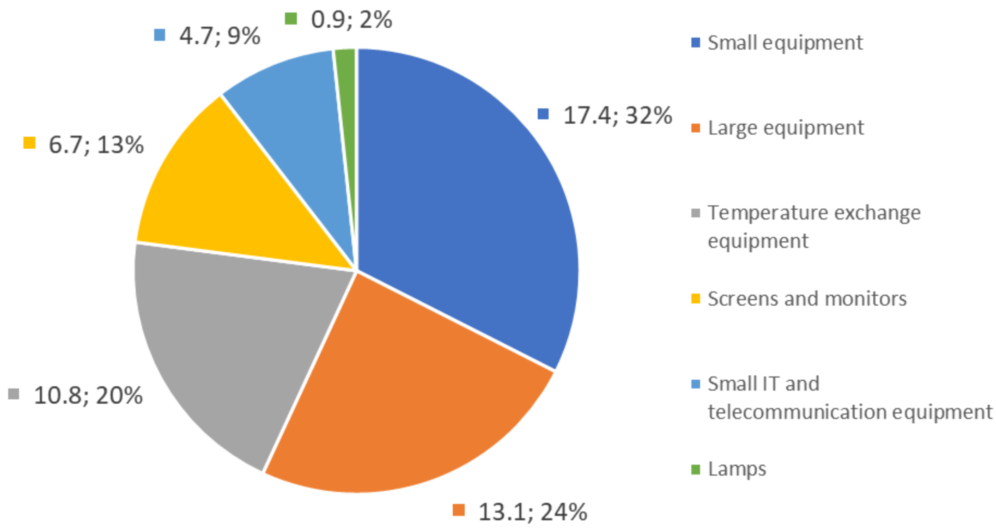

Figure 1.2 – Six categories of E-waste generated in 2019 (Mt, %)

Source: prepared by the author based on the Global E-waste Monitor 2020

Higher consumption rates of EEE, short life cycle, and few repair options, all of which lead to the growing amount of e-waste. Figure 1.3 shows e-waste generated in each continent (Mt), generated per capita (kg per capita), e-waste documented to be collected and properly recycled (Mt), and proportion (%). Asia generated the highest quantity of e-waste in 2019 at 24.9 Mt. Americas was second (13.1 Mt), followed by the Europe (12 Mt), while Africa and Oceania generated 2.9 Mt and 0.7 Mt, respectively. Europe ranked first worldwide in terms of e-waste generation per capita with 16.2 kg per capita, followed by the Oceania (16.1 kg per capita) and Americas (13.3 kg per capita), while Asia and Africa generated just 5.6 and 2.5 kg per capita, respectively. Additionally, Europe had the greatest formal e-waste collection and recycling rate (42.5%) among all continents (Forti et al., 2020). The amount of e-waste that has been officially documented as being collected and recycled is much less than the predicted amount of e-waste generated on the other continents. The current data shows that in 2019, Asia came in second place with 11.7%, the Americas and Oceania were similar at 9.4% and 8.8%, respectively, and Africa ranked last with 0.9%. However, statistics might range significantly between different regions because consumption and disposal habits depend on a variety of factors, such as income level, policy in force, waste management system structure (Forti et al., 2020).

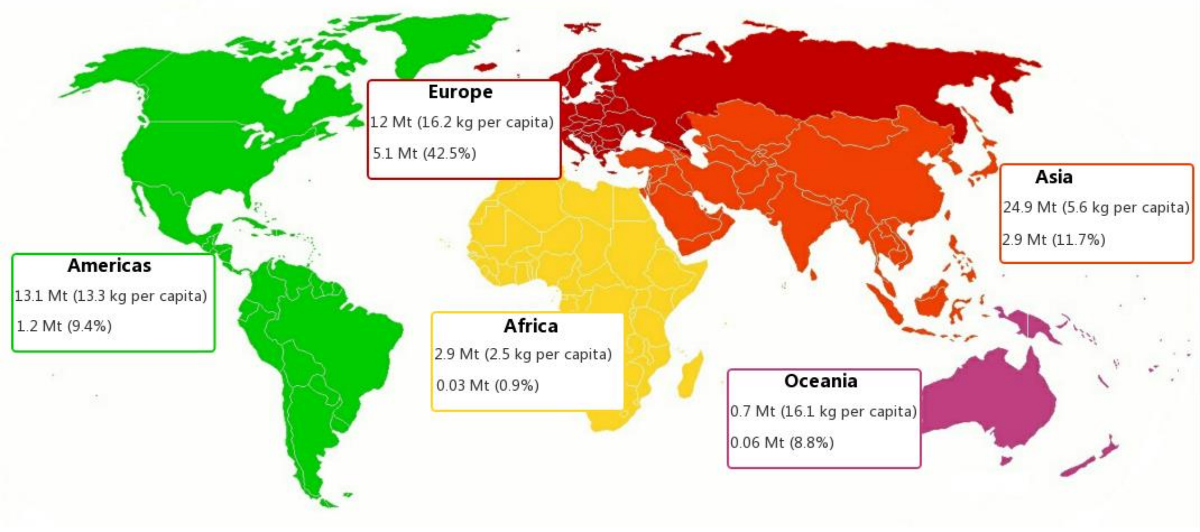

Figure 1.3 – E-waste generation and recycling by continent in 2019

Source: prepared by the author based on the Global E-waste Monitor 2020

The fate of 82.6% (44.3 Mt) of e-waste generated in 2019 is uncertain, with fate and environmental impact varying by region. In high income countries, a waste recycling infrastructure is usually developed, and: (i) About 8% of the e-waste, mainly consisting of small devices and small IT, ends up in waste bins and then landfilled or incinerated. (ii) Discarded products can sometimes be refurbished and reused, so they are often shipped as second-hand products from high-income to low- or middle-income countries. Transboundary movements of used EEE or e-waste are estimated to represent 7-20% of e-waste generated. (iii) The majority of undocumented household and business e-waste is presumably mixed with other waste streams, like plastic and metal waste (Forti et al., 2020). This indicates that while easily recyclable fractions may be recycled, it is frequently done in subpar circumstances, without depollution and without recovering all useful materials. Hence, such cycling is not recommended. In middle- and low-income countries, the infrastructure for managing e-waste is still underdeveloped or nonexistent. Therefore, e-waste is mainly managed by the informal sector. In this context, e-waste is often handled in poor conditions, with serious health impacts on workers, as well as children who often live, or play close to e-waste management activities (Forti et al., 2020).

E-waste is one of the most hazardous categories of solid household waste (Kumar et al., 2017). They contain more than 1000 different substances, representing as many as 60 elements in the periodic table, many of which are toxic, especially lead, mercury, cadmium, chromium. E-waste also contains several toxic additives, including brominated flame retardants, polychlorinated biphenyl and hydrochlorofluorocarbons or chlorofluorocarbons. Significant threats to the environment and to human health are posed by the rising amounts of e-waste, low collection rates, and environmentally irresponsible disposal and handling of e-waste stream (Kuehr, 2012). A total of 50 t of mercury and 71 kt of BFR plastics are found in globally undocumented flows of e-waste annually. In the United States, 70% of mercury and cadmium in the landfills come from e-waste (Tanskanen, 2013).

Serious pollution has been caused in the areas where e-waste was collected (Ruan & Xu, 2016). The association between e-waste exposure and its health impacts was investigated. The number of studies on the negative effects of e-waste are increasing. These studies have highlighted the risks to human health associated with exposure to well-studied toxins, such as cadmium, lead. Adverse effects include negative birth outcomes, altered neurodevelopment, negative learning outcomes, DNA damage, negative cardiovascular effects, negative respiratory effects, negative effects on the immune system, hearing loss, skin diseases, and cancer.

Physical health outcomes, such as thyroid function, reproductive health, and lung function, are the most vulnerable to the human body effects of e-waste exposure, especially in children and infants (Song & Li, 2014). Because of their unique vulnerability and susceptibility to environmental toxicants, associations between exposure to informal e-waste recycling and the health of them have been focused. According to studies, exposure to informal e-waste recycling is linked to adverse birth outcomes (stillbirth, premature birth, lower gestational age, smaller birth weight and length, and lower Apgar scores), growth acceleration or retardation, altered neurodevelopment, negative learning and behavioural outcomes, immune system function, and lung function. Brominated flame retardants found in e-waste plastic have negative effects on the nervous system and interfere with mammalian reproductive. The lead component, which is typically found in antique televisions' cathode ray tube, lead-acid batteries, cable sheathing, and printed circuit board solder, causes symptoms such as vomiting, diarrhoea, convulsions, coma, and even death. Cadmium can bioaccumulate in the environment and is extremely toxic to humans; in particular, it adversely affects kidneys and bones, as well as flu-like symptoms (Grant et al., 2013).

Informal treatment methods including open burning, coal-fired grill heating, and acid bath leaching have caused lasting damage to soil, plant, groundwater, and nearby air, as well as large increases in heavy metal concentrations in food (Song & Li, 2014). According to tissue samples, residents living near e-waste handling/processing sites and personnel at e-waste recycling facilities show high levels of contaminants associated with e-waste, such as Polybrominated biphenyl, Polybrominated diphenyl ether, polychlorinated dibenzo-p-dioxins and dibenzofurans, polychlorinated biphenyl, and heavy metals (Wang et al., 2016). Workers engaged in unauthorized e-waste recycling and dismantling suffer a higher risk of injury because there are no standards governing workplace health and safety. Additionally, stress, headaches, shortness of breath, chest pain, weakness, and dizziness have been reported by e-waste workers.

Improper e-waste disposal and processing not only harms the local environment and human health, but also contributes to global warming and climate change by emitting substantial amounts of carbon dioxide. As World Loop's analysis of sustainable e-waste management shows, every ton of e-waste properly collected and recycled saves 1.44 tons of CO_2 emissions (Offsetting the Negative Impacts of E-Waste, 2021). If the materials in e-waste are not recycled, they cannot substitute primary raw materials and reduce greenhouse gas emissions from extraction and refinement of primary raw materials. Additionally, some temperature exchange equipment uses refrigerants that are greenhouse gases. Unsustainable disposal of discarded refrigerators and air conditioners resulted in the emission of 98 Mt of CO_2 equivalents into the atmosphere. This represents roughly 0.3% of the world's emissions related to energy in 2019 (O'Neill, 2020).

E-waste is an 'urban mine', since it contains several precious, critical, and other non-critical metals that, if recycled, can be used as secondary materials. But the complex composition of e-waste, which contains both valuable and hazardous substances, requires specialized, often “high-tech” methods to dispose of e-waste as an urban mine to maximize resource recovery and minimize potential harm to humans and the environment. Unfortunately, the specialized techniques are rarely used, with a significant amount of e-waste handled outside of appropriate systems. One of the major issues was the transportation of e-waste to developing countries. There, crude techniques are often used to extract precious materials or recycle parts for further use. These local “backyard” techniques pose dangers to poorly protected workers and their local natural environment. Furthermore, these methods are very ineffective at recovering resources because recycling in these situations typically concentrates on a few valuable elements like gold and copper (with frequently low recycling yields), while most other metals are thrown away and inevitably lost.

The UNU estimates that the value of raw materials generated in the global e-waste is equal to approximately $57 billion USD in 2019. Gold, copper, and iron are the main contributors to this value. With the documented e-waste collection and recycling rate of 17.4%, 4 Mt of raw materials could be made accessible for recycling, with a raw material value of $10 billion USD recovered from e-waste in an environmentally sound manner globally. A net 15 Mt of CO_2 was saved by recycling iron, aluminium, and copper, equal to the emissions from the recycling of secondary raw materials in place of virgin materials (Liu et al., 2023). To take advantage of the opportunities and concurrently mitigate pollution, good regulations are required to build an infrastructure that will guarantee that all collected e-waste is handled using cutting-edge technologies and that green employment opportunities are created.

As the sense of crisis surrounding e-waste, governments all over the world are developing national e-waste regulations and legislation to deal with the increase in end-of-life electrical and electronic products. Such policies outline strategies or plans of action and suggest potential outcomes for a society, institution, or company in a non-binding way. As of October 2019, 71% of the world's population was covered by a national e-waste policy, legislation, or regulation. This is an improvement over 2014, when only 44% of the population was covered, as the most populous countries like China and India now have functioning national legal systems (Patil & Ramakrishna, 2020). But currently, less than half of all countries in the world (78 out of 193) are covered by a law, policy, or regulation.

In most countries, current e-waste legislation includes bans on e-waste import/export, recycling requirements for specific types of e-waste, and EPR (Ilankoon et al., 2018; Shuptar-Poryvaieva et al., 2020). The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal was signed in Basel, Switzerland, to prevent the transportation of hazardous waste from developed countries to developing countries in Asia and Africa. The convention went into effect in 1992, and it has been ratified by 187 countries now. The Convention aims to protect human health and the environment, but fails to eliminate e-waste exportation totally.

The European Union (EU) is predicted to produce 7 Mt of e-waste with the largest amount per capita at 15kg. The EU has a relatively long-running history of e-waste legislation. The WEEE Directive of EU was been in law since early 2003. Further, in 2012, WEEE directive (2012/19/EU) was passed by commission for uniform regulation of e-waste management in its country (Patil & Ramakrishna, 2020). This directive is a comprehensive e-waste management law that governs the collection, recycling, and resource recovery processes. The directive has implemented with the EPR principle in which the manufacturers shall also take the responsibility of product recycling over the post-consumer stage of a product's lifecycle. The WEEE Directive set collection, recycling, reuse, and recovery targets for all six categories of e-waste. The other directive is "Restriction of Hazardous Substances" directive 2012/ 95/EC (Shittu et al., 2021), which intended to modify product designing and packing to restrict consumption of six specific materials: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyl, and polybrominated diphenyl ether utilized in the manufacturing process (Shittu et al., 2021). This directive attempts to reduce waste creation by increasing the recycling rate of equipment. Other countries, such as China, Japan, Canada, and the US have also been found to be impacted by these two stated directives to pass legislations to enhance domestic WEEE recycling rates.

The Americas generated nearly 13.1 million tons of e-waste, with the United States generating the most at 6.92 million tons. In the USA, there is no federal legislation on e-waste management, but 25 states and the District of Columbia have enacted some form of legislations. The laws cover 75-80% of the USA population (Vishwakarma et al., 2023). However, many regions of the country, including the states where laws are in place, lack practical collection opportunities due to the disparities in scope. All state that has passed legislations, except for California and Utah, employs an EPR strategy. Canada does not have a national law in place, since the federal agency lacks this authority. All but Nunavut, Canada's least populous territory, 12 provinces and territories have regulations with the management of e-waste in effect. The product scope is much wider than USA, and in many Canadian provinces, the EPR requirements can be met by signing up for an authorized e-waste compliance program (Xavier et al., 2021).

Few countries in East Asia, such as Japan and South Korea, have advanced e-waste regulation. Since 2001 Japan has already had recycling laws of home appliance. Japan was one of the first countries to use an EPR-based e-waste management system in the world. The current e-waste collection and treatment is carried out under the Act on Recycling of Specified Kinds of Home Appliances and the Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment (Terazono et al., 2006).

China is a developing Asian country that leads the region both in terms of population and overall e-waste volume. China faces problems of accelerated production and illegal exportation of e-waste to China. In 2019, China generated approximately 10.13 million tons of e-waste, and ranked in the top place of e-waste production in the world. It is predicted that the number will continue to increase in the future (Lu et al., 2015). According to Lu et al. (2015), about 57,700 tons of e-waste are illegitimately transferred to China from other countries. This continuous increase in the amount of e-waste raises important issues related to environmental and health concerns.

In 2002, China enacted a law prohibiting the import of hazardous e-waste in addition to ratifying the Basel Convention. In 2006, the Chinese government passed the Management Measure for the Prevention and Control of Pollution from Electronic and Information Products which was considered as the China Restriction of Hazardous Substances Directive, specifying limits on materials like the EU directive. In 2009, China enacted Regulation on the management of Collection and Treatment of WEEE which are the China WEEE Directive (Alabi et al., 2012). This regulation stipulates that a qualification licensing system for the disposal of waste electrical and electronic products should be implemented. China has established a disposal fund for waste electrical and electronic products, which is used to subsidize the recycling and treatment waste electrical and electronic products. The current national legislation regulates the collection and treatment of fourteen types of e-waste from initially five types. The fourteen different categories of e-waste that must follow regulations include: monitors, printers, copiers, fax machines, televisions, refrigerators, washing machines, air conditioners, personal computers, range hoods, electric water heaters, gas water heaters, mobile phones, and single-machine telephones. In 2016, China implemented new management measure for the Restriction of Hazardous Substances in Electrical and Electronic Equipment to replace 2006 promulgated.

Despite the intentions of national rules and hazardous waste laws, most of the e-waste is discarded or crudely processed by burning or acid baths, with only a few valuable elements recovered. As furans, dioxins, and heavy metals are generated, it is inevitable to harm to the environment, employees, and inhabitants. The faster growth of e-waste in developing countries than in developed countries portends the continued emergence of a pervasive and low-cost informal processing sector (Sthiannopkao & Wong, 2013). Domestic e-waste generation in China has increased substantially. However, low-level informal recovery practices emerged in China which resulted in low legal recycling rate of e-waste. If e-waste is correctly processed, it can provide significant benefits to urban mining in terms of precious metal recovery. China's e-waste is expected to be worth $23.8 billion by 2030 (Lu et al., 2015). Therefore, it is a significant challenge for all parties involved, including governments, electronics manufacturers, and customers.

The E-waste recycling system in China is very imperfect and consists of the formal sector and informal sector, among which the informal sector is dominant before 2003. The informal sector mainly refers to the unregistered vendors, including street peddlers, household appliance repair shops, waste collection stations and disassembly workshops (Xiao et al., 2018). This kind of recycling is generally dismantled and recycled by the unit of the family workshop, and is not subject to supervision. In contrast, the formal sector mainly refers to specialized recycling agencies authorised by the government, which usually have a fixed location. Since the recycling and disposal led by informal sector could not only pollute the environment but also harm the health and safety of demolition employees and inhabitants near the workshops, the government has focused on increasing e-waste recycling rate in the formal sector.

In June 2009, China issued the “old for new” Replacement Home Appliance Policy. The customers can receive a certain amount of cash deduction when buying a new electronic product if they return an old product of the same type. This temporary economic incentive policy mainly encouraged consumers to participate in the recycling of waste home appliances through formal channels, which indeed increased the e-waste recycling rate in formal sector, and finally collected 83.73 million discarded home appliances from June 2009 to December 2011 (Cao et al., 2016). The number of formal e-waste collection and treatment facilities is also increasing, with over 1,000 collection companies and over 100 certified recycling enterprises registered by the end of 2011 (Lu et al., 2015).

On July 1, 2012, the Chinese government began to implement management measures for WEEE Recovery Fund and give fixed subsidies to accredited e-waste treatment plants based on the actual amount of e-waste products dismantled. The special subsidies are funded by taxes on electronics manufacturers and importers by implementing the EPR system. In 2014, the official dismantling volume of China’s five main household appliances (TV sets, refrigerator, air conditioners, washing machines and computers) was 71.63 million units, with a total subsidy of $910 million. Among them, the total number of TV sets and computers is 66.45 million, accounting for 93% of the overall dismantling volume (Zhou & Xu, 2012). The government released a new catalogue for recycling waste electrical appliances, increasing the types of waste electrical appliances to 14 in January 2015.

In 2020, China carried out the programme on improving the recycling and processing system of waste home appliances and promoting the renewal of household appliances consumption. Many concrete actions have been taken, for example, improving the recycling network that connects cities, streets, communities, and households through “smart city” service system, supporting home appliance production, sales and recycling enterprises to establish diversified recycling channels, promoting technology research development and application to enhance the disposal capacity of waste household appliances. For reasonably guiding the recycling and processing of WEEE, the subsidy standard has been adjusted to improve the subsidy policy of the WEEE disposal fund since 2021. Adjusted subsidy standard for household WEEE was shown in Figure 1.4. The fluctuation of subsidy price can guide enterprises to adjust the structure of dismantling WEEE in a reasonable direction.

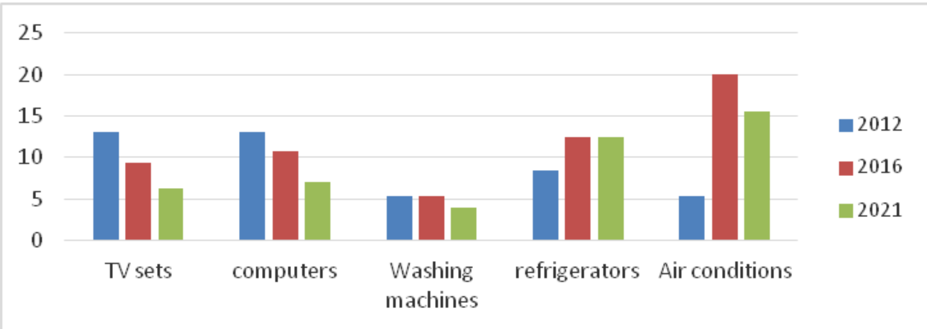

Figure 1.4 – Adjusted household WEEE subsidy standard (dollars/unit)

Source: prepared by the author

As the largest consumer market in the electronics industry all over the world, China is faced with the generation of a large amount of e-waste in domestic market and imports of e-waste from various foreign sources. Domestic e-waste is mostly made up of post-consumer electronics, with a small proportion coming from industrial processes. The import of e-waste involves legal and illegal, the former is handled and controlled by China’s General Administration of Customs and the State Environmental Protection Administration and the latter is smuggled illegally. However, there is currently no official data available in China on WEEE generation and streams.

Generally, there are six main ways for e-waste processors in China to divert e-waste as follows. Peddlers collect about 60% of the recyclable e-waste by riding bicycles or tricycles around neighbourhoods and residential areas to directly buy a variety of e-waste products from the users (Wang et al., 2011). Then these recycled e-wastes are resold by them to special collectors or waste treatment plants. About 20% of the recyclable e-waste is collected by dealers or retailers mainly through trading in “old for new” policy. Some dealers could provide door-to-door service in collecting e-waste. Only 10% of recyclable e-waste is recycled by specialized collectors. Most of the time, they collect e-waste from peddlers and retailers, after categorization, the waste is either transferred to a waste treatment plant for further processing or sold on the secondary market. Only a small amount of e-waste is directly recycled in the second-hand market. Most used electronic products require different degree of repair or upgrading at the treatment plant before they are sold. The second-hand market is more prosperous in rural or poor areas. Small-sized discarded electronic products, such as old mobile phones, always end up at home because they are neglected or users are worried about revealing personal information (Yang et al., 2008). A final way to divert e-waste is to mix them with municipal solid waste and discard them. The last two treatment methods could be eliminated by raising the residents’ CE awareness through education and publicity of CE knowledge. In summary, the E-waste governance and legislation are shown in Figure 1.5, where the six current recycling models in China are summarized.

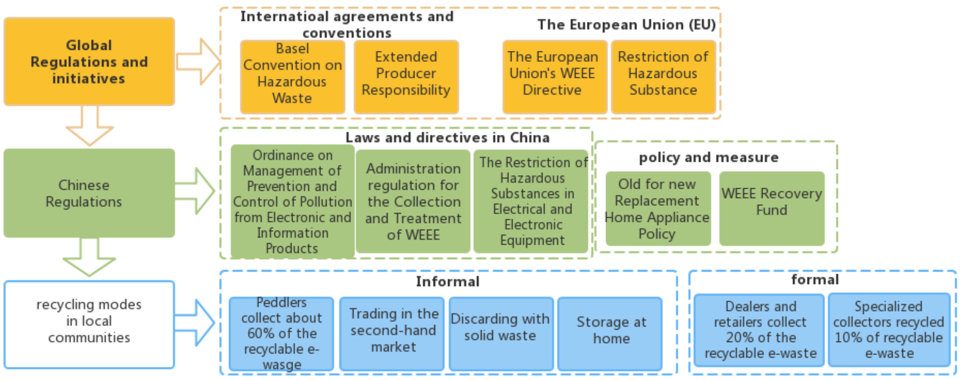

Figure 1.5 – E-waste governance with a focus in China

Source: prepared by the author

The initiatives and organizations addressing e-waste issues summarized in the Table 1.2 bellow.

Table 1.2 – Initiatives and organizations addressing e-waste issues

Initiatives and organizations	Key content
Solving the E-waste Problem (StEP)	Initiated by UN agencies to encourage the reuse of recovered materials to reduce e-waste generation, support strategic approaches towards sustainability such as CE and zero waste / emissions.
3Rs (Reduce, Reuse, Recycle)	Japan took the initiative to prevent e-waste generation, which permits exportation to other countries for recycling and remanufacturing. It is incompatible with Basel Convention treaty.
The United Nations University (UNU)	Dedicated to create and disseminate information and strengthen capacities related to international concerns about human security, welfare, and development.
The International Telecommunication Union (ITU)	ITU has developed a series of international standards (such as ITU-T Recommendations) to support urban stakeholders and the ICT industry in developing sustainable e-waste management systems, assessing the environmental impact of WEEE, defining safe procedures for rare metal recycling, implementing e-waste reduction targets in the Connect 2020 Agenda, moving towards a CE. ITU highlights the emerging role of ICTs and DTs in accelerating climate action and addressing the e-waste challenge.
The International Solid Waste Association (ISWA)	The International Solid Waste Association (ISWA) is a global, independent, and non-profit making association, working in the public interest promoting sustainable, comprehensive, and professional waste management and the transition to a CE.
The Global E-waste Statistics Partnership (GESP)	The GESP collects data from countries in an internationally standardized way and ensures that this information is publicly available via its open-source global e-waste database. Since 2017, the GESP has made substantial efforts by expanding national and regional capacity on e-waste statistics in various countries. The Global E-waste Monitoring Report is one result of this partnership effort.
International	Strengthen utilization of environmentally suitable waste management

Environmental Technology Centre (IETC) – UNEP	methods technologies in developing countries.
Global Enabling Sustainability Initiative (GeSI)	Focus to engage ICT companies, industries, and organizations to concern e-waste management.

Source: prepared by the author

The 3Rs (Reduce, Reuse, Recycle) initiative was introduced by Japan at a 2004 G8 summit. Japan has promoted use of the 3Rs domestically and internationally. The initiative present "Reduce" as the priority to prevent the generation of waste by promoting reusable and recycling technologies. Goals of the initiative include advancing reuse technologies, collaboration between developed and developing countries on reuse and recycling projects, and removing obstacles to the international flow of recycled and remanufactured materials. This last objective conflicts with the principles of the Basel Convention, which emphasizes the responsibility of producer countries.

The United Nation launched the initiative of Solving the e-waste Problem (StEP) to improve and coordinate global efforts on the reuse of recycled materials. StEP collaborates with renowned academic and governmental organizations (such as MIT and the USEPA) to promote the reuse of recycled materials and control of e-waste contaminants. The StEP initiative, which includes stakeholders from industry, academia, governments, non-governmental organizations (NGOs), and international organizations, has produced a set of guiding principles to develop e-waste management systems and legislation. It consists of five aspects including policy, redesign, recycle, reuse and capacity building. Redesign with disposal in mind is an emerging concept. One consideration is designing with the minimize use of toxic materials; another is designing for ease and safety of ultimate disassembly and recycling.

EPR emerged in academic circle as an approach to environmental policy strategy that sustain producer's responsibility for total life cycle improvements of product system up to its final disposal. EPR’s primary goal is to prevent and reduce e-waste production with a focus on maximizing reusability and reduction of natural resources consumption. Currently, most laws and policies refer to the concept of "Extend Producer Responsibility," which is widely used internationally. This EPR program was initially required by German directive on reducing packaging waste, and placed financial pressure on manufacturers to assemble, dispose and recycle products (Chatterjee & Abraham, 2017). There are four broad categories of EPR implementation, according to the Organization for Economic Co-operation and Development (OECD).

(1) Take - Back protocol. This asserts that it is the duty of manufacturers or producers to control the generation of waste and product impacts on the environment. Producers need to implement a "take-back" or "buy back" approach by providing incentives to customers who return products to licensed retailers.

(2) Financial foundation for the implementation of EPR, economic and market-based instruments are available in four variants.

(i) Deposit - refund: Consumers are responsible for returning end of life (EoL) products to the retailers. Customers must comply with this by making a deposit that will be refunded after the merchandise is returned.

(ii) Advance disposal fee (ADF): Consumers may be charged an expected collection and processing fee by public or private entities, which may be used to fund the management of the end-of-life product system.

(iii) Material tax: Producers are charged a fee for using new, harmful, non-recyclable materials. The funds collected might go toward collection and handling of EoL products, which creates incentives for using recycled and less toxic materials. This aims to increase material recycling and reusability so that less waste is produced (Kiddee et al., 2013).

(iv) Upstream Combination Tax/ Subsidy (UCS): Taxes are placed on producers or manufacturers to encourage waste treatment, while subsidies are given to change product design and material to facilitate recycling and treatment processes.

(3) Performance standard and regulation. Encourages producers to employ a take-back strategy and recycle post-consumer products. Industries may be required to adapt this legislation to strengthen the incentive for product redesign.

(4) Public knowledge of EPR projects. Measures include raising consumer understanding of producers' obligations regarding the environmental impact of the product system, as well as post-consumer product recycling and management.

The United Nations Environment Programme (UNEP) International environmental Technology Centre (IETC) was established in Osaka in 1992 to promote and support the use of environmentally sound technologies in developing countries and other countries around the world on waste management. UNEP-IETC works with a wide range of partners, including national and local governments, academia, civil society, and the private sector, to provide scientific and technical knowledge and tools to promote the CE and environmentally sound waste management. UNEP-IETC aims for a more sustainable future through actions of everyone, and calls for individual actions to achieve zero waste. UNEP-IETC also works in a variety of inclusive ways to promote waste segregation, landfill regulation and gender-equitable waste management systems.

The Global Enabling Sustainability Initiative (GeSI) focuses on involving Information and Communication Technology (ICT) companies, industries, and organizations to concern e-waste management. GeSI, in partnership with members from leading ICT companies and organizations around the world, is a leading source of impartial information, resources and best practices for designing strategies that address all dimensions of electronics in an increasingly digitized world. StEP applies an integrated, science-rooted approach to create salient solutions to global e-waste challenges along the entire electronics life cycle. In this respect StEP addresses especially UN Sustainable Development Goals 12 “Responsible Consumption and Production” GeSI reports that DTs can have ‘transformational’ effect on achieving the UN Sustainable Development Goals. StEP has five founding principles: (1) Scientific basis. StEP’ work is founded on scientific assessments and incorporates a comprehensive view of the social, environmental, and economic aspects of e-waste. (2) Life cycle approach. StEP conducts research on the entire life-cycle of electronic and electrical equipment and their corresponding global supply, process and materials flow. (3) Solution oriented. StEP's research and pilot projects are meant to contribute to the solution of e-waste problems. (4) Legal compliance. StEP condemns all illegal activities related to e-waste including illegal shipments and reuse/recycling practices that are harmful to the environment and human health. (5) Socially responsible. StEP seeks to foster safe and eco/energy-efficient reuse and recycling practices around the globe in a socially responsible manner.

E-waste management closely relates to many SDGs (Shevchenko & Kronenberg, 2017) which were adopted by the United Nations and all member states in September 2015 for ending poverty, protecting the planet, and ensuring prosperity, such as good health and well-being (SDG 3), clean waste and sanitation (SDG 6), decent work and economic growth (SDG 8), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and life below water (SDG 14). Since e-waste has a high residual value and the potential hazardousness, more specific sub-indicators have been used to track the increase in the e-waste stream. National recycling rate and tons of material recycled on e-waste (SDG 12.5.1) have been officially included in the documentation. According to the current data, the sub-indicator of SDG 12.5.1 on the e-waste recycling rate in 2019 is 17.4%. The significance of considering e-waste is further explored in sub-indicator on hazardous waste (SDG 12.4.2). Target 11.6 in SDG 11 specifically focuses on municipal waste management, and reduces the adverse per capita impacts on the environment. Since majority of e-waste will be generated in urban areas, it is crucial to effectively manage e-waste, increase collection and recycling rates, and reduce amount of e-waste that ends up being dumped in landfills. The move towards smart cities and the use of ICT for waste management offer new and exciting opportunities.

According to McCann and Wittmann (2015), there are at least three generic financing models, or stakeholder groups, that have the potential, individual, or shared responsibility for end-of-life EEE, based on the variations in the operational and financial structures of systems in place around the world:

(i) Entire society: the first model aims to set upfront fees to be paid by the manufacturer when the product is put on the market.

(ii) Consumers: the second model requires the person or entity responsible for disposing the e-waste financially liable for the cost of the collection and recycling.

(iii) Producers: the third model employs a market-share financing strategy to cover all actual operating expenses associated with running the collection system.

Additionally, the EPR principle is frequently considered when creating new laws and policies around the world. With this, the manufacturers will also oversee the post-consumer phase of a product’s lifecycle. Therefore, it was anticipated that EPR policies will stimulate product design that promotes reuse and recycling. But it is increasingly clear that most producers are unable and likely unwilling to accept their accountability without a joint effort with other important stakeholders, including governments, municipalities, retailers, collectors, recyclers, and consumers.

Additionally, producers are becoming more interested in being connected with CE strategies rather than e-waste efforts like StEP or the Basel Convention's Partnership for Action on Computing Equipment (PACE).

The idea of CE was born in the 1960s when the environmental protection movement rose. In 1966, The American economist Boulding wrote the brilliant essay "The Economics of the Coming Spaceship Earth" in which he pointed out that the earth is flying in space like a spaceship, with limits for both extraction and pollution, if the existing resources are not recycled, when the resources are exhausted and the cabin of the spacecraft is full of garbage, the earth will eventually go to destruction like a spaceship. This is the earliest germination of the idea of CE. Boulding's theory mainly emphasizes that the traditional linear economic growth model must be abandoned and that a feedback system, which should be a two-way interaction between mankind and nature, should be created if the world is not to perish due to resource depletion. The production process is environmentally friendly, minimizing the harm to the natural environment, while fusing ecological benefits and economic benefits to form a good interactive system. In 1990, the term of "CE" was formally used in the book "Economics of natural resources and the environment" the first time by British environmental economists Pearce and Turner, who believed that CE was based on the principles of resource management for sustainable development, and viewed economic development as a component of ecological development. They constructed a CE model consisting of natural circulation and industrial circulation. The natural circulation mainly focuses on the absorption and digestion of waste generated by the economy, and transforming it into reusable raw materials. While the industrial circulation primarily refers to the recycling of resources and energy in the production process to reduce waste emissions. CE is gaining prominence as a viable framework for transforming our current economy to a more sustainable and resource-efficient one.

A CE is fundamentally different from a linear economy. A linear economy traditionally follows the “take-make-dispose” step by step plan which means that raw materials are collected, then transformed into products that are used until they are finally discarded as waste. Value is created in this economic system by producing and selling as many products as possible. CE comes as an alternative to the method of the linear economy, which works in a far smoother and more sustainable way. The focus of CE is to maintain the added value of material while minimizing waste, and concentrated on the usage of products as resources. Looking at the whole lifecycle of a product, Cradle to grave is the standard lifecycle mode in the linear economy. In contrast, the CE adheres to Cradle-to-Cradle (C2C) design, which seeks to reuse all materials and eliminate waste.

The concept of CE has aroused great interest among scholars and practitioners (Qu & Shevchenko, 2022), and currently there are various definitions. The Ellen MacArthur Foundation (EMF, 2013) defines CE as “an economic system of closed loops in which raw materials, components and products keep their quality and value for the longest possible and systems are fuelled by renewable energy sources”, which is widely used in the public spheres. By methodically analyzing 114 definitions of the CE, Kirchherr et al. (2017) conceptualized the notion. Some definitions confuse CE with recycling, show weak link to sustainable development, notably in terms of social equity. Similarly, several academics considered that CE is an important factor and a relevant method to accomplish sustainable development (SD), given that the latter concept has been deemed too nebulous to be put into practice and is starting to lose momentum. The concept of sustainable development emphasizes the harmonious coexistence of society, economy, and ecological environment (Qu & Shevchenko, 2020), which includes restraints on resource exploitation, pollution discharge during production, and the random disposal of production waste and garbage. CE is a new mode of economic growth, which not only balance the environmental problems of economic development, but also achieve positive interaction between the economic system, environmental system, and human social system, satisfying sustainable development requirements. Therefore, CE has further improved the concept of sustainable development. Research of Kirchherr et al. (2017) shows that the definitions of CE is typically regarded as a combination of reduce, reuse, and recycle activities, however it is commonly not underlined that CE requires a systemic shift. To the best of our knowledge, the CE is a new economic system that replaces the "take-make-dispose" linear model with the "cradle to cradle" concept in the whole life cycle of materials by reducing, reusing, and recycling the resources and assets in the process of production and consumption (Ghisellini et al., 2016), aiming to decouple economic growth from finite resource consumption and environmental degradation by reducing waste and maximizing resource utilization (EMF, 2019).

The 3R principles (reduce, reuse, recycle) are widely acknowledged as the foundation of CE. The reduction principle is aimed at the input side, and its purpose is to minimize resources consumption without affecting the production process, to achieve the purpose of saving resources, reducing the pressure on natural resources, and improving production efficiency. The reuse principle focuses on the production process, which means to find new ways to use things that otherwise would have been thrown out. Reuse the all or part of waste directly or after repair, renovation, and remanufacturing through clean production technology, and at the same time improves the production process to maximize the use of input resources. Manufacturers are required to extend the product life longer, to prevent products from becoming waste prematurely, and resist disposable goods. The principle of recycling is mainly aimed at the output side (Shevchenko & Kronenberg, 2020). Its purpose is to turn something old and useless into something new and useful, realize the closed-loop of material flow, transform waste into renewable resources and further reduce the original exploitation and utilization of natural resources.

The 3R principles form the core of CE (Shevchenko et al., 2020), but this does not mean that they are equally important in CE implementation. CE prioritizes the need of reducing resources rather than merely waste recycling through recycling. The thorough application of the 3Rs is made based on resources consumption and waste generation. Therefore, reduction comes first, reuse ranking second, and recycling comes last in the hierarchy of the 3Rs. R strategies have been conceptualized in different ways. According to Potting et al. (2017), the 10 circular R strategies was ranked by environmental benefits, refusing consumption has the largest potential. R1 - Refuse, R2 - Rethink, and R3 - Reduce are linked to the smarter use of products and manufacturing; R4 - Refuse, R5 - Repair, R6 – Refurbish, R7 - Remanufacture and R8 - Repurpose focus on extending the lifespan of products and their parts; R9 – Recycle and R10 - recover, refer to the useful application of materials. Reike et al. (2018) classified 10R strategies into three different types of loops according to the duration of the cycle time. The first four cycles R0 - Refuse, R1 - Reduce, R2 - Resell/reuse, and R3 - Repair which are called the short loops, because products are close to users and functions. R4 - Refurbish, R5 - Remanufacture, and R6 – Repurpose which are called the medium and long loops, as products are upgraded and producer participate again. R7 - Recycle, R8 - Recover, and R9 - Remine which are called the long loops, because the products lose their original function. The research results suggested that policymakers and enterprises should concentrate their efforts on realizing the more desirable, shorter loop retention options.

The CE has the potential to positively affect everyone's lives for a more sustainable future. In an ideal CE all waste generated would be reused as raw material in production processes. Implementing a CE can bring the benefits for enterprises: (i) Directly reduce costs for businesses by reducing the need to purchase raw materials, (ii) Reduce risks by being less dependent on the supply and cost of raw materials, (iii) Encourage the development of innovative new products, show consumers that a business is concerned about the environment, (v) Differentiate a business from its competitor.

The CE is the optimal point of sustainability (Qu et al., 2021), because it provides a set of practices that can produce more sustainable operations, making sustainability possible in organizations (Rossi et al., 2020). DTs are widely used in urban sustainability management practice. Through digital techniques, computer simulations provide a quick and effective approach for forecasting energy consumption and carbon emissions throughout a building's lifecycle (Gan et al., 2020). Çetin et al. (2021) identified ten DTs that support the transition of the construction industry to a CE, and they find that additive manufacturing has a prominent role in enabling the use of bio-based materials in the construction industry. Robotics can be used in workplace settings for the sorting of mixed waste that are hazardous to human health (Sarc et al., 2019). The application of IoT/blockchain system helps manufacturers to control their electronic products throughout their life cycle, innovate business models, and go beyond traditional methods that only focus on manufacturing or waste management (Magrini et al., 2021). Digital twins can promote circular supply chain management and resource circularity (Preut et al., 2021). Big data was used for life cycle assessment and microstructural analysis of materials (Vacchi et al., 2021). With the development of a 5G networks, artificial intelligence (AI), IoT, and other new technologies, all countries in the world need to seize opportunities to vigorously develop DTs such as digital governance, digital education, digital medical care, and digital industries, and promote the application of DTs in a sustainable CE.

The CE's implementation is primarily the lack of information, so digital transformation becomes the ideal enabler of the CE (Wilts & Berg, 2018). It can be mitigated by improving the availability of information. The development of DTs will improve the coordination of information and material flows, which will speed up the shift to a CE. A vast amount of information about products, their quantities, especially the quality of the raw materials they contain, their usage patterns, and their location in the waste system can be stored and tracked digitally, all of which provide the necessary conditions for the implementation of a CE.

1.2 Exploring the digital technologies as a driving force of electronic waste management in line with the principles of circular economy

Intelligent methods were used in waste management in the construction of smart cities. The solid waste management in smart cities is shifting from simplified manual collection and sorting procedures to sustainable systems based on various smart technologies. It has great potential to develop more sustainable business practices (Ranjbari et al., 2022) to manage waste from a closed-loop lifecycle perspective. The transition to CE requires innovation and a more sustainable circular supply chain ecosystem, such as building eco-cities, zero-waste cities, and industrial symbiosis parks. The self-driving multi-benefits mobility system integrates the autonomous waste collection with the intelligent dustbin, to realize the automatic garbage collection in Japan (Onoda, 2020). Cyberjaya city in Malaysia aspires for a smart 3R (recycle, reduce, reuse) theme, concentrating on alternative solid waste management to tackle the challenges of creating a low-carbon, healthy material society (Rejab et al., 2012). Facing the challenge of solid waste management, the city of Singapore tried to achieve the goal of building a zero-waste city through industrial greening.

Smart technologies have been used in the solid waste management at different stages from collection to final treatment. The recycling process for e-waste can be categorized into three primary subsequent stages: collecting, pre-processing which includes sorting, dismantling and mechanical treatment, and end-processing. Due to insufficient waste sources, formal dismantling and processing plants were often shut down. As the first step of the entire recycling chain, collection is a key process in e-waste recycling. Currently, the research and practice of smart technologies in the field of e-waste collection are relatively abundant, but the research on intelligent sorting of e-waste is still limited, and the practice is still in its fancy due to high investment costs.

The rapid development of DTs facilitates waste management process towards CE. Smart enabling technologies in the field of CE use electronics, software, sensors, and actuators to exchange and process data for better results. Esmaeilian et al. (2018) identified four types of smart waste management system technology: advancements in sensor-based and data acquisition technologies, communication and data transmission technologies, field experiment technology, and truck route planning and scheduling technologies. Smart technologies such as geographic information system (GIS), global positioning system (GPS), remote sensing (RS), and data acquisition technology mainly including radio frequency identification (RFID) tags, near field communication sensors that can be utilized to collect the data on urban waste in real time to facilitate decision-making on waste recycling activities. Recently, several studies (Gu et al., 2019; Wang et al., 2018; Wang et al., 2020) related to online e-waste collection systems with mobile applications were conducted to ensure environmental protection and sustainable resource supply in the electronics industry. IoT based smart bins can be controlled and monitored by being equipped with sensors to record information about e-waste disposal (Ali et al., 2020). These devices are wirelessly connected to a central hub to transmit the information, facilitating the tracking of waste collection, optimizing container loads and vehicle routes by a decision-support system. Ramya and Ramya (2023) employed AI algorithm for smart e-waste classification, collecting e-waste images from IoT nodes and storing them in the cloud. These intelligent components use deep learning and machine learning approaches to handle massive volumes of data to deliver real-time information and promote efficient decision-making with less human involvement (Gupta et al., 2019; Ihsanullah et al., 2022). The blockchain-based IoT-enabled e-waste management system could keep track of all post-production activities, business processes, and operations carried out on electronic devices (Khan & Ahmad, 2022). This kind of transparent information flow makes consumers more positive to participate in the waste management process. Table 1.3 shows research results from the literature on the application of smart technologies for e-waste collection and recycling.

Table 1.3 – Smart technologies applied in waste management

Source	Smart technologies	The effect in smart e-waste management
Gu et al. (2019), Cao et al. (2018), Tong et al. (2018), Wang et al. (2018)	Internet based e-waste systems	1.Online e-waste collection systems provide consumers a easy and convenient way to report e-waste through a website or mobile application. 2. Online collection allow collection teams to schedule e-waste pickups and track the status of e-waste collections. 3.Integration with recycling facilities can be used to track the entire e-waste management process from collection to recycling or disposal.
Alqahtani et al. (2020), Ali et al. (2020), Harith et al. (2020)	IoT including RFID tags, NFC sensors and GPS	1.IoT sensors can be used to monitor the fill levels of e-waste collection bins and alert collection teams when the bins need to be emptied. This helps to optimize collection routes and reduce the time and energy required for collection. 2.IoT sensors generate a wealth of data on e-waste management processes, including collection rates, recycling rates, and energy consumption. 3.IoT sensors can be used to track the location and condition of individual electronic devices, allowing for more efficient and effective recycling or refurbishment processes.
Gupta et al. (2019), Idwan et al. (2020), Adedeji et al. (2019)	AI(include machine learning, compute vision, deep learning, and robotics)	1.AI is used to automate the sorting and categorization of e-waste based on its type and condition, as well as repair and refurbishment processes, 2.to automate e-waste recycling processes, including the disassembly of electronic devices and the recovery of valuable resources

		by robotics, 3.to automate repair and refurbishment processes for e-waste, to monitor the quality of e-waste recycling processes and ensure that the resulting materials meet certain standards, 4.to optimize e-waste collection and recycling processes, including optimizing collection routes and scheduling collection times.
Sharmin et al. (2016), Aazam et al. (2016), Mishra et al. (2020)	Cloud Computing	1.Data from IoT sensors and devices can be stored and analyzed in the cloud. This allows e-waste management teams to monitor and manage the entire e-waste collection process in real-time. 2.Cloud-based data management also allows for the integration of other data sources, such as weather data and traffic data, to optimize e-waste collection routes and schedules.
Gu et al. (2017), Zhang et al. (2019), Bilal et al. (2016)	Big data analytics	1.Predictive analytics can be used to forecast waste generation. 2.provide insights into the efficiency of the collection process. 3.Big data analytics can be used to analyze the composition of waste, track recycling rates and identify areas where recycling can be improved.

Source: prepared by the author

Figure 1.6 shows a clustered bar chart of the DTs currently applied in e-waste management. In the Figure 1.6, the numerical value of the digital technology represents the frequency of occurrence in the topic searching in WoS database. In terms of the number of articles, if this technology appears multiple times in the title, abstract, and keywords of an article, it is only calculated once. That is, the technology with larger number was more widely used in smart e-waste management system currently. Based on the results, the main DTs for smart e-waste management are identified in the upper part of Figure 1.6: IoT, AI, Internet technology, cloud computing, big data analytics, and blockchain. IoT is the most utilized in e-waste Management with 92 articles, and therefore, plays a significant role in the research domain of smart e-waste management. The second and third most frequently used technologies are AI and Internet with 64, and 56 publications, respectively. Overall, IoT, AI, and Internet Technology are closely integrated with smart e-waste management, followed by cloud computing and big data analytics.

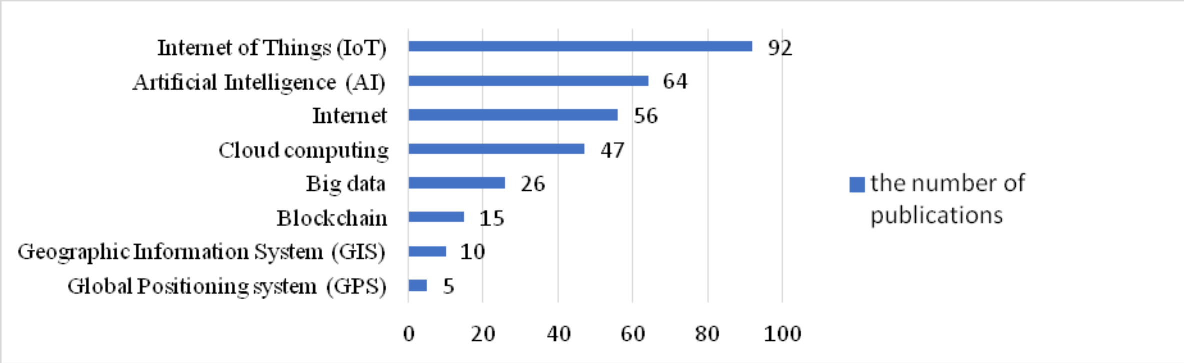

Figure 1.6 – DTs applied in smart e-waste management regarding the number of publications

Source: prepared by the author

Internet-Based Smart E-waste Collection Systems

In the e-waste management system, smart recycling is crucial. The Internet-based collection emerged to overcome the limitations of traditional e-waste collection by taking use of the rapid expansion of Internet technology and the popularity of e-commerce (Cao et al., 2018; Gu et al., 2019). It provided consumers with a simple and formal channel to deal with e-waste, which is an innovative practice in formal mainstream e-waste collection system. Shevchenko et al. (2021) studied a smart e-waste reverse system, integrating local delivery services to collect e-waste and connecting with interactive online maps of users' requests, and relying on IT tools. In China's Internet-based e-waste collection system, the government, platform, and customers are three main stakeholders, which is based on the current popular e-commerce model Online to Offline. Participants include recycling professionals and individuals who schedule appointments online and then collect or transact e-waste on-site (Gu et al., 2019). Internet-based e-waste collection system can track information, material and capital flow of stakeholders which include consumers, e-commerce platforms, registered processing factories, third-party transportation firms, cooperative collecting organizations, and second-hand purchasers (Sun et al., 2018; Tong et al., 2018). Figure 1.7 depicts the system architecture for Internet-based e-waste collection.

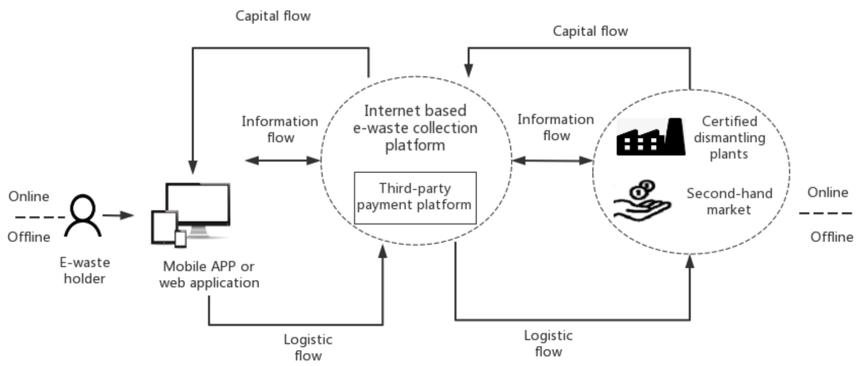

Figure 1.7 – The system architecture for Internet-based e-waste collection in China

Source: prepared by the author

E-waste collection based on the Internet has the potential to raise formal collection rates, reduce environmental damage, and increase venture investment value (Ma & Ren, 2018; Xiao et al., 2018). First, it guarantees the convenience of collection and recycling. Consumers can readily participate in formal recycling by using information technologies such as the Internet, big data, and smartphone applications. Second, it solves the problem of information asymmetry between consumers and recycling companies. In traditional recycling methods, formal recycling companies do not have sufficient e-waste supply because of ineffective recycling methods. Internet-based e-waste collection not only benefits stakeholders, but also improves the recycling system's efficiency. In 2015, the Development and Reform Commission of the Chinese Government announced the CE Promotion Plan, actively supporting the development of new recycling methods such as smart recycling and automatic recycling, and advancing the Internet-based e-waste collection and recycling strategy (Wang et al., 2018).

Internet-based e-waste collection is a well-known approach in the Chinese e-waste collection industry, but it is still in its infancy. Tong et al. (2018) created a qualitative evaluation methodology to assess the performance of the e-waste recycling system based on the Internet in urban China. Three emerging customer-to-business(C2B) e-waste collecting strategies are identified: community-based recycling programs, automatic reverse vending machine chains, and pure Internet platform, and were evaluated by authors using action research. Gu et al. (2017) investigated the status of e-waste recycling entities in China. Wang et al. (2018) discovered the problems faced by Internet-based recycling companies and showed four typical Internet recycling models by investigation. Sun et al. (2018) chose two representative Internet-based collecting firms, to represent the C2B (customer to business) and B2B (business to business) online collection models in China.

E-Waste Collection System based on IoT and Cloud Tools.

Waste management based on IoT and cloud platforms have created a smarter way of waste management and disposal. The research of Wang et al (2021) found that the adoption of IoT based technological solutions supports transition towards smart waste management for a CE by enabling accountability in waste source separation. IoT technology as part of the smart waste management initiative, monitors on the lids of bins collect information about the content and location, and transmit the information to the waste collection team via a central server. The route of waste collection vehicles can then be optimized. Kang et al. (2020) designed a smart household e-waste collection bin, in which sensors were fixed to obtain e-waste level measurement. When the capacity of the smart e-waste recycling cabinet reaches the threshold value, it will automatically notify the collectors through the backend server. The system includes mobile applications, which can guide users to the nearest collection point, record the behavior of users returning household e-waste, and provide bonus points for users. The architecture of e-waste collection IoT platform is shown in Figure 1.8 and Figure 1.9.

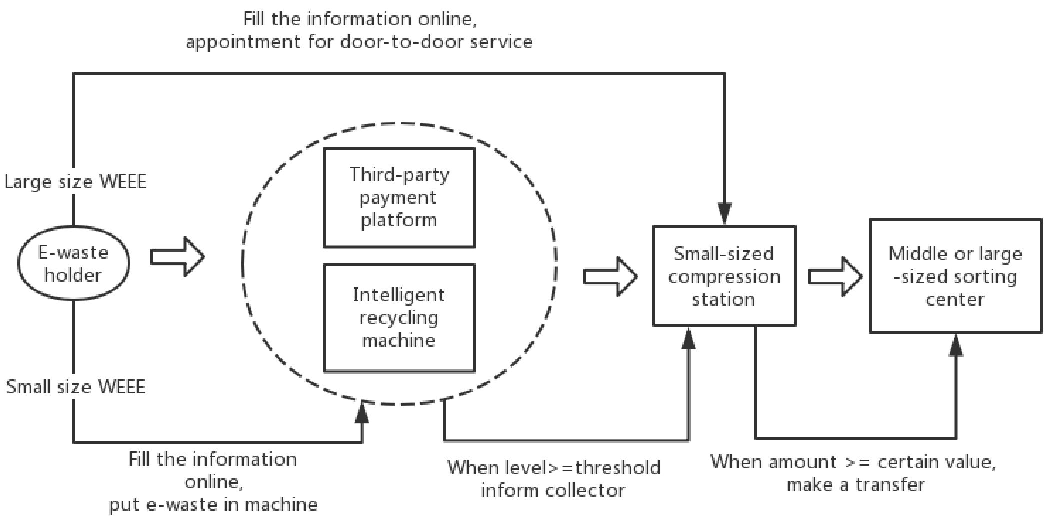

Figure 1.8 – The architecture of e-waste collection IoT platform in China

Source: prepared by the author

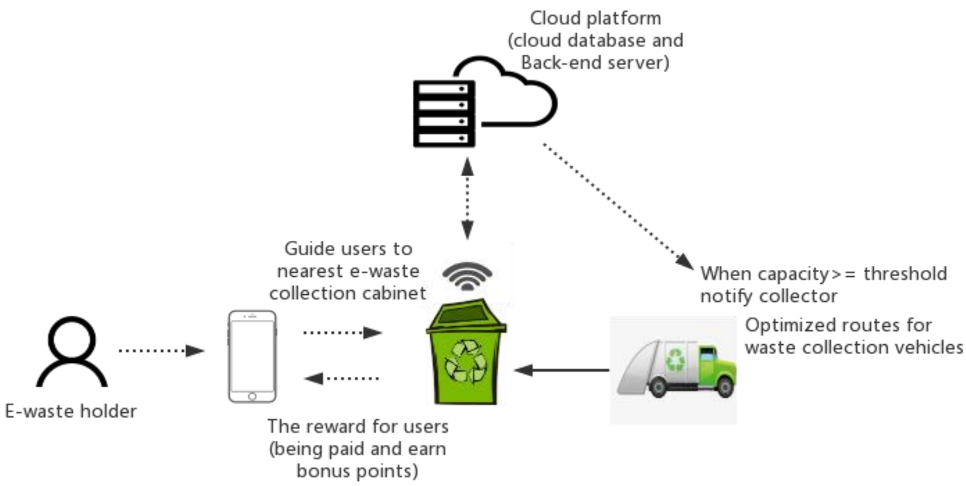

Figure 1.9 – The architecture of IoT based e-waste collection platform

Source: prepared by the author

IoT based e-waste management system enables efficient collection and sorting of electronic waste materials. The sensors integrated into the IoT devices can identify and categorize the different types of e-waste, making it easier to sort them for recycling and disposal. The real-time monitoring feature allows for instant detection of e-waste disposal sites, helping to prevent illegal dumping and unauthorized recycling activities. The system can track and record the entire e-waste disposal process, ensuring organizations comply with regulatory standards and guidelines for e-waste disposal by using IoT facilitate. In addition, the system can identify the most efficient routes for collection and transportation, reducing fuel consumption and overall operational costs. Sharmin and Al-Amin (2016) presented a smart cloud-based dynamic trash management system for cities, which collects the weight and volume information of the waste in trash bin through the sensor, then send it to the cloud server through the microcontroller and GPRS. Ant Colony Optimization (ACO) technique is applied to discover the shortest viable collection path for garbage collection vehicles. Aazam et al. (2016) proposed cloud-based smart waste management mechanism, optimize waste collection path for higher fuel efficiency and time efficiency. Mishra and Kumar (2020) adopted an improved Dijkstra algorithm, using trash can sensors and real-time road traffic data, and established a new cost function mathematical model to optimize the waste collection vehicles path. Abdullah et al. (2019) investigated the usage of IoT in a smart city's waste management system. Based on the data collected from sensor devices, such like RFID sensor devices and GPS devices, the control office can take action to help keep the urban environment clean.

Alqahtani et al. (2020) created an IoT-based waste management system and used Cuckoo Search Optimized Long Short-Term Neural Networks to analyze IoT-based waste data, making it easier to analyze waste, bin sizes, vehicle kinds, and waste materials. The trash management centers were alerted because of this information, and appropriate action could be done. In the study of Ali et al. (2020), a smart waste bin monitoring and municipal solid waste management system based on IoT is proposed. The system contains a prototype based on IoT connected with sensors to monitor the level of garbage inside the waste bin in real time. When the threshold level is achieved, garbage trucks are arranged to collect in the order of decreasing garbage filling value in different areas. The system is also equipped with temperature and humidity sensors to forecast fire hazards in bin. Harith et al. (2020) proposed a prototype of smart bin based on IoT, in which an automatic centralized monitoring system is implemented using wireless sensors and GPS. Many scholars (Al-Masri et al., 2018; Chaudhari & Bhole, 2018; Chen et al., 2018; Soh et al., 2019) conducted researches on municipal solid waste management based on IoT clouds and sensors from different levels. Al-Jubori and Gazder (2018) optimized the garbage truck collection path using ArcGIS-based dynamic routing. For waste management, Marques et al. (2019) proposed smart cities network infrastructure architecture based on IoT.

AI in E-waste recycling management

There is a growing body of literature on the application of AI in waste management. AI technology has the potential to revolutionize e-waste management by improving efficiency, accuracy, and sustainability. After collection, the e-waste can be categorized using AI algorithms, making it easier to recycle and recover valuable elements, reducing the demand for virgin resources. AI technology can also be utilized to create decision support systems for managing e-waste that can recommend the most appropriate recycling practices, disposal choices, and resource recovery techniques based on data analysis and machine learning algorithms. The review of Abdallah et al. (2020) indicated that the frequently used AI systems for smart waste management included Artificial Neural Network, Support Vector Machine, Linear Regression, Decision Trees, and Genetic Algorithm. In the field of solid waste management, AI is extensively used to detect bin level, forecast waste characteristics, predict process parameters, and process output, optimize waste collection vehicle routes, locate waste management facilities, and plan waste management, among others.

Smart waste bin can be effectively used to prevent overloading and improper waste disposal by bin level detection model. The algorithms are typically fed with real-time data from level or image sensors installed inside to identify the level and the type of waste in smart waste bins. Few research studies have incorporated AI in real-time monitoring of waste level within the bin to improve the solid waste collection process, especially focusing on e-waste category. Morison et al. (2013) detect bin level in terms of wall entropy perturbation in e-waste collection, taking the recycling of discarded mobile phones as an example. When analyzing entropy perturbation, several classifiers were examined, and the multilayer perceptron, logistic model tree, and K-nearest neighbors showed great performance. Hannan et al. (2016) investigate a content-based image retrieval system to study the application of image retrieval with an extracted texture from the image of a bin to detect the bin level. The study uses a range of feature extraction approaches, including Gabor wavelet filter, gray level co-occurrence matrix, and Gray Level Aura Matrix to determine bin level with 87.5% accuracy. Kang et al. (2020) designed an e-waste collection box with sensors to assess the volume of e-waste and record the disposal information. The smart system was successfully constructed, and it could help the household e-waste collection. Similarly, Sampedro et al. (2021) developed a smart e-waste bin using You Only Look Once v4 (YOLOv4) to identify the type of e-waste stored inside and reward users for participating in e-waste recycling. The developed system can successfully and accurately (93.33% on average) identify the type of e-waste.

Collection expense typically accounts for 70 to 85% of the overall solid waste management costs, so waste collection vehicle routes optimization is an essential part of a successful smart waste management system (Karadimas et al., 2007). Genetic algorithm, its hybrid versions, artificial neural networks (ANN) and regression models are frequently used in Studies of waste collection frequency and route planning optimization models. Idwan et al. (2020) use genetic algorithm operators such as selection, crossover, and mutation to compute the optimal route for the sector's dumpsters. Vu et al. (2019) integrated nonlinear autoregressive neural networks with GIS route optimization to investigate the effect of waste composition and weight on the optimized vehicle routes and emissions. Szwarc et al. (2021) explore an evolutionary approach to the vehicle route planning in e-waste mobile collection on demand. Nowakowski et al. (2020) presents an online e-waste collection system that employs the Harmony Search algorithm for waste collection vehicles route optimization. Yu et al. (2021) optimized waste collection with a short distance by utilizing machine learning and graph theory in the Hybridized Intelligent

Framework. Batoo et al. (2022) propose the behavior-based swarm model using a fuzzy controller (BSFC) which solve the problem based on routing associated with the time window for the heterogeneous fleet of the e-waste collection vehicle. For those who request e-waste pickup, Nowakowski et al. (2018) offers an online solution that addresses the vehicle routing problem with time windows (VRPTW). The system includes four algorithms as parametric models: simulated annealing, tabu search, greedy, and bee colony optimization.

Given that different waste types require different disposal methods, accurate classification system is an essential part of waste management. Gupta et al. (2019) used machine learning to classify the waste type, such as plastic, metal and glass. Adedeji and Wang (2019) employed the 50-layer residual net pre-train Convolutional neural network model and Support Vector Machine to construct image-based waste management system. The data set's images were utilized to identify garbage types and materials. The prediction accuracy rate of waste types reaches 87%. Chen et al. (2021) discuss e-waste effect on the climate and human health, proposes a hierarchic AI technique model for the analysis of hazardous pollutants in e-waste. To identify and classify waste electrical and electronic equipment from photos, Nowakowski and Pamuła (2020) apply a deep learning convolutional neural network (CNN) was to classify the type of e-waste, while a quicker region-based convolutional neural network (R-CNN) was used to detect the category and size of e-waste in the images. Latha et al. (2022) suggested an innovative technique for managing e-waste that makes use of the dynamic convolutional neural network (DCNN). By precisely mapping the features of the photos, it enhances the classification accuracy. Abou Baker et al. (2021) uses transfer learning which is a special AI technology by fine-tuning AlexNet's output layers as a pre-trained model and implementing the model on a small-size dataset with 12 classes of photo images from 6 smartphone brands. Batoo et al. (2021) provide an effective e-waste management system based on adaptive optimal neural network. Fuzzy c-means clustering approach is used to categorize the household e-waste. Johnson et al. (2022) developed the battery detection which enables recyclers to close the loop on battery recovery and resource efficiency by easily identifying and separating e-waste containing batteries from the primary waste stream. This system utilizes computer vision systems together with AI engine and pattern recognition. Ramya et al. (2023) devised Fractional Horse Herd Gas Optimization-based Shepherd Convolutional Neural Network and fractional Henry gas optimization based deep convolutional neural network for classifying e-wastes in IoT-cloud platform.

Robot waste sorting and segregation involves the use AI technology to identify and sort different types of waste materials based on their size, shape, and composition. To separate and grade e-waste, the WEEE ID project, supported by VINNOVA (the Swedish Agency for Innovation Systems), developed an automated, intelligent sorting equipment to increase sorting accuracy and efficiency (Barletta et al., 2015). It protects workers from segregation processes to hazardous compounds of e-waste, and allows for higher recycling rates in subsequent processes. New robotic application enables sorting shredded e-waste that include wires, plastics, and circuit boards. Karbasi et al. (2018) explored deep learning model which combined a ResNet101 feature extractor with the Faster R-CNN algorithm. A fast parallel robot is used to divide the materials into different bins. The results of the material classification reach an overall purity rate of 98%. According to the latest empirical research results, the training and operation of an AI robotic sorting system are promising in terms of the purity of sorted waste fragments (Wilts et al., 2021).

Summary of algorithms mentioned by previous researchers for AI in e-waste recycling is provided in Table 1.4.

Table 1.4 – Summary of algorithms mentioned by previous researchers for AI in e-waste recycling

Source	Research Topics	Algorithms or Models
Morison et al. (2013)	Predicting bin level	Wall entropy perturbation
Hannan et al. (2016)	Predicting bin level	Image retrieval with an extracted texture
Kai Dean Kang (2019)	Designing a smart household e-waste collection box with	Backend server and a mobile application were developed

	level measurement sensors	
GA Sampedro (2021)	Developing a smart e-waste bin to identify the type of e-waste and reward users	You Only Look Once v4 (YOLOv4)
Idwan et al. (2020)	Computing the optimal route for dumpsters	Genetic algorithm
Vu et al. (2019)	Optimizing vehicle routes and emissions	Nonlinear autoregressive neural networks with GIS
Szwar et al. (2021)	Determining the vehicle route plan for e-waste mobile collection on demand	Evolutionary and Memetic Algorithms
Nowakowski et al. (2020)	Optimizing waste collection vehicles route	Harmony Search algorithm
Yu et al. (2021)	Optimizing waste collection with a short distance	Machine learning and graph theory
Batoo et al. (2022)	Optimizing e-waste collection vehicle route	Behavior-based swarm model using a fuzzy controller
Piotr Nowakowski (2018)	Solving the vehicle routing problem with time windows for waste collection	Parametric models of four algorithms: simulated annealing, tabu search, greedy, bee colony optimization
Adedeji et al. (2019)	Identifying garbage types and materials	50-layer residual net pre-train Convolutional neural network model and Support Vector Machine
Nowakowski et al. (2020)	Identifying and classifying of e-waste from photos	Deep learning object classifier; Convolutional neural network
Latha et al. (2022)	Classifying e-waste from photos	Dynamic convolutional neural network (DCNN)
Abou Baker et al. (2021)	Sorting e-waste accurately to support automated e-waste recycling	Transfer learning; fine-tuning AlexNet's output layers as a pre-trained model
Batoo et al. (2021)	Categorizing the household e-waste	Fuzzy c-means clustering approach
Johnson et al. (2022)	Identifying and sorting e-waste containing batteries from the primary waste stream	Robotics;AI;computer vision
Ramya et al. (2023)	classifying e-wastes in IoT-cloud platform	Fractional Horse Herd Gas Optimization-based Shepherd Convolutional Neural Network; fractional Henry gas optimization based

		deep convolutional neural network
Karbasi et al. (2018)	Sorting the materials into different bins	ResNet101 feature extractor with the Faster R-CNN algorithm

Source: prepared by the author

Smart e-waste management applications in China

Since 2015, the Internet-based e-waste recycling platforms have increased rapidly. There are many e-waste collection platforms in China based on the Internet, by which users can submit orders online and choose door-to-door pickup or express delivery for recycling. They provide services including equipment detection, classification, dismantling, and data removal. Shenzhen Taolv IT Co., Ltd. (Taolv) and Shenzhen Boolv Environmental Technology Co., Ltd. (Boolv) are two representative Internet-based e-waste collection platforms. Taolv provides a site for recycling transaction of used mobile phones and tablets for industry through the business to business (B2B) plus online to offline model. The platform integrates Internet thinking into the traditional recycling industry, combining IoT and big data analysis to transform the traditional transaction method into an Internet plus recycling model of online services transaction and offline pickup and sorting. It mainly serves recycling industry enterprises, individual practitioners or individuals who support public welfare and willing to protect environment by properly dispose of e-waste. It helps the traditional recycling model of mobile phones upgrade, and promote the development of CE. Taolv divides the waste mobile phones and tablets into reusable and non-reusable, and eliminate user data which is the most important things for users to protect personal information security. The reusable mobile phones are re-sold through professional second-hand terminals, and the non-reusable mobile phones are handed over to third-party companies with the qualification and ability to dispose of e-waste in formal way. The processing flow is shown in the Figure 1.10. Some Internet-based e-waste recycling platforms that also evolve second-hand electronic products trading, for example Love recycling, keep recycled high-quality mobile phones for resale. Love recycling is one of the earliest 3C (computer, communication, consumer electronic) electronic product recycling companies in China, and it is also the largest second-hand electronic products trading platform in China, through which users can sell idle electronic products. The platform also cooperates with mobile phone manufactures and introduces old-for-new policy to sell new mobile phones.

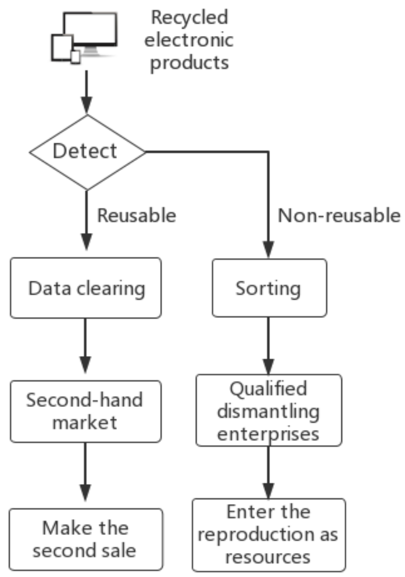

Figure 1.10 – Processing flow of e-waste

Source: prepared by the author

The prominent Internet company Baidu works with the United Nations to establish a big data joint laboratory, using Baidu's big data technology to explore innovative models for solving global e-waste problem. Its mobile app "Baidu Recycle Bin" connects users who want to dispose of waste home appliances with formal recycling companies certified by the national government, allowing more e-waste to flow into formal recycling enterprises through the Internet. Users can take photos of waste home appliances and upload them, after which the system completes the evaluation, and finally the collectors will come to the door. The Internet company Tencent which serves the largest number of users in China, has launched a WeChat mini program named Tencent micro recycling to provide convenient, high-priced, and safe recycling of old mobile phones and tablets with the help of the extensive user groups of WeChat social software. The recycling process includes online evaluation, door-to-door pickup, professional quality inspection and fast payment. Alibaba, China's largest e-commerce company, also focuses on the recycling of e-waste products mainly including mobile phones and laptops. Its subsidiary company Huishoubao recycled 10 million mobile phones over the past four years.

Many cities have begun to implement a mandatory waste classification in China, which has promoted waste classification industry. The application of IoT and AI technology enables smart waste sorting machine from the source. Yingchuang, a renewable resources recycling Co., Ltd. in Beijing, independently developed a smart recycling machine for beverage bottles, which is the first example in China that combines IoT technology with a renewable resource recycling system, which motivates users through various rebate methods such as mobile phone bills and coupons. It has put into operation at the capital airport, Beijing subway and major universities. Little Yellow Dog, an environmental protection technology company, uses the innovative model of IoT plus smart recycling. The four-class waste recycling machine developed by them has realized the dynamic monitoring and intelligent management of waste classification. The user downloads and registers the mobile application, scans the QR code on the recycling machine, selects the type of waste under the guidance, and the system will indicate which bin the waste should be put in. It is also equipped with a smart waste recognition module to further ensure the accuracy of waste placement. Such smart waste collection machines have been installed and used in residential quarters in many cities. The smart waste bin developed by Beta intelligence company can perform waste full-load warning and smoke alarm. The information of equipment overflow will be pushed to the back management to timely cleaning and transportation. It is currently in use in some parks and smart communities (Han et al., 2023b).

Alpheus launched an automatic sorting AI bin based on the mixed object sorting technology of AI and image recognition. It integrates advanced technologies of AI, IoT, cloud computing, and big data, and establishes a scene-adaptive waste classification cloud deep learning model. The learning model realizes the automatic intelligent rapid classification of waste. Users put waste into the bin as usual, and the AI smart bin can automatically complete the classification, with an accuracy rate of over 95%. The company's smart products include: two-classification Rui Bucket, four-classification Rui Bucket, and six-classification Rui Station. In addition to classification, they also provide smoke alarms, overflow alarms, accurate weighing, voice broadcasts, and reminders of placement errors. They have been applied in municipal office halls, high-tech industrial parks, and smart parks in China.

Waste sorting is the most difficult job in the waste recycling process. With the development of AI technology, several waste sorting robots have been manufactured to improve the classification efficiency and reduce harm to human health. Zen Robotics, a Finnish waste sorting robot, is based on a computer vision system and classifies according to the type and size of the waste. The robotic arm will accurately grab the sorted waste and throw it into the target bucket. AMP Robotics developed in the United States, can sort 80 items per minute with an accuracy rate of 95%. The built-in algorithm of the robot is trained through many images, and then uses the vision system to scan the waste on the conveyor belt and classify the waste according to its color, size, and material. When the sorting is completed, the suction cup on the robotic arm can be used to pick up the waste and throw it into the sorted container. Alphabet X, built by Google X in the United States, can not only sort waste, put wrongly sorted waste in the right place, but also walk around the community to pick up waste. The Waste Robot launched by FANUC in Japan uses a new technology of Waste Robotics Autonomous Recycling Technology, specially designed for waste sorting. China has also carried out research and development of waste sorting robots. An intelligent smart identification and sorting robot developed by Bocheng Robot Company has been put into use in Hangzhou. However, compared with developed countries, the research and development of waste sorting robot in China is still in its infancy, and the future prospect is promising.

Due to the relative complexity of e-waste recycling, the current e-waste collection in China mainly relies on online services through websites or mobile applications, combining with professional local store recycling on site. The majority of the smart sorting waste boxes based on the IoT and AI focus on automatic classification and recycling of solid waste. IoT intelligent recycling machines for electronic waste classification and recycling are still in the laboratory stage and have not been promoted in the market. At present, the e-waste sorting process is still dominated by manual sorting in China, with only a small amount of mechanical assistance.

Strengths and Challenges of Smart E-waste Collection and Recycling System

As an emerging technological innovation, the smart e-waste collection and recycling system has unique advantages and can solve some problems in the traditional recycling system. The system directly connects e-waste holders with e-waste recycling enterprises, skips intermediate links, and guarantees high prices. The collection price is determined based on the second-hand market demands and calculated through big data. The evaluated process is transparent, standardized, and systematic. The smart collection and recycling system not only committed to the research and development of online platform technology, but also constantly improved services on site. In addition to ensuring the convenience of collection and recycling, there are more reliable services. Table 1.5 shows the comparison of two different ways.

Table 1.5 – Comparison of smart way and traditional informal way for e-waste

E-waste collection method	Traditional informal way	Smart way
Higher collection price	Selling to scalpers, there are many intermediate links, and the price is increased layer by layer. It is difficult to guarantee the price. The high price is reported first, and then the price is bargained on the spot.	Directly connects e-waste holders with e-waste recycling enterprises, minus intermediate links, and guarantee high prices. The quotation process is transparent, standardized and systematic.
Convenience	Collection by Peddlers,	Offline stores and staff which can

	lack of fixed service site	provide users with convenient services nearby
Information security	Peddler change places with one shot, do not pay attention to information security of customer, and it is impossible to trace the service process	Professional data removal team to ensure information security of customer by Powerful IT system, service process can be fully traced.
Environmental protection	Most e-waste collected flows into informal recycling channels	Non-recyclable e-waste enter the formal recycling and processing channels, and do professional environmental dismantling

Source: prepared by the author

Smart enabling technologies can help waste management under CE model (Ranjbari et al., 2022). The Chinese government is encouraging smart e-waste management solutions, but there are many challenges in the implementation process. Wang et al. (2020) used Stakeholder theory to create a clear and integrated map of the obstacles to an Interne-based e-waste collection system. The government, platform, and consumers are the three key stakeholders in the system. Zhang et al. (2019) put forward 12 specific barriers in smart enabling waste management through investigation, and identified three key causal barriers using scientific prioritization technology, fuzzy decision experiment and evaluation laboratory. Table 1.6 shows the barriers to smart e-waste management based on the literature review.

Table 1.6 – Barriers of smart E-waste management in China

Main stakeholders	Barriers related to stakeholders
Consumers	Lack of knowledge or understanding in smart waste management
Consumers	Lack of environmental education and culture of environmental conservation

Government	Lack of effective supervision regulatory pressures
Government	Lack of tax incentives and mature subsidy mechanisms
Government	Lack of good instruction and practice promotion
Platform	Difficulties with technologies and how they’re used
Platform	Financial difficulties and high operational costs
Platform	Lack of successful business model

Source: prepared by the author

Electronics consumers have no concept what smart e-waste collection and recycling is and how to engage in it, so leads to low willingness to participate, which shows that consumers lack environmental knowledge and culture of environmental protection. Environmental education is still lacking in Chinese schools, but publicity and education on e-waste collection and recycling are crucial to increasing the rate of e-waste formal collection. The government lacks of popularization and promotion of practices for smart e-waste collection and recycling platforms. The government should encourage and support smart e-waste collection and recycling by disseminating best practice. In addition to the government, the smart platform lacks of effective guidance and promotion for e-waste consumers. Innovative technology platform, which has emerged for a short time, needs to provide users and potential users with opportunities to understand and use it. The platform needs to solve users’ technical difficulties associated with smart e-waste management.

Smart platforms face financial challenges because of high operating costs. Many of them focus on investing in the construction of offline systems to keep up with the development of online systems, such as providing door-to-door services, which leads to higher operating costs, including human and material resources. To cope with the competition of informal recycling channels and increase the formal recovery rate, smart e-waste collection and recycling platforms provide higher collection prices, which leads to higher costs. The current fund subsidies focus on the centralized dismantling and disposal of hazardous waste, rather than the entire process. The government lacks tax incentives and mature subsidy mechanisms for smart e-waste collection platforms (Shevchenko et al., 2019). In developing countries, in the initial stage of e-waste recycling, it is a common and necessary practice for the government to provide financial subsidies to collecting companies. The financial pressure on smart e-waste collection enterprises can be alleviated by tax incentives. Subsidies can provide financial support for the smart-enabled e-waste recycling industry.

In China, smart e-waste collection has just started, and there is no successful business model. Considering uncertain economic benefits, it is difficult for smart e-waste collection companies to achieve sustainable development without the pressure and needs of stakeholders. If companies who illegally recover and dispose of electronic waste are not severely punished, this kind of illegal e-waste management will continue to exist. The lack of effective supervision regulatory pressures will hinder the development of smart e-waste recovery system.

1.3 An in-depth analysis of the application of advanced digital technologies in the field of e-waste management in developed countries

Recycling of waste electronic products involves national legislation, payment mechanisms, definition of the responsibility of the relevant recycling and processing entities and government supervision. Relevant laws and regulations are the prerequisites for the effective recycling of waste electronic products - in the recycling legislation of the EU countries, the EPR system has become a recognized principle, the EPR system not only strengthens the responsibility of manufacturers of electronic products, but also promotes the implementation of eco-design by manufacturers to facilitate the recycling and treatment of used and end-of-life electronic products; a reasonable payment mechanism provides financial security for the implementation of the recycling and treatment system; the relevant recycling and treatment of the main responsibility definition and government supervision and other related factors. A reasonable payment mechanism for the implementation of waste electronic product recycling and treatment system to provide financial security; related recycling and treatment of the main responsibility of the clear is the implementation of waste electronic product recycling and treatment of an important guarantee; government supervision is a necessary condition for the market-oriented operation of waste electronic products.

E-waste recycles and process models in developed countries

(a) The Netherlands

The Netherlands is an early adopter of e-waste management legislation and practice in Europe. Before the EU WEEE Directive was introduced, the Netherlands passed a domestic law in 1998 and started a recycling management system for large household appliances in 1999, and small household appliances were also included in the system in 2000, and in 2004, the Netherlands passed the E-waste Management Decree, which covers all types of e-waste stipulated in the EU WEEE Directive in the recycling system. system. In accordance with the decree, the Netherlands has established an EPR-based e-waste recycling system, whereby appliance manufacturers fully delegate their recycling and disposal responsibilities to the Producers' Responsibility Organization (PROS). Consumers (individuals and businesses) pay a recycling fee, which is aggregated to PROS and used to pay recycling outlets (including retailers) and processors. Currently, municipal recycling points collect about 90% of e-waste, which accounts for the majority of e-waste; retailers collect about 8%, and about 2% of e-waste is handed over directly to municipal recycling centers by users. Through this recycling management system, nearly 100% of the e-waste in the Netherlands is effectively recycled. The Netherlands has established three recycling organizations for different product categories: NVMP (household appliances), ICT systems (IT products, office equipment, telecommunication products) and Stichting Lightrec (lighting equipment) (Golsteijn & Valencia Martinez, 2017).

NVMP is the Dutch association for the disposal of metal and electrical products (the Dutch association for the disposal of metal and electrical products) established in accordance with the Dutch Act on the Recycling and Disposal of White Goods and Brown Goods of 1998, which deals mainly with white goods and small appliances. The system is an umbrella organization that, in addition to the general association (board of directors), which carries out the system construction, has five independent foundations responsible for five types of products - white goods, brown goods, ventilation equipment, power tools and metal and electrical products. The Government attends the meetings of the Board of Directors as a supervisor.

(1) NVMP system

The NVMP system began operation in January 1999 and became responsible for all product categories covered by the EU WEEE Directive on August 13, 2005.The NVMP currently has 15 staff members. As of October 2005, there were 1,350 producer and importer members of the NVMP, covering almost all the large and small appliance markets.

NVMP implements visible fees for the treatment of all wastes, including historical and orphaned wastes (i.e., wastes whose producers have disappeared). Producers pay a bimonthly disposal fee to the NVMP Foundation, based on the type of product and the quantity sold. NVMP delegates the management of the recycling and disposal fee to an independent financial company, which provides monthly reports to the Board of Directors and conducts audits of member organizations to ensure that the relevant responsibilities are fulfilled. Disposal fees for individual appliances range from €1 (e.g., for coffee makers and vacuum cleaners) to €17 (e.g., for refrigerators, freezers, etc.). Many small appliances such as hairdryers, electric shavers and audiovisual equipment are not subject to a disposal fee. In principle, the disposal fee rates will remain unchanged for at least two years. The NVMP coordinates the collection and transportation of WEEE in the Netherlands, and provides WEEE recycling services to municipal recycling points, regional sorting centers, retailers, and elementary school (starting from 8 large appliances or 8 boxes of small appliances). The NVMP selects the transport companies it cooperates with through a bidding process, and there are currently four contracted transport companies. There are currently four contracted haulers, each of which is responsible for an area based on its location, and the NVMP system currently has five contracted treatment companies (11 treatment plants), which are also selected through a bidding process. To sign up for the NVMP system, the treatment companies must be able to demonstrate that they can meet the target recovery rates, and the NVMP system logistics companies and treatment companies are contracted for a period of three years.

(2) ICT systems

The ICT system, which deals mainly with IT products, office supplies and telecommunication products, was established in 1998 with the joint funding of 160 manufacturers and importers. However, ICT does not use visible fees; each member company pays for the actual recycling costs incurred and absorbs these costs internally; ICT distributors receive WEEE from ordinary consumers or commercial users, and producers are responsible for transporting it to treatment plants. Most of the old equipment is collected through "trade-ins". Recyclers are responsible for registering the quality and quantity of the equipment they receive, from which the producer's share of the costs is calculated. The way in which the collection and processing fees are collected is left to the discretion of the producers, and since 2003, ICT has been sharing the recycling fees based on the market share of each producer, following a proposal by Ericsson, Hewlett-Packard, Philips, and others. Producers are now responsible for collecting and disposing of all "gray" products, not just their own branded products, making sorting much simpler and creating a fairer fee system. ICT system producers and importers pay a monthly fee for recycling and disposal, which includes sharing the cost of disposal of orphaned products as well as those produced by companies that avoid responsibility. Disposal costs vary for different types of products. Disposal costs vary for different types of products, e.g. around €2.75 per printer and €15 per complete PC. If the producer disposes of the used equipment themselves, the fee will be lower, but the appropriate declaration form (sent to the member with the recycling invoice) will be required.

(3) StichtingLightrec

StichtingLightrec is a recycling organization specializing in the treatment of commercial and domestic waste light bulbs and luminaires (appliances with at least one light bulb), using visible charges, established in December 2003 by companies including Philips, SLIBenelux, Cooper Menvier and others to meet the recycling obligations of waste electrical and electronic equipment (WEEE). NVMP will undertake the actual recycling and disposal of its products.

(b) Belgium

On February 19, 2001, 15 Belgian industry associations and three regional environment ministers signed the Recupel Environmental Convention, which entered into force on July 1, 2001. Accordingly, Belgium established the Recupel recycling organization, which is responsible for the collection, transportation, and treatment of WEEE throughout Belgium, and has been in full operation since February 2002. Recupel is a non-profit organization, with no government funding and no recycling tax, and operates entirely on a market basis (Vanegas et al., 2014). Recupel is divided into six sections - Recupel A/V for audiovisual equipment; Recupel B/W for brown and white goods; Recupel SDA for small electrical appliances; Recupel ICT for IT and office equipment; Recupel ET & Garden for power tools including gardening tools; Recupel-LightRec for household and professional lighting. Recupel-LightRec is responsible for the recycling of household and professional lighting fixtures.

Consumers can send their WEEE to municipal recycling points free of charge, or to retailers free of charge when they buy a new product, and Recupel will take care of the subsequent disposal and recycling.Recupel is responsible for the transport of WEEE throughout Belgium in cooperation with a specialized transport company, which organizes the transport of WEEE from municipal recycling points and from recycling points set up by retailers to the designated disposal sites. Recupel also collects WEEE directly from the consumer's home if required, and has agreements with 4-5 specialized recyclers and processors of WEEE. These recyclers are selected based on very strict environmental and efficiency criteria. These specialized treatment companies are required to submit accounts to Recupel for the costs of collecting, treating and reusing WEEE, and Recupel employs an independent auditing firm to audit the company's accounts annually to ensure that the recycling fees are spent appropriately. In addition to paying the current year's management, transportation, recycling, and treatment costs, Recupel also draws down a reserve from the current year's income to ensure the company's strength in the future.

The recycling fee is passed on to the consumer in a fixed way, and when purchasing a new electrical or electronic product, the consumer must pay a recycling and disposal fee based on the type of product, which is recorded separately by the retailer and invoiced separately. The fee is standardized as an estimate based on the amount of recycling Recupel expects to collect each year and the cost of collection, processing, and recycling. The pre-payment fee is levied by the retailer and then given to its suppliers and then to the manufacturer or importer. The final payment is made to Recupel by the manufacturer and importer.

(c) Sweden

Under the Waste Decree of 1990, local governments in Sweden have been responsible for the recycling of discarded refrigerators and freezers since 1995, and in 2000, Sweden implemented the Producer Responsibility Decree for electrical and electronic products, which makes producers responsible for the disposal of some products. To fulfill its legal obligations, Sweden has set up a recycling system, mainly responsible for the recycling of electrical and electronic products, owned and operated by the relevant industry associations, with costs borne by manufacturers and importers. Enterprises have the option of joining the organization or independently assuming responsibility for the recycling of their own products.

Since January 2002, some WEEE has been included in the list of hazardous wastes, and in order to prevent consumers from getting into the habit of sending their obsolete WEEE to retailers, the law stipulates that a retailer's "obligation to accept WEEE" is usually considered fulfilled if the retailer informs the consumer of the place where the WEEE will be sent to. The retailer's "obligation to accept the WEEE" is deemed to be fulfilled by telling the consumer where to send the WEEE, but the retailer may also voluntarily accept the WEEE from the consumer.

So in effect, local governments organize and finance recycling points, which is slightly at odds with producer responsibility. Producers are obliged to organize the recycling of WEEE. Retailers, suppliers, and repairers who receive WEEE can deliver it to municipal recycling points free of charge, or they can use the service provided by E1-Kretsen to haul it away at regular intervals. Non-household users can give their used products to designated recycling points on a one-for-one basis when purchasing a replacement product, or if they have not purchased a replacement product, they must send it to a recycling processor and pay a fee. Currently, there are more than 600 acceptance points for household electrical and electronic products, with an additional 250 supplementary collection points for commercial electrical and electronic waste and 33 specialized recycling plants (Julander et al., 2014).

Refrigerators and other products containing ozone-depleting substances are recovered by systems other than E1-Kretsen, as the Swedish Waste Decree of 1990 has long since stipulated that from 1995 the Government must recover and dispose of discarded refrigerators and freezers, and that the recovery of these products is mandatory and prohibited for export.

The operating costs of the recycling system are borne by the producer depending on the size of their sales and the type of product. E1-Kretsen determines specific cost rates for each industry, which do not overlap. The main costs include transportation from the collection point, reuse, cost recovery and information collection. Of these, reuse is the main cost, depending on the reuse rate achieved.

In 2005, E1-Kretsen levied an initiation fee of SKr 3500 (approx. EUR 280) per supplier, followed by a fixed annual fee of SKr 500 (approx. EUR 40) per year. Suppliers are also required to pay a variable fee based on the volume of their sales. For most products, the fee is shared based on turnover, and suppliers are required to pay a fixed fee upfront each year (e.g., based on volume, weight, or a percentage of sales), which is then refunded to the supplier or offsets against the supplier's due for the following year, as appropriate, at the conclusion of the end-of-year accounting settlement. In the case of ICT products, the suppliers do not have to pay a fee upfront, but rather E1-Kretsen calculates the actual recycling and disposal costs monthly, which are then apportioned according to the supplier's market share (the ratio of the total volume of sales of each supplier to the total volume of all sales in the previous year). For some specific products, a debit model, or a liability model (biting model) will be used.

The difference in the cost per unit of different types of products is partly due to the difference in their recycling and disposal costs, but of course it also depends on the rate of return, e.g., if a household buys a new washing machine, it will certainly throw away the old one, but if it buys a new camera, it does not necessarily have to throw away the old one.

(d) German

According to the EU WEEE and Restriction of Hazardous Substances directives, Germany started to formulate its own waste electronic product recycling regulations, March 24, 2006 promulgated the "Electrical and Electronic Product Use, Recycling and Environmentally Sound Disposal Act", the basic content of the regulations with the EU WEEE and RoSH directives are consistent with the clear provisions of the recycling of waste electronic products, the responsibility of all parties concerned, the recycling of waste electronic products in the management of the implementation of EPR in the recycling of waste electronic products. In the recycling management of used and end-of-life electronic products, the EPR system is implemented, in which the producers refer to the manufacturers and importers of electronic products. Each state has also formulated corresponding local regulations, thus constituting the recycling system of waste electronic products in Germany.

Germany's waste electronic products recycling and treatment has formed an industry, respectively, the establishment of municipal system of professional recycling and treatment companies, manufacturers of professional recycling and treatment companies, social professional recycling and treatment companies and professional hazardous waste recycling and treatment companies, etc., which are in accordance with the law to carry out recycling and treatment of waste electronic products business. In Germany, the recycling of WEEE is mostly undertaken by municipal enterprises directly under the municipal government. To facilitate the recycling work, Germany has adopted a variety of recycling methods: (a) free recycling. The unpaid recycling method is operational for the government and relatively difficult to implement; (b) paid recycling. Mainly by municipal professional recycling enterprises door-to-door recycling, although consumers bear the transportation costs of recycling; (c) timed recycling. Consumers are required to take their used electronics to a designated recycling point at a time specified by the municipal recycling company. The German antitrust authorities do not allow any industry to have a market share of more than 25% of the market for recycling programs in any category of the WEEE market. To prevent possible monopolistic behaviour by producer organizations, Germany allows producers to adopt as many recycling schemes as possible and to establish individual or industry-based recycling schemes, thus ensuring competition in the field of recycling and disposal of used electronic products.

Since 2006, Germany has been recycling at least 4 KG of WEEE per capita per year (nationwide). Owners of WEEE must ensure that WEEE is treated separately from other household waste. Municipalities are required to establish at least one WEEE collection point for household WEEE, either through door-to-door collection or in accordance with the closed-circuit material management law. Manufacturers are responsible for providing recycling containers at the collection point, consumers can bring WEEE to the municipal WEEE collection point free of charge, and retailers can voluntarily collect WEEE. At the same time, municipalities are required to sort the collected WEEE into six categories (major appliances, refrigeration equipment, information communication and technology equipment, telling machines, surveillance equipment, lighting equipment and sports equipment) free of charge and provide them to the manufacturers.

Once the volume of a certain type of WEEE collected by a municipal recycling point reaches a certain volume (30 cubic meters for large appliances, refrigeration equipment and information and communications technology equipment, and about 15 cubic meters for monitors and televisions and small electrical and electronic equipment), the municipality should notify the "Joint Organization" (described below). Municipal recycling points become the legal owners of these WEEE when they collect them and must keep them in a safe place. If they dismantle any useful or valuable parts, they may not pass them on to the producer, but dispose of them in accordance with the law (this article was added at the request of a municipal government to allow municipal companies to carry out manual dismantling, which would solve the problem of employing 8,000 to 10,000 mentally or physically handicapped people). Manufacturers can set up their own recycling systems to collect WEEE directly from consumers.

Duals System Deutschland (Duals System Deutschland, referred to as "DSD") is a non-profit social intermediary organization specializing in the organization of recycling and disposal of packaging waste in Germany, which was formed in 1995 by the joint efforts of 95 product manufacturers, packaging manufacturers, commercial enterprises, and garbage collection departments. DSD internal implementation of most of the voting mechanism, the government in addition to its recycling tasks and indicators and legal monitoring, other aspects are carried out in accordance with market mechanisms. DSD 1998 operation of the surplus, because it is a non-profit organization, so the profit part of the 1999 as a return or reduce the second year of fees. The intermediary nature of DSD is manifested in the fact that it does not say that it is a waste disposal enterprise but an organization, which organizes the enterprises that have the will to entrust the recycling of packaging waste into a network, and puts a green dot mark on the packages that need to be recycled, and then entrusts the recycling enterprises to be processed by the DSD. The "Green Dot" logo is a circle made up of green arrows connected at the beginning and the end, which looks like a green dot from a distance, meaning recycling. Any commodity packaging, if it is printed, it indicates that its manufacturers participate in the "commodity packaging recycling program", and for the disposal of their own products, waste packaging fees. The logo is now used in 10 countries in the European Union. The basic principle of the "Green Dot" program is that whoever produces waste must pay for it. The "Green Dot" fee paid by companies is used by the DSD to collect packaging waste, which is then cleaned, sorted, and recycled (Chaudhary & Vrat, 2018).

(e) Switzerland

Switzerland has been a pioneer in e-waste management legislation. Legally speaking, the management of e-waste in Switzerland was introduced by the Swiss Federal Office for the Environment (FOEN) in 1998 through the Ordinance on 'The Return, the Taking Back and the Disposal of Electrical and Electronic Equipment (ORDEE) was introduced. However, the formal collection and management of WEEE began before the legislation came into force, and it was important that the initiative was driven by Producer Responsibility Organizations (PROs). Producer Responsibility Organizations (PROs) are industry co-operatives that aim to take on the responsibility of their member companies and meet their EPR obligations. PROs take on operational responsibility for ensuring the proper management of e-waste by managing the systems of financing, collection, transport, and control. in 2007, there were four PROs in Switzerland, all of which are not-for-profit organizations that manage a range of products from housewares, to office and consumer electronics, to toys and leisure products, and lighting. SWICO recycling guarantee and SENS (Swiss Foundation for Waste Management) are the two largest PROs. They manage large and small household appliances, IT and telecommunications equipment, consumer equipment, Lighting equipment, electrical and electronic tools, toys, leisure, and sports equipment. The other two PROs, SLRS (Swiss Light Recycling Foundation) and INOBAT (Stakeholder Organisation for Battery Disposal), are small organizations dealing with lighting equipment and consumer batteries, respectively. SWICO and SENS have established a collection, disposal, and financing system. They are organized as voluntary member organizations, with producer representative committees making decisions on important matters such as setting the Advance Recycling Fee (ARF) and scrutinising bids for recycling contracts. The close interaction between the FOEN (the Swiss Federal Office for the Environment) and the PROs has significantly reduced the burden on the federal authorities to establish an e-waste management system using a top-down approach. Legislation on e-waste management helps to provide a legal framework for the various players involved in collection and recycling activities and creates a level playing field.

ORDEE deals with the return, take-back and disposal of end-of-life electronic products. It outlines the obligations of users to return WEEE correctly and the obligations of traders and manufacturers to take back WEEE. Switzerland is a signatory to the Basel Ban on transboundary movement of hazardous wastes. The Swiss e-waste management system is an EPR-based system that clearly defines the roles and responsibilities of all stakeholders, as shown in the Table 1.7.

Table 1.7 – Actors and responsibilities in the Swiss e-waste management system

Actor	Roles and responsibilities
Government	The federal government plays the role of an overseer, framing the basic guidelines and legislation. Cantonal authorities play a part in the overall control and monitoring in their capacity as the licensing authority for recyclers.
Manufacturers/Importers PROs (SWICO, SENS)	Importers carry the economic and physical responsibilities of their products. Have the role of managing the day-to-day operations of the system, including setting the recycling fees, as well as licensing and auditing recyclers.
Distributors & retailers	Bear a part of the physical and informational responsibility of the product. Are obligated to take back products in categories they have on sale, irrespective of whether the product was sold by them or whether the consumer purchases a similar product as replacement. Are responsible for clearly mentioning the amount of the ARF in the customer invoice.
Consumers	Are responsible, and obligated by law, to return discarded appliances to retailers or designated collection points. Bear the final financial responsibility through the recycling fee on new product purchases.
Collection points (specifically designated locations)	Collect all kinds of WEEE free of charge and ensure the safety of the disposed products to prevent pilferage or illegal exports
Recyclers	Must adhere to minimum standards on emissions and take adequate safety measures concerning employee health. Need authorisation to operate a recycling facility from the cantonal

	government, as well as a license from the PROs

Source: prepared by the author

(f) Japanese

Japan's Home Appliance Recycling Law was promulgated in June 1998 and implemented on April 1, 2001, which required the transfer of responsibility for the recycling of four types of household appliances (television sets, refrigerators, washing machines, and air conditioners) from local governments to manufacturers. The law requires that the responsibility for the recycling of four types of household appliances (televisions, refrigerators, washing machines, and air conditioners) be transferred from the local government to the manufacturer, and the law was amended on April 1, 2009, to add LCD televisions, plasma televisions, and washing machine dryers to the list of recycling targets. Construction of a recycling system for home appliances in Japan. The Home Appliance Law establishes the targets for the implementation of the recycling system and the requirements for recycling and treatment. The Home Appliance Law clearly stipulates the re-commercialization rate of the above products: more than 50% for refrigerators and washing machines, more than 60% for air-conditioners, and more than 55% for televisions and computers; it also requires that Freon in refrigerators and air-conditioners should be focused on recycling, destroying, or reusing (Chaudhary & Vrat, 2018). These products were chosen because these five types of electrical appliances account for most e-waste, and their recycling is difficult for local governments in Japan to handle, and the products themselves are portable and easy to re-commercialize.

There are three main groups of used home appliance recycling and processing plants in Japan: Group A consists of 24 used home appliance recycling processors established by home appliance manufacturers such as Matsushita, Toshiba, etc.; Group B consists of 14 used home appliance recycling processors established by home appliance companies such as Mitsubishi, Hitachi, etc.; and Group C consists of a smaller number of small businesses whose appliances are processed by Designated Bodies. There are more than 190 recycling centers throughout the country for A, B and C group of processors to recycle used appliances. At the same time, the Japanese government has also established designated recycling centers for residents in different areas, and most of the recycling centers are retail stores of large home appliance manufacturers.

Consumers are responsible for the costs of recycling and disposal of used and end-of-life appliances. Consumers should try to extend the service life of their appliances by handing them over to sellers or disposers at the time of their disposal; at the same time, the law stipulates that consumers should bear the costs associated with collection, transportation, management, and re-commercialization. The Law on Home Appliances stipulates that consumers should pay for the disposal of products, mainly because the consumption time of home appliances is generally long, so it is difficult to determine the cost of their disposal at the time of purchase; moreover, the manufacturer of home appliances may close down for a period of time due to operational problems, so it is not very practical for the manufacturer to pay for the disposal of the appliances; moreover, paying for the disposal of appliances at the time of their eventual abandonment is conducive to the prolongation of their life by the consumers. Secondly, the seller should be responsible for the collection and transportation of used home appliances. After receiving used home appliances from consumers, sellers should separate and collect and manage them and transfer them to manufacturers or recyclers for final treatment or disposal. At the same time, sellers have the responsibility to collect used appliances from households when selling new appliances. Thirdly, manufacturers are responsible for receiving and disposing of used and end-of-life appliances.

To implement the legal requirements for the responsibility of home appliance manufacturers, the Japan Home Appliance Products Association has established a Recycling Kits Management Center (RKC) within the Japan Home Appliance Products Association (JHAPA), which is responsible for the operation and management of home appliance recycling and disposal fees, and the issuance of home appliance recycling kits in accordance with the requirements of the law. Japan's home appliance recycling coupon is a five-part document that contains information about the consumer of the used home appliance, the manufacturer and specifications of the home appliance, the retailer, the receiving transportation provider, and the cost. The voucher is affixed to the body of the used appliance when the consumer hands it over to the recycler (retailer, recycling center, etc.), and the related information is handed over to the relevant units and individuals along with the recycling, transportation, and treatment of the used appliance, and the funds are finally pooled together in the RKC, which distributes the financial subsidies to the relevant recycling centers and treatment plants according to the management information on the voucher. RKC has a great responsibility in the whole appliance recycling and treatment system. It is an independent corporate body, supported by government funding, and is a semi-government, semi-private consortium, headed by a retired government official. At the same time, each manufacturer sends personnel to participate in the operation of the RKC, most of whom are familiar with the recycling of used and end-of-life appliances and are enthusiastic about the business.

As can be seen from the recycling system constructed by the Japanese Home Appliance Law, the Government of Japan has mobilized to a greater extent the participation of direct stakeholders, such as producers, distributors, and consumers, so that they can assume their respective responsibilities; and has made effective use of the partnership among enterprises that has already been formed in the supply chain management of the home appliance industry.

(j) United States of America

The United States is the world's largest producer and consumer of electronic products, with large quantities of electronic products being produced and consumed each year, and is the largest generator of waste electrical and electronic products. The U.S. government formulated some mandatory rules and regulations on the recycling of used and end-of-life electronic products in the early 1990s. California took the lead in the adoption of waste electronic products recycling regulations - "2003 Electronic Waste Recycling Act," January 1, 2005 came into force. January 1, 2006, Maine formally implemented the "Hazardous Waste Management Regulations," which clearly stipulates the mandatory recycling of household televisions and computer monitors. So far, the U.S. laws and regulations on waste electronic product recycling mainly include: (1) product coverage. Recycling products mainly include televisions, washing machines, refrigerators, air conditioners and other home appliances and personal computers and other electronic products. (2) Funding. Maine and Washington state mandated manufacturers to bear the recycling treatment fee; California mandated consumers to bear the recycling treatment fee; Maryland stipulated that the government and electronic product manufacturers jointly bear the recycling treatment fee; other states also appointed a study committee on the recycling treatment of used and end-of-life electronic products. (3) Government Taxation. Through the collection of landfill tax and incineration tax in the process of disposal of waste electronic products, it can effectively stop the landfill and incineration of waste electronic products, and at the same time, it can also prompt the producers of raw materials recycling. For example, in New Jersey and Pennsylvania, landfill taxes and incineration taxes are levied on used electronic products, thus prompting manufacturers to dispose of used electronic products in an environmentally friendly manner and to realize the recycling of resources (Kahhat et al., 2008).

In California and Maine in the United States, consumers are responsible for delivering used electronics to designated recycling points, and specialized recyclers are responsible for the recycling and collection of used electronics. Some domestic electronics manufacturers in the United States, such as Canon, Hewlett-Packard, Kodak and IBM, are committed to recycling used electronics. Dell Computer Corporation also cooperates with the American Waste and Recycling Federation to promote recycling programs for used computers in universities and public institutions.

At present, the United States has several companies with advanced technology and well-managed specializing in the recycling and treatment of used and end-of-life electronic products. The processing companies use advanced ecological processing technology and professional waste electronic products dismantling mode, and gradually formed the dismantling of waste electronic products, precious metal refining and other specialized companies. The recycling of waste electronic products has all reached more than 97%, and the recycling and processing effect is good. However, relative to the huge number of waste electronic products in the United States, the United States of America's waste electronic products recycling and processing capacity is very limited, many e-waste products are secondary sales to developing countries, such as Southeast Asia, posing a serious threat to the environment and human health.

The integrated recycle and treatment mode of e-waste

Integration strategy is a business consortium formed by combining a few associated units together, mainly including: vertical integration strategy, horizontal integration strategy and hybrid integration. Vertical integration, refers to the enterprise will be production and raw material supply, or production and product sales together in the form of a strategy to develop the field of operation to the depth of the strategy, is the enterprise in the two possible directions to expand the existing business operations of a development strategy, is the company's business activities backward to the supply of raw materials or forward to the end of the sales of a strategic system. It includes backward integration strategy and forward integration strategy.

By adopting a vertical integration strategy, a firm internalizes its external market activities and is able to save on the economics of transaction costs and stabilize relationships; reduce the uncertainty of upstream and downstream firms discontinuing transactions at will; weaken the price negotiating power of suppliers; improve the firm's ability to differentiate itself from other firms by providing a range of additional value within management's control; and keep key input resources and distribution channels under its control. in their own hands, thereby discouraging new entrants to the industry.

Horizontal integration strategy refers to a strategy of joining forces with enterprises in the same industry to expand the scale of production, reduce costs, consolidate the enterprise's market position, improve the enterprise's competitive advantage, and enhance the enterprise's strength. The essence is the concentration of capital within the same industry and sector, with the aim of realizing the expansion of scale, reducing product costs and consolidating market position. By adopting the strategy of horizontal integration, enterprises can effectively realize economies of scale and quickly acquire complementary resources and capabilities. In addition, through acquisitions or partnerships, enterprises can effectively establish fixed relationships with customers and maintain their competitive position and competitive advantages.

Mixed integration, which refers to the association of firms in different industrial sectors, in different markets and with no particular technological links between them, takes three forms: product-expansion, i.e. the association of firms producing and operating related products; market-expansion, i.e. the association of a firm with firms producing similar products elsewhere in order to expand its competitive territory; and unconnected, i.e. the association of a number of firms producing and operating products or services that are not linked to each other. Unconnected, which is a combination of several firms producing and operating products or services that are not related to each other.

One of the goals of the reuse of waste electrical and electronic products is to make enterprises or organizations within the industry to gather into a socially recognized degree of scale, so the use of integration strategy can enable enterprises to obtain the scale and sales growth, can improve the economies of scale of the enterprise, diversification of operational and financial risks, but also to strengthen the competitive advantage of the enterprise's original or core business.

A vertically integrated manufacturer-centred recycling model refers to the direct recycling of WEEE by manufacturers, or it can be recycled by distributors responsible for intermediary sales or by specialized third-party organizations and forwarded to manufacturers for processing, as shown in Figure 1.11.

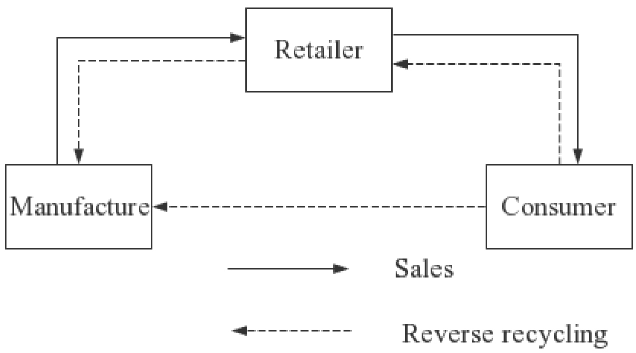

Figure 1.11 – Vertically integrated model centered on manufacturers' recycling and processing

Source: prepared by the author

The advantages of the integrated recycling model centered on producers' recycling treatment include: (1) Producers are responsible for the recycling, sorting, and testing, dismantling and reuse of products, and are able to implement supervision and management of the entire recycling process. (2) Manufacturers are responsible for the recycling of their own products, and the products they handle are in their own areas of expertise, such as the parts and functions of each type of product that are easily damaged and can be reused, and then they can use this part of their experience to guide the design of their products, and carry out the design of product recycling (removable design, design to extend the life of the product) is beneficial to improving the differentiation of their products and the degree of specialization. (3) Product sales information and recycling information are in the hands of the manufacturer, so the manufacturer has an information advantage, and the degree of information sharing is relatively high, which can reduce the uncertainty of the recycling process and minimize waste.

The vertical integration model centered on third-party recycling and processing refers to the manufacturer in the sale of products, who are not directly involved in the recycling and processing of waste electrical and electronic products, but specifically select the third-party reverse logistics service enterprises responsible for recycling and disposal work, usually these third-party reverse logistics service enterprises and specialized dismantling and processing enterprises to form a partnership, as shown in Figure 1.12.

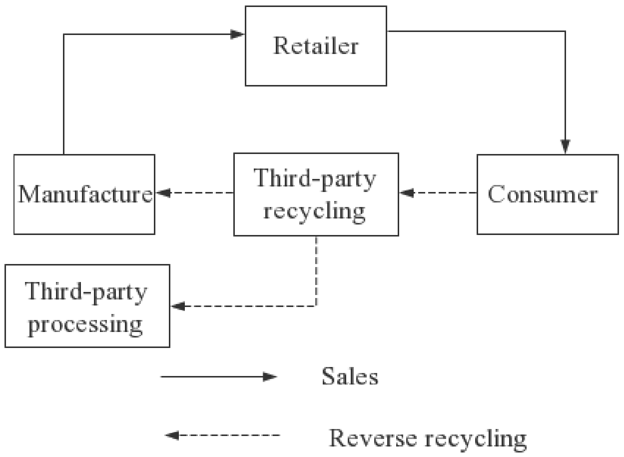

Figure 1.12 – Vertical integration model centered on third-party recycling and processing

Source: prepared by the author

Advantages of a vertically integrated model centered with third-party recycling are as follows: (1) A third party responsible for recycling and processing can liberate producers from recycling and processing activities, enabling them to focus on developing their core competencies and promoting the industrialization of e-waste management from the point of view of specialized division of labor. (2) Providing specialized third-party services for all enterprises in the industry, especially small and medium-sized enterprises, is conducive to the development of socialized services. (3) The logistics cost in the vertically integrated model centered on third-party recycling is the lowest.

Joint recycling refers to the formation of a joint liability organization by producers of similar products and the responsibility of that organization for the recycling of similar products produced by those producers, as shown in Figure 1.13.

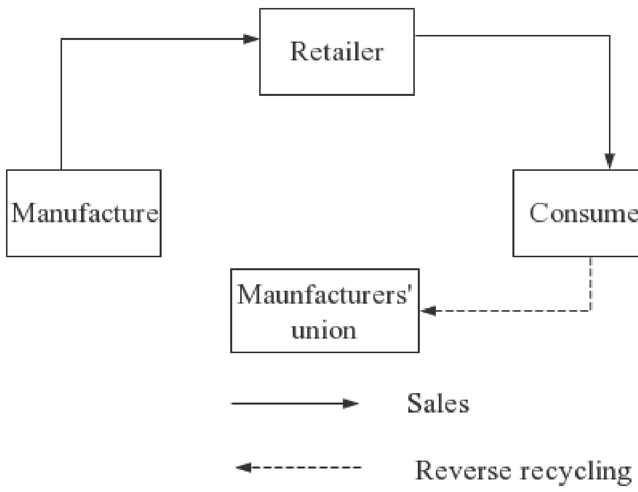

Figure 1.13 – Horizontal integration model centered on joint recycling and processing

Source: prepared by the author

Advantages of the horizontal integration model centered on joint recycling and processing include: (1) Joint recycling and processing of similar products, products with similarity, only a small number of product recycling and processing centers need to be set up, reducing the intermediate links in product recycling, with the effect of scale recycling and processing, and saving social costs. (2) Joint recycling treatment can promote the comparison and exchange between enterprises of similar products, with technology spillover effect, which can prompt enterprises to complement each other's strengths and promote the development of the recycling industry.

E-waste refurbishment/remanufacturing decision factors analysis

E-waste is recycled, refurbished, and remanufactured, and then sold to the buying public, which is the market for refurbished/remanufactured electrical and electronic products. The market has its own unique characteristics compared to the brand new electrical and electronic products market. (1) The size and volume of the refurbished/remanufactured electrical and electronic products market is small. Compared with the high consumption and high profitability of the brand-new electronics market, the market for refurbished/remanufactured electrical and electronic products is much thinner, with a large geographical area, dispersed populations, and an obvious lack of individual purchasing power. According to the statistics of the National Bureau of Statistics, the urban population, which accounts for a little more than 40% of the country's population, obtains nearly 70% of the country's income, while the rural population, which accounts for nearly 60% of the country's population, obtains only 30% of the country's income; on the other hand, the income gap between high-income groups and low-income groups is also widening further, which leads to a big gap between the scale and capacity of the refurbished/remanufactured electrical and electronic products market and that of the brand-new market. These factors have resulted in the size and volume of the refurbished/remanufactured E&E market being much smaller than the brand-new market. (2) Asymmetry of information in the market for refurbished/remanufactured electrical and electronic products leads to different marketing approaches. New electrical and electronic products market information is extremely developed, consumer groups in the purchase of the first time before the general comparison and screening about 80% of the consumers in the market with a certain purpose and lock target to the corresponding stores for comparison and verification, and ultimately the transaction. The refurbished/remanufactured electrical and electronic products market information dissemination is relatively undeveloped, because of this inherent "asymmetric information" factor, making the refurbished / remanufactured electrical and electronic products consumers in the transaction process is mostly at a disadvantage. (3) Consumers do not have high requirements for product functionality indicators, and tend to be more economically practical. Consumers in the refurbished/remanufactured electrical and electronic products market are not looking for new and different functions as the main appeal point, but rather economic and practical as the main selection factor. Consumers in the refurbished/remanufactured electrical and electronic products market do not demand complex functions, but are more concerned about the price factor behind the product. If the price exceeds their psychological expectation, more functions are not attractive to these consumers.

The high or low utilization rate of WEEE means the profitability of enterprises for refurbishment/remanufacturing, so it has an important influence on the decision-making of WEEE refurbishment/remanufacturing. The main factors that determine the utilization rate of WEEE are: (1) the product recycling rate. The sum of the mass of the recycled portion of the new product (including the reuse portion, the reuse portion, and the energy recovery portion) as a percentage of the quality of the new product. Due to differences in product design and the use of product materials, even for similar products, their product recyclable utilization rate is different. Ways to improve the recyclability of electronic products include: (i) use of materials that are easy to disassemble. Electronic products with high metal content, high recycling rate; electronic products with high plastic and glass content, the recycling rate is relatively low. (ii) To use easy to disassemble the design. (iii) To adopt a design that is easy to reuse. (iiii) To adopt designs that can be reused.

Due to the different ways of use, frequency, and intensity of use of each consumer, the utilization rate of recycled electronic products varies greatly, and consumers are generally not in a hurry to deliver outdated or unusable products to recyclers, so the utilization rate of recycled products also varies due to the degree of damage and the time of placement. Recycling WEEE refurbishment/remanufacturing costs are divided into two parts: recycling costs and refurbishment/remanufacturing costs. Recycling and processing costs include the purchase price of WEEE, recycling logistics costs and testing and sorting costs. Refurbishment costs include repair costs, cleaning costs and packaging costs. Remanufacturing costs include dismantling and shredding costs, reprocessing costs, and environmental treatment costs.

Conclusions to section 1

In section 1, this study focuses on the theoretical fundamentals of e-waste management system. The global volume of e-waste is growing at an alarming rate of nearly 2 million tons per year, and in terms of its quantity and impact on the earth's environment, e-waste has become the fastest growing waste stream in the world.

The number of studies on the negative impacts of e-waste is increasing, and e-waste is one of the most hazardous categories of household solid waste. The areas where e-waste is collected have caused serious environmental pollution, and exposure to e-waste can have adverse effects on human health. However, e-waste contains a variety of valuable substances such as precious and critical metals, which, if recycled for use as secondary materials, can solve the shortage of raw materials and resources in cities. Countries around the world are developing national-level e-waste legislation and regulations to manage the increasing amount of e-waste. Using the concept of CE for e-waste management can realize the reuse of resources from e-waste and reduce the generation of waste. The main conclusions are summarized below.

1. China, as one of the world's major producers and consumers of electronic items, has generated a large amount of e-waste. E-waste contains harmful ingredients, which could produce great harm to the environment and people's health if not handled properly. On the contrary, e-waste contains a lot of recyclable resources, which has a certain use value and solves the problem of resource shortage in industrial manufacturing. Therefore, e-waste management has attracted wide attention in recent years. To improve e-waste management, the Chinese government has formulated and implemented relevant laws and policies, which have achieved partial results. The e-waste management system, on the other hand, is far from perfect. The e-waste recycling and treatment is still in the initial stage. In China, the traditional e-waste collecting mode, which is dominated by informal recycling, has severely hampered the growth of e-waste management.

2. By systematically reviewing the theoretical and practical exploration of e-waste management, we summarized the systematic approach and innovation of e-waste management in China. With the rapid development of various intelligent information technologies, the chaos of e-waste management can be solved through technological innovation. To strengthen the intelligent China e-waste recycling system, the Chinese government and enterprises vigorously utilize a variety of emerging technologies, such as the Internet, IoT, cloud computing, big data, and AI

to improve the intelligence of China's e-waste recycling system, provide convenience for electronic waste holders, and improve the standardization level of e-waste recycling.

3. Smart e-waste management is considered a unique and effective new approach to solving the e-waste problem in China. Many scholars have conducted research on smart enabling waste management systems. Based on the rich theoretical results, some innovative practices of smart recycling have emerged. The emergence of e-waste recycling platforms based on the Internet and IoT has become the key to changing the traditional recycling methods in China. However, there are some challenges in practice. This paper proposes that the main barriers to smart e-waste recycling include consumers' lack of understanding and practice of smart e-waste recycling, the high operating costs of smart application platforms, and the lack of effective government regulation. This study proposes countermeasures to support the development and practice of smart e-waste collection and recycling technologies. The combination of smart technology and e-waste management is the key to the development of e-waste recycling in China.

4. The Recycling of e-waste products involves national legislation, payment mechanisms, definition of responsibilities of relevant recycling and treatment entities, and government supervision. China's e-waste management is relatively backward, and the e-waste management system and practical experience of developed countries can provide us with learning and reference. This study analyzes the e-waste recycling and treatment systems of the Netherlands, Belgium, Sweden, Germany and Switzerland, the countries in Europe where e-waste management legislation and practice were carried out earlier, and the EPR system has become a recognized principle. The Japanese government's home appliance law and constructed recycling system, and the U.S. state laws and regulations on the recycling and treatment of waste electronic products as well as the possession of professional waste electronic product recycling and treatment companies were also presented.

5. The recycling of e-waste is to achieve the reuse of resources, and it can adopt an integrated strategy, which is divided into three types: vertically integrated recycling mode with the producer as the core, vertically integrated mode with the third-party recycling and processing as the core, and horizontally integrated model with the joint recycling and processing as the core, and analyzes the advantages of the various modes. This study also analyzes the characteristics of the market for refurbished/remanufactured electrical and electronic products after e-waste recycling, and examines how to improve the utilization rate of used electrical and electronic products and reduce the cost of refurbishment/remanufacturing.

SECTION 2. METHODOLOGICAL BASIS FOR THE FORMATION OF AN URBAN ELECTRONIC WASTE MANAGEMENT SYSTEM BASED ON RESOURCE-SAVING AND ASSESSMENT OF ITS FUNCTIONING

2.1 Developing an original conceptual framework for a digitally enabled circular economy in the context of the product life cycle

Recent studies have advocated that DTs positively affect the transition of a linear economy model to a CE model and facilitate enterprises in implementing circular strategies. Despite this general statement, the literature still overlooks how enterprises should apply various DTs of Industry 4.0 across the entire product lifecycle to operationalize CE-related strategies. Based on insights gained through a systematic literature review, we clarify how DTs can facilitate CE performance objectives through the three stages of the product lifecycle: product design, product use, and product recovery or recycling. Furthermore, we study how various Industry 4.0 DTs, such as the IoT, big data, and cloud computing, are utilized to operationalize the transition toward a CE.

The CE is a restorative or regenerative industrial system that prompts exploring the reuse of materials or product components. The CE improves efficiency and productivity through circular strategies, such as reduce, reuse, repair, recycle, and restore (Geissdoerfer et al., 2017; Ghisellini et al., 2016). The CE promotes a “cradle-to-cradle” model of economic operations through innovative frameworks, such as product-service system (PSS), and industrial symbiosis. By incorporating the methodology of the 5R strategies (i.e., refuse, reduce, reuse, repurpose, and recycle), the CE can reduce the demand for limited original resources by decreasing the flow of materials and energy into the production and consumption processes and extending the life of products and services. The CE also advocates the protection of biodiversity and habitat by reducing emissions and pollution levels and by not treating the natural environment as a place to dump wastes (Irani & Sharif, 2018).

The rapid development of DTs, such as the IoT, cyber–physical systems, cloud computing, AI, big data analytics, and digital twins, mobilizes automation and data exchange in the process of smart manufacturing and production to reduce overconsumption and production errors and improve efficiency, thus driving sustainable development (Rajput & Singh, 2019). Many scholars have investigated the relationship between CE and DTs to determine the role of DTs in supporting CE implementation. Ranta et al. (2021) conducted a multicase study regarding a DTs-enabled business model innovation. Bressanelli et al. (2018) developed a conceptual framework that validates the role of DTs as a CE enabler in usage-focused business models.

The relationship between Industry 4.0 and CE is also a hot research topic in recent literature. Rosa et al. (2020) analyzed the overlaps between Industry 4.0 research and CE research and established an innovation framework to highlight the link between the two topics via hybrid categories, such as Circular I4.0 and Digital CE. Pham et al. (2019) used electric scooter-sharing platforms to show that Industry 4.0 can provide an enabling framework for implementing the sharing economy and enhancing the sustainability of manufacturing sectors in the CE context. Dev et al. (2020) built a real-time decision model for a sustainable reverse logistics system by integrating Industry 4.0 and CE. Yadav et al. (2020) developed a framework to overcome the challenges of sustainable supply chain management through Industry 4.0 and CE-based solutions.

Various business model innovation approaches have been proposed to support CE (Pieroni et al., 2019). DTs can achieve circular goals through interrelated monitoring, control, optimization, and automation functions. Ingemarsdotter et al. (2019) asserted that the IoT allows companies to track products throughout their lifecycle, which helps support R strategies, such as reuse, remanufacturing, and recycling, as well as product sharing. Guzzo et al. (2019) proposed and verified a circular innovation framework using different PSS cases. Alcayaga et al. (2019) addressed CE, IoT, and smart PSS from a holistic perspective. They also analyzed and built a smart circularity system framework that examined the binary interrelationships between smart circularity, circular PSS, and smart PSS. Kristoffersen et al. (2020) designed a circular strategy framework based on DTs to support the efforts of manufacturing enterprises in meeting the requirements for achieving the 12th Sustainable Development Goal within the United Nations 2030 Agenda for Sustainable Development.

Transforming enterprise thinking from a linear economy to a CE encounters many challenges and requires proper management of sustainable production and consumption patterns, closed-loop supply chains, and PSS. Grafström and Aasma (2021) examined barriers to CE implementation from four angles: technology, market, system, and culture. Rajput and Singh (2019) used principal component analysis to study the factors linking Industry 4.0 to CE use and identified AI and service and policy frameworks as significant enablers. Abdul-Hamid et al. (2020) evaluated the challenges faced by Industry 4.0 in implementing CE and how to address those challenges.

A few recent studies have explored the role of digitalization in circular business creation. Okorie et al. (2018) conducted a comprehensive literature review of the connections among CE, DTs, and Industry 4.0. The authors highlighted that, while publications in the field are increasing, only a handful of publications have connected them. Ingemarsdotter et al. outlined how the IoT can theoretically support circular strategies and demonstrated the progress of the application of this technology. Scholars have concluded that while some businesses have utilized the IoT to extend product lifetimes, only a few have used the tool to close the loops. In addition, several case studies have explored this topic from a similar perspective (Alcayaga & Hansen, 2019; Bocken et al., 2018). Although these studies provide useful insights into the digitalization of circular business models, additional research is required to fully comprehend the effects and functions of DTs in the creation of circular businesses that consider whole lifecycle management, especially in the design and recovery phases.

Role of Industry 4.0 in CE. In promoting the transformation from the traditional economy to the CE, DTs has shown good prospects for application via monitoring, control, optimization, and automation in achieving circular goals (Trevisan et al., 2021). The term “Industry 4.0” was first introduced by the German federal government in 2013 as a strategic policy initiative. The “cyber–physical production system” refers to the integration of different systems to achieve a high degree of automation in the manufacturing industry based on customer needs, which is increasingly blurring the boundaries between the virtual world and the real world (Rajput & Singh, 2020). The goal of Industry 4.0 is to use disruptive technologies, such as cloud services, IoT, big data and big data analytics, and AI, to interact with one another and improve the manufacture of high-quality products at a minimal cost. Industry 4.0 provides alternatives to sustainable production and consumption that minimize energy losses, resource consumption, and environmental degradation (Yadav et al., 2020). Industry 4.0 provides a fresh perspective on how manufacturing can use new technologies to create value with maximum output and minimum resource utilization.

The Boston Consulting Group (Rüßmann et al., 2015) identified the main technologies that help build Industry 4.0: big data analytics, autonomous robots and vehicles, additive manufacturing, simulations, augmented and virtual realities, horizontal/vertical system integration, IoT, cloud, fog, edge computing, and AI, as well as blockchain and network security. According to the literature analysis, six technologies have been identified as the main Industry 4.0-based technologies related to CE: cyber-physical systems, IoT, AI, big data analytics, additive manufacturing, and simulation. Figure 2.1 shows the DTs in Industry 4.0.

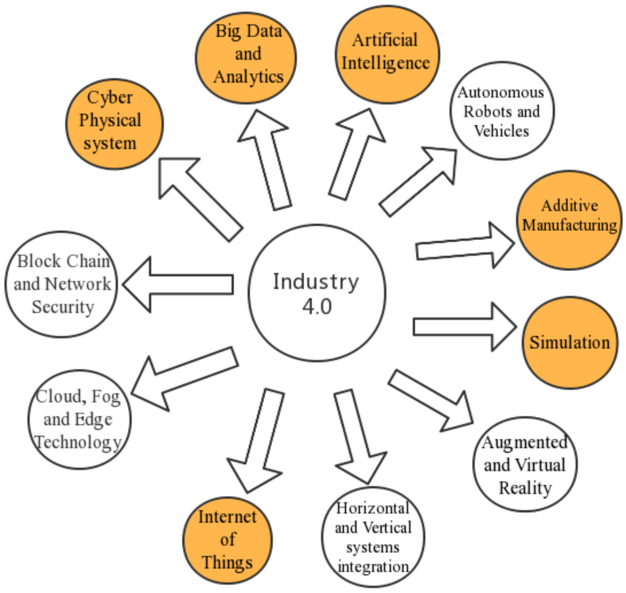

Figure 2.1 – DTs in Industry 4.0 (the six CE-relevant technologies are highlighted)

Source: prepared by the author

Against the background of the new round of scientific and technological revolutions, many countries have formulated their own national strategic plans to gain a competitive advantage in the manufacturing industry. In 2012, the United States spearheaded the implementation of the "National Strategic Plan for Advanced Manufacturing" to consolidate the US manufacturing industry's world-leading position, optimize its structure, and enhance its global competitiveness (Bag et al., 2021). To accelerate the technological transformation of the manufacturing industry, the United Kingdom released "The future of manufacturing: A new era of opportunity and challenge for the UK" in 2013 and established seven high-value manufacturing R&D centers, such as advanced manufacturing and forming technology (Paton et al., 2023). China proposed its "Made in China 2025" strategy, which was deployed to drive the implementation of its manufacturing strategy (Li, 2018). Through continuous R&D and innovation, China's manufacturing industry has mastered key technologies and filled the gap in the development of high-tech fields. Industry 4.0 is about transforming interactions between technology and the environment.

New DTs have a profound impact on industry. The first is the use of data (big data and open data), connectivity (IoT), and computing power (cloud computing). The second is data analysis, which improves the performance of machinery through “learning” by analyzing collected data (Lee et al., 2018). The third is the interaction between humans and machines (data visualization representations and augmented reality). The fourth is the transition from data to reality (additive manufacturing and 3D printing, AI) (Liu et al., 2017). The CE model considers the entire lifecycle of products and focuses on the high-level recycling of industrially produced materials. First, in the DTs-enabled design phase for a new product lifecycle, the combination of remanufacturing, reuse, repair, and recycling dramatically changes the cycle characteristics of the production process. Second, IoT technology enables the reintegration of maintenance processes, as well as the reusability of components and products. Finally, digitization enables the optimization of logistics and greatly improves the flexibility and reaction times of industrial and logistics systems.

DTs play a significant role in environmentally sustainable operational decisions, and the synergy and sustainability of Industry 4.0 may further drive a sustainable society (Dubey et al., 2017). Based on the findings of Agrawal et al. (Agrawal et al., 2022), integrating Industry 4.0 tools into circular business models can improve logistics, resource efficiency, safety, and product quality and reduce fossil carbon footprints. Several studies (Abdul-Hamid et al., 2022; Ahmed et al., 2021; Çetin et al., 2022; Chauhan et al., 2022; Kalogiannidis et al., 2022) have indicated that data-driven Industry 4.0 can be used to solve such CE-related issues, as Industry 4.0 features vertical integration, virtualization, automation, traceability, flexibility, and energy management. As part of Industry 4.0, machine learning methods are applied in the CE. Rakhshan et al. (2021) determined that advanced supervised machine learning techniques can be used to predict the reuse potential of structural components at the EoL of a building. Uribe-Toril et al. (Uribe-Toril et al., 2022) demonstrated the application of deep learning techniques to predict business survival. Arranz et al. (2022) combined the regression method with machine learning to explore how institutional pressures affect the development of CE in companies.

This study used the example of a bike-sharing platform to study both DTs and CE. This case has not previously been considered among the fields for application in the literature. Abdul-Hamid et al. (2022) and Çetin et al. (2022) studied the relationship between Industry 4.0 and CE, which is in line with our research; however, they focused on different fields of applied research. Abdul-Hamid et al. selected the palm oil industry to illustrate how the application of Industry 4.0 can improve unsustainable practices. Çetin et al. studied the promotion of DTs for CE in the construction industry. de Sousa Jabbour et al. (2022), Kalogiannidis et al. (2022), and Kurniawan et al. (2022) collected data from Brazil, Greece, and Indonesia to support a digitalization-based CE, respectively. Here, we considered the real-world situation of bike sharing in China as an example to illustrate how DTs can play an important role in transitioning to CE. Ahmed et al. (2021) studied the role of cyber-physical systems in promoting CE, and Delpla (2022) asserted that IoT technology can solve problems in the implementation of closed-loop supply chains. This study employed various DTs in Industry 4.0 as our research object, and we verified the positive role that various DTs play in CE practice from the perspective of the three stages of product lifecycle: product design, product use, and product recovery.

Exploring DTs in promoting CE business model innovation

CE as a new industrial paradigm. The most widely accepted definition of CE is provided by the Ellen MacArthur Foundation as “a framework for an economy that is restorative and regenerative by design,” which aims to preserve the maximum utility and value of products, components, and materials. The CE is different from the cradle-to-grave and governance economies. The CE supports the “cradle-to-cradle” model of economic operation through innovative methods, such as PSSs and industrial symbiosis. Many countries and macroregions are currently promoting CE not to obtain short-term and medium-term benefits, but to achieve long-term sustainable growth and save more resources for upcoming generations. The CE can be considered an optimization of the triple bottom line and can be used to create new business models and jobs.

The effective implementation of the CE can be split into three different levels according to scale and unit of analysis: micro-, meso-, and macro-levels. The micro-level refers not only to the specific measures of a single company's transition to a CE (Franco, 2017), but also to the specific measures taken at the product level. The meso-level extends this to the inter-enterprise level and enables inter-enterprise cooperation to emerge through industrial symbioses, such as eco-industrial parks (Geng & Doberstein, 2008). The macro-level covers measures implemented by cities, regions, or countries to promote CE at a high level (Murray et al., 2017).

From a topology perspective, CE is a closed-loop economy, whereas the traditional economic model belongs to an open-loop or linear economy (Bilitewski, 2012). The CE is composed of several closed-loop cycles, such as reuse, remanufacturing, and recycling, which can help save costs, moderate resource price fluctuations, and achieve economic growth without environmental damage and overuse of precious resources. The closed-loop cycle formed by the different principles of the CE is shown in Figure 2.2.

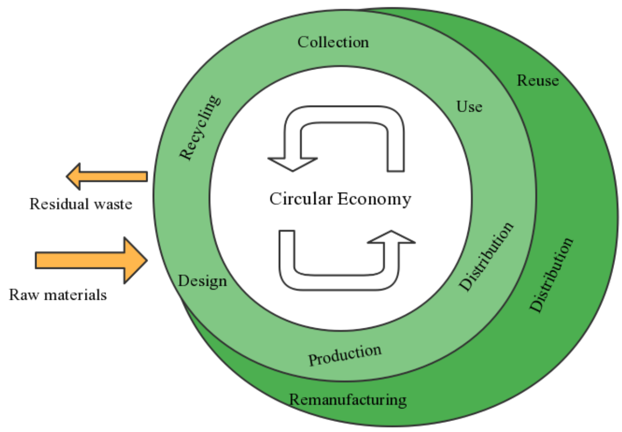

Figure 2.2 – Closed-loop diagram of a CE

Source: prepared by the author

The CE pays equal attention to the forward and reverse flows of products, components, and materials through the implementation of reverse logistics and closed-loop supply chains (Spring & Araujo, 2017). The environmental impacts of a product are considered upstream at the design stage before manufacture and use. A CE product is designed to be durable, have multiple lifecycles (Go et al., 2015), and reconfigure its resource dependencies in a sustainable and systematic way. Several design-for-x strategies can therefore be employed for eco-design, product life extension, modularization, remanufacturing, standardization, and material selection (Bakker et al., 2014; Mont, 2008).

The implementation of a circular strategy must start from the beginning; that is, in the product design stage, fully utilizing the advantages of DTs combined with the idea of circular design. After the product enters the sale-for-use phase, DTs can provide innovation in the business model, allowing enterprises to divorce from the old model of selling products for profit. The CE business model, if appropriately designed, not only provides the enterprise economic and environmental benefits, but also enables it to better deliver its value proposition at the social level.

Innovations in business models. The business model refers to the value creation function of an enterprise and how it benefits customers and makes profits (Teece, 2010). An ample amount of literature has analyzed the business models. For example, Richard and Peter (1999) identified four types of business models: embedded services, comprehensive services, integrated solutions, and distribution control. This classification is based on service content but does not consider product ownership. Michelini and Razzoli (2004) established the concept of product ownership and distinguished several types of services, including whole lifecycle services of tangible assets, leasing services of tangible assets, and the use of shared products. The transaction model dominated by one-off product sales is not conducive for enterprises to carry out technological innovation, and companies do not have access to usage data from product users. To motivate enterprises to adopt CE principles, researchers have proposed a shift from “product sales” to “service provision” (Bocken et al., 2016), in which a company moves toward a service-oriented business model where it owns the products and internalizes product maintenance and updating (Dimache & Roche, 2013). Such models are conducive to product management, thereby improving competitiveness and the sustainable development of the company under the condition that the enterprise owns and is responsible for the product (Tukker, 2004). The service-oriented business model can use lifecycle data to improve internal processes, customer relationships, and circularity (Morlet et al., 2016), thus establishing a lasting relationship between suppliers and customers, which are all driven by DTs (Valencia et al., 2015).

Baines and Lightfoot (2014) observed three different types of services that the company provides: essential services, which focus on product supply; intermediate services, which focus on maintenance; and advanced services, which focus on the effect of the product. Tukker (2004) classified business models into three types: product-oriented, use-oriented, and result-oriented models. Table 2.1 shows our analysis of PSSs and their relations with CE and the main advantages and drawbacks of each type of PSS.

Table 2.1 – Analysis of PSS and their relations with the CE

Product–service business model	Ownership of the product	Advantages regarding the CE	Main drawbacks regarding the CE
Product-oriented business model	Customers	The enterprises will provide pre-sale services and corresponding after-sale services	Negative environmental impacts of products, which will probably become wastes
Use-oriented business model	Enterprises	It avoids the risk of customers holding many fixed assets, increases product utilization rates, and creates additional economic value	Difficult to measure remanufacturing and reconditioning activities and short lifetime of some user-oriented products
Result-oriented business model	Enterprises	Customers are provided with the highest degree of service, which can make customers directly evaluate the effect of service and can help enterprises transition to	Difficult to measure results in terms of product/system performance

		a CE	

Source: prepared by the author

Product-oriented business models, which incentivize customers to purchase products to maximize product sales, make it challenging to achieve CE goals. These services mainly include pre-sale services for product-related components and quality services during maintenance.

The use-oriented business model is conducive to the improvement of resource-use efficiency, prolonging product lifespan through advanced maintenance and achieving the value of the CE. For instance, the product circulation loop can be closed by signing a recycling agreement. Use-oriented enterprises sell services only via leasing, sharing, or pay-per-use and not through tangible products. Their customers do not need to buy products but must only pay for access (Reim et al., 2015). These enterprises provide customers with whole lifecycle services, such as maintenance, repair, and control (Kujala et al., 2010). As these enterprises retain ownership of the “products,” they pay special attention to product design, and the lifecycle is increased by upgrading through easy maintainability and component reuse at the EoL (Adrodegari & Saccani, 2017).

Result-oriented business models help consumers use products better and improve product usage efficiency by providing consumers with information or services rather than just specific products. The customer pays variable fees according to contractual provisions based on the performance of the product or the results of its use. This business model is conducive for enterprises to minimize operating costs, improve resource efficiency, extend product life, and recycle products for multiple lifecycles, which significantly enhances their market competitiveness. In this model, customers buy performance rather than products and related services (Reim et al., 2015).

Product-oriented business models may produce additional waste; however, the product/system performance of result-oriented business models is difficult to measure. Here, as our focus is on the advantages of a user-oriented product service business model for CE, we selected a user-oriented PSS for the following analysis. Previous scholars (Adrodegari & Saccani, 2017; Reim et al., 2015) have suggested that this model can cause careless product usage by customers, resulting in rapid wear and tear. However, this drawback can be avoided by IoT technologies that, with the user's authorization, can enable the tracking and monitoring of product usage activity. Using the products to control users' activities in a way that prevents inappropriate use behaviors is possible. Use-oriented business models have enormous potential to improve resource efficiency, extend product service life, and close the loop of products through the positive impact of DTs.

To measure the effect of DTs on the development of CE, we must define CE performance objectives. The Ellen MacArthur Foundation established three CE performance objectives: increasing resource efficiency, extending the product lifespan, and closing the loop (Morlet et al., 2016). Bocken et al. (2016) proposed narrowing the resource flows by using fewer resources to make each product, reducing the flow of resources by extending the lifetime of the product, and closing the loop of resource flows by redirecting them into raw materials.

This study adopted the following CE performance objectives: (1) using fewer materials and resources by improving resource efficiency, (2) extending product lifespan, and (3) closing the loop. In this section, we presented a conceptual framework for how DTs can facilitate CE performance objectives in terms of the three stages of product lifecycle: product design, product use, and product recovery (Han et al., 2023a).

Product design. Intelligent manufacturing is an important way to develop and transform the manufacturing industry, including intelligent design, production, service, management, logistics, and system integration (Rusch et al., 2022). Among them, intelligent design is the core of intelligent manufacturing and the key point that determines the transformation of the entire intelligent manufacturing system. Products are traditionally designed in a way that does not consider what would happen when they are no longer used and only works to introduce new models to satisfy consumer needs and temptations. As a result, numerous EoL products ultimately end up landfilled, causing not only huge losses of materials, energy, water, and labor, but also damaging the environment. Product design for CE is a complex process that requires a shift in thinking from a product-centric to a system-based design approach. Circular design challenges the next generation of products and materials to minimize the use of primary raw materials (Talla & McIlwaine, 2022). The focus of circular design is to reduce the loss of value by maintaining the closed-loop cycle of these products and materials. These cycles, such as reuse, repair, remanufacture, refurbishment, or recycling, extend the lifecycle of products and improve resource productivity. When the product is scrapped, the parts can be recycled and remanufactured, and the materials can be reused through recycling.

The product design phase affects product longevity and reprocessability. Product design is the starting point for fulfilling the challenge of CE; thus, we should use integrated approaches for sustainability assessment to reconfigure our resource dependencies. The CE demands cross-disciplinary collaboration and active communication among designers, materials experts and engineers, environmentalists, economists, and end-users during the design phase (Patyal et al., 2022). In contrast to current solutions that focus on the "end" of life, we considered and implemented resource challenges from the "beginning" of the lifecycle of products, components, or materials, that is, the design phase.

Research by the UK's Royal Society for the Encouragement of Arts, Manufactures and Commerce found that circular design can be divided into four modes: design for long life, design for lease or service, design for reuse in manufacturing, and design for material recycling (Medkova & Fifield, 2016). First, design for a long life improves product reliability. Bocken et al. (2016) proposed "design for reliability," in which if the manufacturer's instructions for use and maintenance are followed, then the products are highly likely to work failure-free for a certain period. Dematerialized designs should also be considered, as they reduce the number of materials required while maintaining core functionality. Second, in "design for leasing/service," which is a business model to provide services to more users, the producer or manufacturer retains ownership of the product. This model has evident benefits for users, as it enables them to use high-spec, high-tech products. In addition, the model of leasing, which sells the results, can also avoid low-priced disposable tools, saving resources and time. Third, in reusable design, damaged product parts are made replaceable. Users can purchase parts through an online ordering system, and manufacturers can provide high-quality and cost-effective maintenance services. Obsolete products are returned from users to manufacturers for remanufacturing through reverse supply chain management (Krstić et al., 2022). Fourth, the reprocessing of recycled products into new materials in material recycling design requires products to use a single material rather than complex materials and involves the development of a second-hand material certification system (Talla & McIlwaine, 2022).

The new technologies and innovations provided by Industry 4.0 have promoted information-oriented and knowledge-oriented business models to achieve economic and sustainable development. Such models require manufacturers to further expand their focus on potential environmental impacts, enhance product design quality, and explore their contribution to sustainable development (Neligan et al., 2022). Additive manufacturing technology innovates traditional processing. It uses computer control to add materials layer by layer to manufacture objects and is thus able to produce an increasingly wide range of goods. It not only enables complex and revolutionary design and manufacturing, such as topology-optimized structural design, complex 3D shape printing, and lightweight design, but also agile, integral, low-cost manufacturing, such as full digitalization, no tooling, and one-shot molding, all while minimizing transport. As a strategic technology trend of Industry 4.0, the digital twin is gradually maturing and becoming a mainstream technology. This tool is essentially a combination of physical entities, and twin models can then optimize continuous processes and help achieve precise control in the real world. Therefore, digital twin is also featured among the core technologies of cyber-physical systems. The tool can help enterprises reduce costs, resource consumption, and carbon footprints while supporting innovation, business agility, and customercentric business models that are highly aligned with CE. Using Industry 4.0 for product design is conducive to the realization of CE, as shown in Table 2.2.

Table 2.2 – List of different product design strategies for CE performance objectives

Design-for-x strategies	Analysis of the strategies	CE performance objectives	Function of DTs
Design for manufacturing	Design for manufacturing helps save resources in product manufacturing and enables rapid high-quality manufacturing	Use fewer materials and resources	Digital design and manufacturing technology provide product design solutions that integrate many advanced technologies, such as CAD/CAPP/CAM
Design for assembly	Design for assembly helps improve efficiency and reduce wear during product assembly	Extend product lifespan	Digital assembly technology uses virtual reality to plan and simulate the actual product assembly process
Design for disassembly	Design for disassembly allows rapid product disassembly, improves reparability, and reduces consumable input and waste output	Close the loop	The virtual disassembly method based on a 3D software platform can guide the product disassembly process
Design for quality	Achieving high-quality product design helps improve product quality to meet customer needs	Extend product lifespan	Digital prototyping technology can be used to improve product function
Design for supply chain management	Designs that consider supply chain-related factors can help improve product efficiency and reduce instability in the supply chain	Use fewer materials and resources	Blockchain and IoT technologies can be used to establish a product supply chain traceability system
Design for lifecycle	Considering the product lifecycle in the design helps assess overall resources consumed and pollution generated in the	Use fewer materials and resources	Virtual manufacturing systems based on digital twin technology consider all important factors at each stage of the product lifecycle

	product lifecycle		
Design for the environment	Considering environmental impacts in product design helps achieve sustainability goals	Close the loop	Additive manufacturing technology can significantly reduce raw materials, waste, transport, and energy inputs in the production and delivery processes

Source: prepared by the author

Product use. From a high-level abstraction perspective, we can observe consumers dealing with PSSs by interacting with physical products to request and enjoy services, as shown in Figure 2.3. In PSS, the "service" part acts as an invisible intermediary between customers and products. Part of the PSS plays the role of the product's user interface, allowing consumers to request services and then receive and use them. At the back end of the PSS, the embedded sensors in the product communicate with the cloud-based product support environment, which collects sensor data to build and maintain the product's digital twin. Data analysis can be used to extract essential usage data and update product status. We can then simulate the product in its current state to determine whether maintenance or software updates are required (Rosen, 2019). Figure 2.3 schematizes the mode of PSS operation. If customers want to find a new app, they can navigate through the phone's user interface to find the app store icon, launch it, and then browse the retrieved apps. At the back end of the PSS, a large-scale cloud-based system is necessary to collect, catalog, archive, validate, and retrieve various apps.

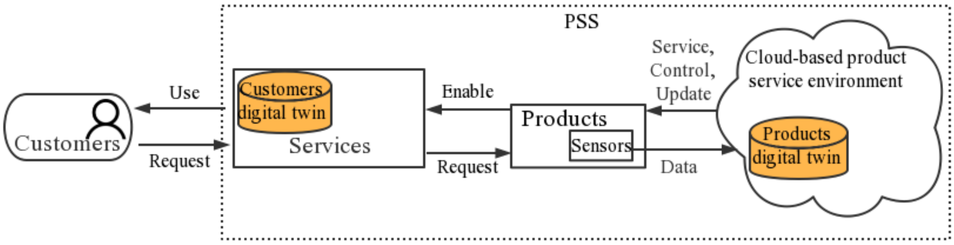

Figure 2.3 – PSS internal interaction process.

Source: prepared by the author

In Figure 2.3, we focused on the operation of the PSS. The back-end cloud-based product supporting the environment should be considered. Digital twin is the representation of a product and the environment's sensor data flow, which keeps the product continuously updated. Certain control and decision-making processes must be present in the system to update product status, analyze data, and simulate product status. To adapt over time and improve its performance and the performance of PSS, we should have an intelligent support system with specific monitoring and execution capabilities.

PSSs should be able to understand consumers to provide better and sharper services. In other words, PSSs should have a digital twin of a customer and use that data representation as the basis for data analysis and simulation. Figure 2.4 schematizes the digital twin of customers and products contained in the “Services” section and the cloud-based product service environment. The smart PSS of the future is expected to have an updated and analytically capable digital twin for the product and consumer. Sensor data support control, analysis, and decision-making activities, enabling the PSS to respond and adapt to consumer needs and the environment where the product is used. In addition, the PSS can learn as the system operates.

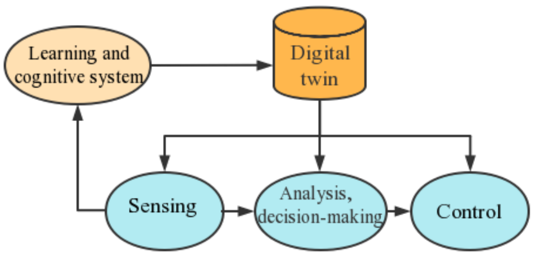

Figure 2.4 – Digital twin of consumers and products in smart PSS

Source: prepared by the author

PSSs can enable the collaborative consumption of products and services and help make CE a reality. The continuous development of the digital twin has become a driving force for the improvement of PSSs. DTs help manufacturers capture operational data on products that customers are using to deliver advanced services, such as operational status monitoring and preventive maintenance. In addition, manufacturing enterprises can engage customers in the whole end-to-end process of product service, from R&D and design to operation, to provide purpose-targeted services (Han et al., 2023a).

Product recovery

Under the linear economy model, consumers discard products at their EoL as waste, which not only pollutes the environment, but also wastes resources that can otherwise be restreamed or recycled for use in remanufacturing instead of consuming valuable raw materials. The CE can support the closed-loop recycling of products or materials through the improvement of the reverse supply chain and progress in smart technology (Shevchenko et al., 2021). The development of Internet technology and e-commerce platforms has led to the emergence of several Internet-based recycling platforms. The platforms are based on the online to offline e-commerce model, which can track user information, monetary information, and logistics information, to manage the reverse recycling chain and generate statistical information. Internet-based recycling platforms combine new technologies, such as the IoT and big data, to build a complete recycling ecosystem. A smart waste collection system based on IoT, including radiofrequency identification tags, near-field communication sensors, and GPS sensors, can obtain real-time data on the status of smart recycling bins and on the users involved in recycling to optimize the recycling process (Han et al., 2022). The recycling platforms consist of a mobile phone–based application through which users can locate the nearest or most suitable smart recycling bin and are rewarded with money or points for participating in recycling (Kang et al., 2020).

AI technologies used in waste recycling systems can identify the types of recyclable products and materials through image recognition technology and analyze user behavior data (Fayomi et al., 2020). Machine learning-based optimization techniques are already being used in IoT-based smart waste collection systems. These methods help analyze incoming waste materials, the size of the waste bins, and the type of waste collection vehicles necessary. For instance, Gupta et al. (2019) obtained data from sensors installed on bins and used machine-learning algorithms to sort recyclable materials by type, such as plastic, metal, or glass, and dispatch the recyclable products and materials to a recycling plant.

Internet technology, combined with mobile apps, establishes direct contact between consumers and manufacturers or recyclers to prevent many recyclable products and materials from becoming solid wastes and provides conditions needed for reverse logistics. IoT technology allows companies to track products throughout their lifecycle, enabling CE strategies, such as reuse, remanufacturing, recycling, and product sharing. Using IoT, cloud computing, big data analytics, and AI technology, smart waste bins solve not only the problem of product recycling, but also the problem of urban waste management.

Reflections and discussions on a bike-sharing platform as an example of access-based product-service systems (AB-PSS)

This research determined that DTs, such as IoT, cloud computing, big data, and AI, act as facilitators for CE business models and enable the transition to a CE. In the initial stage of the product lifecycle, that is, the design stage, DTs help realize the circular design of the product, such as detachable and recyclable components, to achieve the third CE performance objective, that is, to close the loop. In addition, product design to increase lifespan helps achieve the second CE performance objective, that is, to slow down resource flows. In the middle stage of product lifecycle, that is, the use stage, the application of DTs makes the product "smart;" thus, value is no longer generated from the design and production stage but from the use stage (Lenka et al., 2017; Porter & Heppelmann, 2014). IoT technology can monitor and track product activities, collect usage data, and combine with cloud computing, big data analytics, and AI to provide technical support for product use, guide users on optimizing the process of product use, extend product lifetime, and accomplish the CE second performance objective, which is to slow down resource consumption. Based on the usage data, the product design can be improved to satisfy the CE first performance objective, enhance the efficiency of raw materials, and reduce the flow of resources. DTs can also facilitate preventive or predictive maintenance; thus, products can maintain an increased service life. At the end stage of product lifecycle, the loop can be closed by streaming the product into a second life or by efficient recycling through efficient reverse logistics systems. However, CE activities in this final stage of the product life are closely related to the design in the initial stage of the product life. Increasing the investment in DTs in the product design stage is necessary to create conditions for the product to close the loop in the end stage.

The effects of various DTs as drivers of CE performance objectives are as follows. IoT technology can be used to monitor and track product activity, optimize production processes, and supply chains, meet customer needs with less raw materials, and improve resource efficiency, whereas user data captured by IoT can be mobilized to maintain or upgrade products and provide customers with high-quality services. Cloud technology provides customers with convenient and timely access to maintenance services, increasing service demands and extending product lifetimes. Cloud technology provides companies with the opportunity to access large amounts of data in the supply chain, which increases the company's understanding of real-time operations and results in a highly cost-effective and reliable supply chain. The cloud establishes and maintains the digital twin of products by collecting sensor data, simulating physical objects in real time, providing insight into problems that may arise in the process, and making recommendations for product improvements; thus, the need for expensive physical testing is eliminated, and the production costs are reduced. Big data technology, which is widely used at all stages of the product lifecycle, can improve product design to facilitate EoL recycling, and provides for preventive and predictive maintenance. AI technology enables companies to accurately predict the waste generated and optimize demand for products, thus improving supply chain management and reducing unnecessary warehousing and potential shortages, thereby reducing costs. Additive manufacturing combines mechanical manufacturing technology with digital IT to produce customized products and save materials without increasing costs (Han et al., 2023a; Han and Yi, 2023).

The growth of Internet technology has driven the growth of the sharing economy and the resulting peer-to-peer sharing of resources, such as car sharing, power bank sharing, and home appliance sharing (Curtis & Lehner, 2019; Esfandabadi et al., 2022; Pouri & Hilty, 2020). Digitization facilitates the emergence of new circular AB-PSS, where users complete transactions via online platforms and social media that use IoT products (Belk, 2014). Digital infrastructure also facilitates continuous data exchange between service providers and the devices used by users, enabling pay-per-use device services (Bocken et al., 2019).

Circular business models, such as AB-PSS, have been enabled by DTs. A growing number of mobility AB-PSS initiates the implementation of bicycle-sharing systems by consumers (Fishman, 2016; Geissdoerfer et al., 2017). In recent years, shared bicycle systems have flourished in smart cities, and most of them have been successful. As a typical example, an intelligent transportation system can effectively improve transportation mobility and safety while also reducing environmental impacts. Since 2016, the shared bicycle system has begun to grow rapidly in China, drastically altering citizens' travel habits. The bicycle-sharing service is based on a time-sharing rental model by companies, which provides citizens with many public bicycles at public places, such as bus and subway stations, commercial and residential areas, and university campuses. To illustrate the effect of DTs on CE, we thus proposed to study the case of bicycle-sharing service.

Bike sharing is an AB-PSS that allows consumers to pay for the use of a shared bike. This business model can reduce the negative impacts of overbuying by reducing the total number of products required, increasing the use frequency of products, and extending the product lifecycle through maintenance and upgrades. An IoT-based smart lock is installed on the shared bicycle, and functions, such as positioning, unlocking, returning, and paying, are all managed through a smartphone app. Therefore, this AB-PSS relies on DTs and the user's smartphone.

Companies evolving in use-oriented business management systems are usually responsible for product costs over the whole product lifecycle costs (Adrodegari et al., 2017), which is an incentive for them to design their products for a CE. A network capable of performing on-site support, such as transport, repair, maintenance, upgrade, and collection, can maintain the normal operation of the system and extend the lifespan of the shared bicycles. When bicycles become technologically obsolete, they are collected and replaced. Old bicycles are repaired, updated, and cleaned before they are returned to the system.

The entire system underpinning bike sharing can be regarded as the process of data collection, analysis, processing, and operational feedback. IoT technology is key and foundational to interconnecting mobile phones, bicycles, and the cloud. A mobile app can be used by the clients to search for nearby bicycles and carry out unlocking, fee calculation, and mobile payment. The bicycle terminal can collect travel data and transmit the GPS information and status of the electronic lock to the cloud through the subscriber identity module card. The cloud controls the entire system, collects information, and issues commands to control the bicycle terminal. This workflow is shown in Figure 2.5.

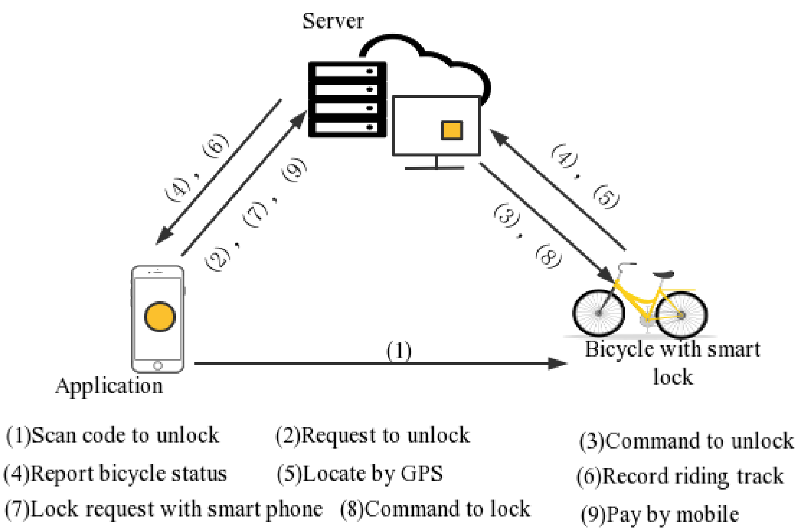

Figure 2.5 – IoT workflow in bicycle sharing

Source: prepared by the author

AI technology supports intelligent scheduling, balancing supply, and demand, and accurately predicting shared bicycle parking areas and peak and valley parking periods. Therefore, AI helps provide rational recommendations on parking spots and no random parking. If the vehicle is not in the specified parking area, it cannot be locked by phone for settlement. The cloud platform mainly operates in data storage and management and is the hub of the entire bike-sharing operation. After the user scans the QR code on the bike, the command requesting the unlocking is uploaded to the cloud system to unlock the bicycle; at the same time, the real-time status and location of the shared bicycle are also uploaded to the cloud, thereby achieving the function of synchronous billing. The cloud platform can help handle user recharge and payment services and, by establishing a user credit system, implement civilized use and proper parking (Shen et al., 2018).

DTs are currently developing at a rapid pace, and the impending 5G technology delivers low communication time delays and highly accurate locations for bike-sharing platforms. This feature enables the realization of improved location-based services, such as an electronic fence and cycling path records. In addition, with sensor and technology developments, more sensors are embedded in the shared bicycle, resulting in increased data collection about cycling. With some data mining methods, these data can be transformed into highly intuitive and understandable forms for decision makers to accept, thus making the city run increasingly efficiently (Adrodegari et al., 2017).

DTs-driven products for AB-PSS adhere to the recycling design strategy, making the design easy to maintain, upgrade, disassemble, and recycle. As illustrated in Figure 2.6, the IoT, cloud platforms, and AI provide the technical foundation for developing AB-PSS. The IoT is mainly used for networking the peer-to-peer sharing of resources and collecting data. Smart shared products have sensors and communication modules that can sense the surrounding environment and communicate with the IoT platform to serve shared product networking. The cloud platform provides data storage and management for shared products, including condition data, distribution of shared products, and demand data. AI is mainly used for big data analysis and feedback to provide technical support for smart operations. Using big data to analyze when and where shared products are commonly used can help rationally plan the deployment of the products and improve resource utilization.

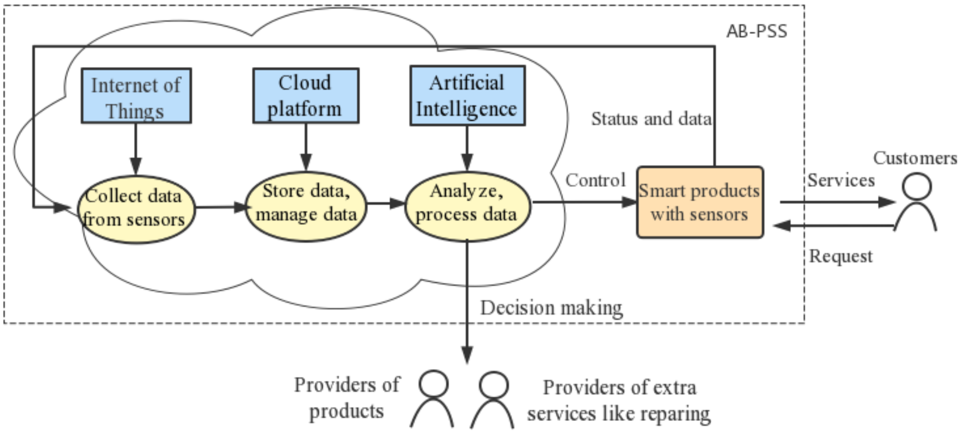

Figure 2.6 – Key DTs work flows in AB-PSS

Source: prepared by the author

AB-PSS extends the product lifecycle by shifting responsibility for repairs and maintenance to suppliers. The information collected by the IoT provides better technical support for on-site maintenance technicians. For example, it analyzes maintenance and fault management data to discover which parts fail most frequently, which can improve the design or quality of the parts. In addition, the big data on users can be analyzed to provide effective preventive and predictive bicycle maintenance (Kim et al., 2020). At the end of the lifecycle, the IoT technology can capture the real-time location and status of the bicycle through GPS, and the appropriate collection activities and recycling conditions can then be organized. In summary, in the case of shared bicycles, DTs enable improvements in CE. DTs combined with the AB-PSS business model can improve resource efficiency, extend product life, and close the loop on resource flows.

2.2 Formation of a scientifically based index system for evaluation of urban circular economy development

The evaluation of the development of urban CE

CE realizes the sustainable development of economy, society, and environment by maximizing the utilization of resources and minimizing waste discharge. The establishment of the evaluation system of urban CE is of great significance to promote the sustainable development of cities. Wu (2019) systematically studied the construction of the urban CE evaluation index system and the selection of evaluation indicators, which provided an important theoretical reference for the evaluation of the urban CE. Wu et al., (2014) proposed a method for constructing an evaluation index system of urban CE based on the concept and characteristics of urban CE, and applied it to practical cases for research. From the development status of urban CE, Xiao and Yang (2012) took Beijing as an example, proposed the construction method of urban CE evaluation index system, and evaluated the development of urban CE in Beijing. Pan (2010) put forward the construction method of the evaluation index system of urban CE, and conducted application research in combination with actual cases. The establishment of the urban CE evaluation system is a systematic program that requires research from multiple aspects such as the current development status of urban CE, selection of evaluation indicators, and construction methods. Previous academic research has provided some important theoretical references and practical cases, which are of great significance for promoting the development of urban CE.

Drawing on various "green" development evaluation indicators at home and abroad, the establishment of a scientific, comprehensive, and concise indicator system for measuring the development of the urban CE is an important element in evaluating and supervising the current situation and development trend of the CE, identifying the key points and difficulties in its development, identifying the development gaps between cities, and evaluating the performance of the Government. The urban CE system is an organic whole with specific functions composed of a few interacting and interdependent parts, which is subordinate to a larger CE system, and at the same time can be divided into several sub-systems such as economy, society, and environment. The design of the urban CE evaluation index system should meet the principles of systematicity, scientificity, comparability and dynamism.

The development of the CE requires that material and energy be reduced and recycled within the system as much as possible, but as an urban CE system, it interacts with the outside world and needs to exchange material, energy, and information with the outside world continuously, so that it can be integrated into a wider circular system, and therefore the urban CE system is characterized by relative openness. From the overall point of view, the urban economic system can be regarded as a subsystem of the total system, and from its own point of view, it is a compound system of "social-economic-environmental", which can be divided into several levels. First, it can be divided into ecological subsystems and human subsystems, which in turn can be divided into social and economic subsystems.

Urban CE is not a static result, but a process of continuous development. As the urban CE develops and urban environment improves, many features of the system change over time, so the evaluation index system should be constantly adjusted. The evaluation index system of urban CE takes the regional CE system as the object of evaluation, evaluates, and monitors it based on the theory of CE and utilizes scientific methods and means, which is of great significance to the introduction, implementation, and control of the CE model. (1) By using the urban CE evaluation index system, the current situation of urban CE operation can be evaluated, and by quantitatively evaluating the overall situation of a certain region's CE development, reflecting the basic operation status, judging the development level, favorable and unfavorable conditions of CE, and providing the governments at all levels, the relevant departments, the enterprises and the public with a scientific basis for judging the current situation of the CE development, as well as providing them with important information. (2) Supervision and early warning of urban CE. Based on establishing relevant alert standards, establish a CE early warning system to monitor and reveal the contradictions and problems in the development of the region and analyze the reasons for them, to reverse the unfavorable trend of change in time, and return the socio-economic development to the track of benign development. (3) Trend analysis of urban CE. Through the application of long-time continuous CE evaluation data, comprehensively reflect the trend of changes in all aspects of the state of the CE, and utilize forecasting means to formulate the development strategic planning of the region to carry out effective macro-management. (4) Provide the basis for optimizing management decisions. Local governments at all levels and various decision-making departments can understand the development status of CE through the evaluation of CE, find out the unfavorable links hindering its development, and provide scientific basis for optimizing management decisions. (5) As an important basis for the government's performance appraisal, it guides the local governments to change their traditional concepts and methods of economic development, implement the idea of CE, and urges them to complete development plans and the basic objectives of CE.

Status of research on CE valuation

At present, most of the domestic research on CE focuses on the discussion of the basic theory, construction mode, realization mode and operation system of CE. Although the research on the evaluation of the development of CE has also been discussed, a set of scientific and reasonable evaluation standards and evaluation index system has not been formed. Although the evaluation levels and evaluation indexes proposed by existing scholars have their own characteristics, there is still no standard or system recognized by the academic community.

Based on studying the international index system for measuring social development, Yu and Feng (2005) proposed a design based on four major systems, namely, industry, urban infrastructure, human habitat and social consumption, which is based on economic development index, green development index and humanistic development index, three major levels, totaling 24 indicators. An empirical study was done with the evaluation of Shanghai's CE development as an example. Based on the analysis of the necessity of the construction of the CE index system and the basic principles of the index system, Xiang and Xiang (2010) constructed the CE evaluation index system, which is divided into three levels, namely, the target level, the control level and the index level, among which, the control level is based on five levels: socio-economic development, resource reduction and input, waste reduction and emission, resource recycling, and ecological environment quality. The control layer focuses on five levels, involving a total of 30 indicators. The shortcoming is that only the indicator system and evaluation method are given, but no empirical research is carried out.

Wang and Zhang (2010) conducted an empirical study on the level of CE development of 16 cities in the Yangtze River Delta region by using three levels and 18 evaluation index systems, and combined with factor analysis to conclude that economic development, the degree of resource consumption, reuse and resourcing are the main factors affecting the level of development of the CE, and through cluster analysis to conclude that the Yangtze River Delta region can be divided into three sub-city circles in accordance with the level of development of the CE, indicating that the formation of the economic structure of industrial division of labor and cooperation with Shanghai as the leader. Through cluster analysis, it is concluded that the Yangtze River Delta can be divided into three sub-city circles according to the level of development of recycling economy, which indicates the formation of the economic structure of industrial division of labor and cooperation in the Yangtze River Delta region with Shanghai as the leader.

Shi and Zhou (2010), based on reviewing the existing methodology and evaluation index system, proposed a CE evaluation index system with 35 indicators in 3 levels of "target-structure-response" based on the connotation of CE development. Through the empirical study of Handan City from 1996 to 2008, it is concluded that the resource productivity of Handan City during the 11th Five-Year Plan period has risen dramatically, while the carbon emission intensity has declined dramatically during the same period, and the economic growth has been significantly decoupled from resource inputs and environmental emissions, with a shift from resource-dependent to resource-efficient development mode.

Ma et al. (2010) provided a methodological decision support tool for resource, waste, and environmental management through material flow analysis, put forward a new idea for regional CE evaluation and research, and combined the material flow analysis method with the real situation and put forward a total of 13 indicators at three levels and four sub-levels (socio-economic indexes, aggregate indexes, intensity-efficiency indexes, and cyclic indexes, respectively). The evaluation index system of regional CE development is proposed. The proposed indicator system provides a new thinking mode and evaluation paradigm for the evaluation of CE.

Through systematic comparison and refinement, Qiao et al. (2009) put forward a regional CE development evaluation index system with three major levels and four sub-levels (respectively, resource productivity level, environmental disturbance intensity, degree of resource recycling, and level of social development) with a total of 16 indicators, which covers the cyclic characteristics of different industries and fields, and through the use of fuzzy mathematics and fuzzy comprehensive evaluation, the evaluation of the development level of regional CE at the macro level was measured, and relatively scientific and reasonable conclusions were drawn in combination with empirical research. The system covers the cyclic characteristics of different industries and fields, and using fuzzy mathematics and comprehensive evaluation, it measures the level of regional CE development at the macro level and draws relatively scientific and reasonable conclusions by combining with empirical research.

Wang (2009) constructed the evaluation index system of regional CE, which consists of three levels and four sub-levels (economic and social development, resource reduction, pollution reduction and resource reuse, respectively) with a total of 16 indicators. Based on the corresponding data of Tianjin from 2000 to 2007, a detailed evaluation of the development level of CE in Tianjin is made by using relevant evaluation methods, summarizing some existing problems, and putting forward corresponding policy suggestions.

Zhou et al. (2003) proposed a regional CE development evaluation index system by combining the concept of industrial eco-efficiency, which is divided into four major levels, namely, the overall level, the system level, the state level, and the variable level. The system layer includes economic efficiency index system, resource and energy index system, ecological and environmental efficiency index system, and recycling characteristics index system, with a total of 30 indicators, which draws on the content of the eco-efficiency index system.

At present, the existing research results on the evaluation index system of urban CE mainly have the following problems:

(1) The "3Rs" principle has been reflected, but it is still not prominent enough. The essence of CE is to realize the harmonious and sustainable development of society, economic growth, and the natural environment through the closed-loop flow of materials and energy, which is the "3R" principle. Although the existing evaluation index system has paid attention to the "3R" principle to a certain extent, most of them have not really taken it as the core of index evaluation. When dividing the sub-systems of the urban CE system, the economic and social sub-systems and the environmental sub-systems are often regarded as equally important, and the number of indexes is also largely the same. The number of indicators is also more or less the same.

(2) The selection of indicators is too arbitrary, making it difficult to obtain or impossible to quantify data. The evaluation of urban CE development is essentially a quantitative evaluation of the degree of development through scientific methods, which aims to reduce the bias and risk of human subjective judgment and make the evaluation itself more scientific and reasonable. However, a study of the existing literature reveals that, although the indicator system listed by many scholars is detailed, many indicators tend to be qualitative in nature and cannot be assigned specific values, or are very inconvenient to calculate, and even if the results can be obtained through calculations, it is too difficult to obtain the data needed for the calculations. A very important principle followed in the selection of indicators is to ensure that the data can be obtained directly or indirectly and conveniently, because the whole evaluation process is a very complex systematic project, and it is possible that the whole evaluation process will be stagnated due to the unavailability of a single piece of data or the overall effect of the evaluation will be affected due to the inaccuracy of a single piece of data. Therefore, when setting the indicators, it is important to consider that the selected data can be quantified, which is very important for the final evaluation results.

(3) The design of evaluation indicators is too theoretical and lacks empirical support, or cannot be empirically verified at all. At present, most of the evaluation of regional CE development model is still at the theoretical stage, which includes

that the selection, design, and classification of indicators are divided into subsystems according to the viewpoint of system theory, and the basis of the division is not clear, so the indicators may be faced with the problem that they are only theoretically established when designing them, but do not exist or are not very significant in practical application. At the same time, theoretical research is disconnected from practice, and some scholars who conduct theoretical research are not directly involved in the practice of governmental departments on the evaluation of regional CE development, which requires that the theory should be linked to the practice in the evaluation of the development of urban CE, and the empirical work should be carefully supported.

Principles for the construction of the evaluation indicator system

The comprehensive evaluation system of urban CE takes the urban circular economic system as the evaluation object, and uses scientific methods and means to evaluate the development status, development level and development trend of the ur-ban circular economic system according to the circular economic theory. When designing the evaluation index system of urban CE, it is necessary to follow certain principles, so that the index system can comprehensively and briefly reflect the construction status and development potential of urban CE.

(1) Scientific principle. The evaluation system of urban CE must be able to objectively reflect the conceptual connotation and basic principles of CE. The design of the evaluation system should be based on a scientific foundation of full understanding and systematic research, with the name, definition, interpretation, calculation method, classification of each indicator being scientific and normative.

(2) Systemic principles. Urban CE involves various aspects of urban natural resources, ecological environment, society, and economy, and is a complex and comprehensive system. Therefore, the evaluation system must be able to comprehensively cover the development indicators of various subsystems related to urban CE, such as resources, environment, economy, and society, etc., and highlight the key points.

(3) Dynamic principle. The purpose of constructing the overall evaluation system of urban CE is to reflect the overall development of the economy and the degree of circularity in the utilization of resources, to serve the decision-making process for the development of the urban CE. The evaluation system of urban CE should not only introduce the static indicators to reflect the actual production capacity and level of the system, but also introduce the dynamic indicators to reflect the sustainable development ability of the system.

(4) Principle of comparability. The evaluation system of urban CE should adopt internationally recognized names, concepts, and calculation methods, with unified dimension and comparability. In this way, it can not only form a time series of CE system, analyze the development status of urban CE construction, but also compare the level of CE construction among cities in the same period.

(5) Principle of operability. In the process of constructing the evaluation system of urban CE, government statistics of past years are used as a basis, and the values of the selected indicators can be obtained directly or indirectly through mathematical methods such as calculations and corrections. Some difficult-to-collect data could be replaced by other indicators.

(6) Territorial principle. Each city has different resources, environmental conditions and economic development levels, and the focus of the construction and evaluation of the CE is also different, which requires that the evaluation methodology, indicator system and the weight of the indicators are also different due to regional differences. Therefore, regional principles should be followed in the construction and evaluation of CE, and objective and accurate evaluation should be carried out according to local conditions.

There is a lot of academic research on CE in different contexts, but the standard for measuring the urban CE is still a lack. Scholars have proposed various evaluation index systems, each with its own set of characteristics. Wang et al. (2018) put forward an evaluation index system for urban CE development (UCDI) that uses a methodology combining expert and entropy weightings. The index was calculated for 40 cities that participated in China's pilot CE cities project for 2012, 2014 and

2016. Geng et al. (2009) proposed an index to measure the urban CE of Dalian in China, with an emphasis on the waste management. Zaman et al. (2013) developed a similar approach named the zero-waste index, which were used to assess three cities. Yu et al. (2005) put forward 24 indicators based on three levels of economic development index, green development index and human development index, and conducted an empirical study in the city of Shanghai. Ma et al. (2010) proposed a regional CE development evaluation index system of 13 indicators, including three major levels and four sub-levels, namely socio-economic indicators, aggregate indicators, intensity and efficiency indicators, and cycle indicators, using the material flow analysis method. According to the proposal of Feng and Yan (2007), evaluation system should be composed of economic development index, green development index, and hu-man development index. The green development index included reduction, reuse, and re-source indicators.

These evaluation approaches for urban CE are useful, but they may not optimally suit urban CE evaluation requirements because (i) some studies were not originally designed for the systematic, closed-loop, and feedback characteristics of CE. The principle of CE has been followed to some extent, but it is not enough to highlight the "3R" principle. (ii) some studies disregarded important indicators of urban CE, such as the resource productivity, energy productivity. Chinese researchers' studies on CE evaluation systems are not well organized or unified.

The methodology applied in urban CE evaluation comprises 4 procedures, which were illustrated in Figure 2.7. Firstly, A critical literature review according to PRISMA was carried out to find the theoretical basis of DTs contributing to CE in smart cities, and establish evaluation framework of city CE. Based on literature review, a reasonable conceptual framework was selected as the foundation to establish indicators, and valid indicators was identified under the context of China based on existing literature. Secondly, standardize the raw data of each indicator. Thirdly, calculate the weight value of each indicator within the framework using the analytic hierarchy process (AHP). Last, calculate the evaluation index of urban CE by the formula.

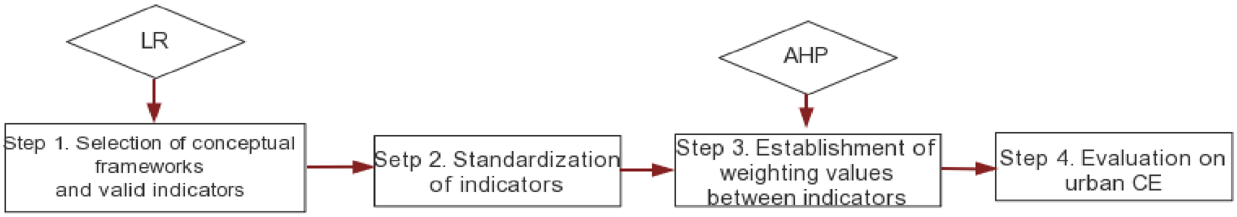

Figure 2.7 - Research methodology for evaluation urban CE

Source: prepared by the author

(1) Framework construction and indicators selection

The hierarchical structure of the evaluation index system, i.e., the target layer, criterion layer, element layer and index layer, constitutes the multi-objective and multi-level structure of the evaluation model and evaluation method in this paper. After determining the overall hierarchical structure of the evaluation index system, it is necessary to screen and determine the corresponding indicators of each level according to certain principles and methods. In the selection of indicators at the corresponding level, this paper summarizes the existing literature and summarizes the relevant information that can be accessed to make a preliminary determination of the evaluation indicator system layer by layer. These references mainly include the research results of the "CE Evaluation Indicator System" group of the National Bureau of Statistics, the research results of domestic and foreign scholars on the evaluation indicator system of urban CE, and the city's statistical yearbook. At the same time, the existing research results of index systems like the evaluation indexes of CE, such as ecological economic development indexes, sustainable development evaluation indexes, green evaluation indexes, urban development evaluation indexes and so on, are also useful for the selection and determination of the evaluation indexes of urban CE.

The Urban CE Development Index (UCEDI), which represents the overall situation of urban CE development. There is a need to further define the guideline layer, the element layer, and the indicator layer.

(a) Guideline layer. The criterion layer corresponds to the sub-target layer, which is a further decomposition of the urban CE development index. If the target layer corresponds to the whole urban CE system, then the criterion layer corresponds to the development status of the subsystems existing in the whole. In this paper, the subsystems of the urban CE system are divided into economic subsystems, social subsystems, and environmental subsystems, and the three aspects are measured comprehensively and examined as a whole. The development status of the whole region depends on the comprehensive evaluation of economic, social, and ecological and environmental benefits, and the harmonious development of the three is an important aspect of the urban CE evaluation system. Therefore, the evaluation index system of urban CE can be decomposed into the evaluation of economic subsystem, social subsystem, and ecological environment subsystem.

(b) Factor layer. For the economic development index, the factor layer of the economic growth index is divided into economic strength and economic efficiency, with economic strength emphasizing the total volume and scale of the economy and economic efficiency focusing on economic growth. For further decomposition of the social development index, it is necessary to focus on resource reduction, reuse, and resourcing in accordance with the 3R principle of CE. The ecological environment sub-system will incorporate indicators of environmental pollution treatment, examining the degree of pollution reduction. In summary, the factor-level indicators are divided into economic strength, economic efficiency, resource reduction, reuse and resourcing, and pollution reduction.

(c) Indicator layer. The indicator layer is a further refinement of the element layer and a direct counterpart of the target for the evaluation data source. It is worth noting that in the preliminary determination of the indicator layer, for each element layer indicator, often corresponds to a lot of indicator layer indicators, but not all indicators can be included in the final evaluation indicator system. After the preliminary determination of the indicator layer, it is also necessary to further screen the indicators in combination with the principles of indicator selection, and at the same time, the principal component analysis and independence analysis of the indicator system, as well as consulting the opinions of experts, etc., are all necessary steps to ensure that the final evaluation indicator system is more complete.

After determining the target layer, criterion layer and element layer, the most important work is to select specific evaluation indicators. According to the analysis and summary of the existing literature and various data, following the principle of screening and determining indicators, we firstly selected the indicators with high frequency, and made a preliminary system of regional CE evaluation indicators, and then carried out the principal component analysis on top of this preliminary system, and combined with the consulting opinions of relevant experts, we made local additions to and deletions from the preliminary system of indicators, and then adjusted the indicators by combining the principal component analysis, independence analysis, etc., and consulted the opinions of experts again on the adjusted indicator system. In the process of changing the indicators, we will adjust the indicators by combining principal component analysis and independence analysis, and consult the experts again on the adjusted indicator system. We try our best to make the indicators as concise as possible and able to cover all the issues to be examined, and at the same time, ensure that the indicators entered the indicator system can obtain accurate data from formal channels, and eliminate those indicators that are cumbersome, ambiguous, and have no way of obtaining data. After several repeated adjustments and modifications to the initial evaluation index system, the final evaluation index system for urban CE development was derived, as shown in the Table 2.3.

Table 2.3 – Evaluation index system for urban CE development

Target layer	Guideline layer	Elementary layer	Indicator layer	Indicator number	Unit	Type of indicators
	Economic development index	Economic strength	GDP growth rate	D1	%	Positive indicators
			GDP Per Capita	D2	Chinese Yuan (RMB)	Positive indicators
			The average wage of workers	D3	Chinese Yuan (RMB)	Positive indicators
		Economic	Consumer price index	D4	-	Positive

Urban CE Development Index		efficiency				indicators
			Ratio of profit to output value	D5	%	Positive indicators
	Resource development index	Reduction of resources	Energy consumption of per-unit GDP	D6	Tons of standard coal/ten thousand yuan	Inverse indicators
			Water consumption of per-unit GDP	D7	Tons of water/thousand yuan	Inverse indicators
			Electricity consumption of per-unit GDP	D8	Kilowatt-hours/thousand yuan	Inverse indicators
			Output value of per-unit land area	D9	Ten thousand yuan/hectare	Positive indicators
		Reuse and recycling	Utilization rate of industrial solid waste	D10	%	Positive indicators
			Reuse rate of industrial water	D11	%	Positive indicators
			Decontamination rate of urban refuse	D12	%	Positive indicators
	Environmental development index	Reduction of pollution	Discharge amount of waste water per-unit GDP	D13	Tons/ten thousand yuan	Inverse indicators
			Exhaust emissions per-unit GDP	D14	Ten thousand cubic meters/ten thousand yuan	Inverse indicators
			Discharge amount of solid waste per-unit GDP	D15	Ten thousand tons/ten thousand yuan	Inverse indicators
			Attainment rate of the industrial waste water discharge	D16	%	Positive indicators
			Rate of industrial practice removal	D17	%	Positive indicators

Source: prepared by the author

As can be seen from the Table 2.3, the evaluation of the level of regional CE development is divided into four levels, with a total of 17 indicators selected. It is worth mentioning that these 17 indicators are all quantitative indicators, and when determining whether the indicators are included in the evaluation system, sufficient investigation and research have been done on whether each indicator can be supported by actual and meaningful data, and indicators that are too qualitative and difficult to be quantitatively processed, indicators that are difficult to obtain data or are not precise enough, and indicators that have poor representativeness and lack of practical application have been excluded, and so on. The 17 selected indicators are representative of the problems they reflect, and at the same time, they are easy to obtain quantitative data information. Intuitively analyzing the distribution of the indicators, it is easy to see that the number of indicators in the resource subsystem and the environmental subsystem is relatively high, because the goal of the CE is to realize the harmony between human beings and the natural world and sustainable development, and the way to achieve this is through the effective solution of the resource and pollution problems. Under the guidance of the "3R" principle of CE, source control is carried out first to realize the reduction of resource inputs and waste of resources, and at the same time, the emission of pollution is minimized in the production process, and attention is paid to the recycling of waste at the end of production. Therefore, there are relatively more indicators for the evaluation of resources and the environment, especially the reduction and control of inputs, which is an important goal of the CE.

Based on a synthesis of previous research, this study developed an evaluation index system shown as Figure 2.8. It is drawn from mature indicator systems EIS2017, and followed 3R recycling principles. This study employed quantifiable indicators based on available data, meanwhile laid attention to production and consumption at urban level. The evaluation index system of urban CE contains three dimensions: economy, resources, and environment. Five evaluation metrics were chosen, including economic strength, economic efficiency, resource reduction, pollution reduction, reuse, and recycling, which contains 17 indicators, as shown in Figure 2.8.

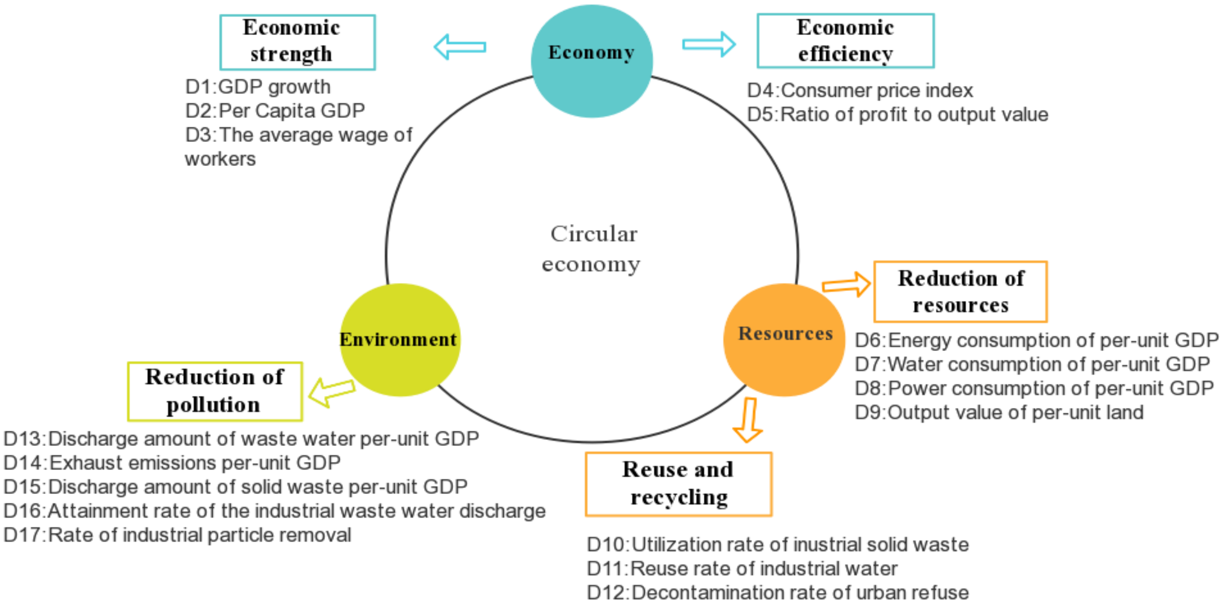

Figure 2.8 – Evaluation indicators of urban CE development

Source: prepared by the author

(2) Standardization of all indicators

After determining the evaluation index system of urban CE development, we get a problem of evaluating the object with multi-attribute indicators, because different indicators often have different units, therefore, there is bound to be a difference between their outlines, and to eliminate the difference between the outlines of different indexes, it is often necessary to do standardization of the index value of the evaluation object. Indicators of different outlines, through a certain method of transformation, into a standardized indicator of the dimensionless, known as the standardization of indicators. Choosing the appropriate standardization method for the nature of the evaluation, the evaluation objectives, and the degree of difference in the evaluation indicators is of great significance to the accuracy of the evaluation results.

There are two types of indicators in this study: positive indicators, which are characterized by the fact that people want their values to be as large as possible, such as output value, profit, efficiency, etc.; and inverse indicators, which are characterized by the fact that people want their values to be as small as possible, such as cost, energy consumption, inputs, etc. There are many methods of standardization, and this study adopts the method of extreme difference transformation. Assuming that there is n decision indicators e_j (1<=j<=n), m programs to be evaluated, the matrix $R=(r_{ij})_{m*n}$ composed of n indicator values of m programs is called decision matrix.

This study uses 17 independent indicators to evaluate the CE performance of 253 sample cities. Since different indicators on the performance of city circularity present different dimensions and ranges, to make effective comparison, all indicators need to be normalized into dimensionless. In the decision matrix $R=(r_{ij})_{m*n}$, Formula (1) is used to normalize positive indicators which perform better with higher number, and formula (2) is used to normalize inverse indicators, on the contrary, the smaller the negative indicator, the better the performance. Indicators D1-D17 are normalized according to formula (1) and formula (2).

The matrix $R= (r_{ij})_{m*n}$ is called the polar transform normalized matrix. The advantage of the polar variation method is that, regardless of whether the indicator values in the decision matrix R are positive or negative, after the polar variation transformation, the standardized indicators satisfy $0 <= r_{ij} <= 1$, and both positive and negative indicators are transformed into positive indicators, with the optimal value being 1 and the worst value being 0.

$$r_{ij} = \frac{x_{ij} - \min\limits_{1 \le i \le m} x_{ij}}{\max\limits_{1 \le i \le m} x_{ij} - \min\limits_{1 \le i \le m} x_{ij}} (1 \le i \le m, 1 \le j \le n) \quad (1)$$

$$r_{ij} = \frac{\max\limits_{1 \le i \le m} x_{ij} - x_{ij}}{\max\limits_{1 \le i \le m} x_{ij} - \min\limits_{1 \le i \le m} x_{ij}} (1 \le i \le m, 1 \le j \le n) \quad (2)$$

(3) Calculation of the weight values

The weight values reflect the relative importance between indicators. In most multi-criteria decision-making methods, AHP is a very popular and widely used attribute weight extraction method created by American operations researcher Satty in the early 1980s (Satty et al., 2007). The basic idea is, first of all, according to the nature of the problem and requirements, put forward a total goal; secondly, the goal will be decomposed according to the level, the same level of the factors within the two comparisons, to determine its relative to the upper level of the goal of the respective weight coefficients, so that layer by layer analysis until the last layer, you can give the importance of all the factors in relation to the total goal of the order. A structural model of hierarchical analysis is required. Usually, the hierarchical structure of hierarchical analysis method includes target layer, criterion layer, element layer, indicator layer, etc. The number of levels is decided according to the difficulty of the required problem solving and the number and complexity of the elements or indicators involved. The evaluation of urban CE development in this study can be constructed into a hierarchical structure as shown in Figure 2.9.

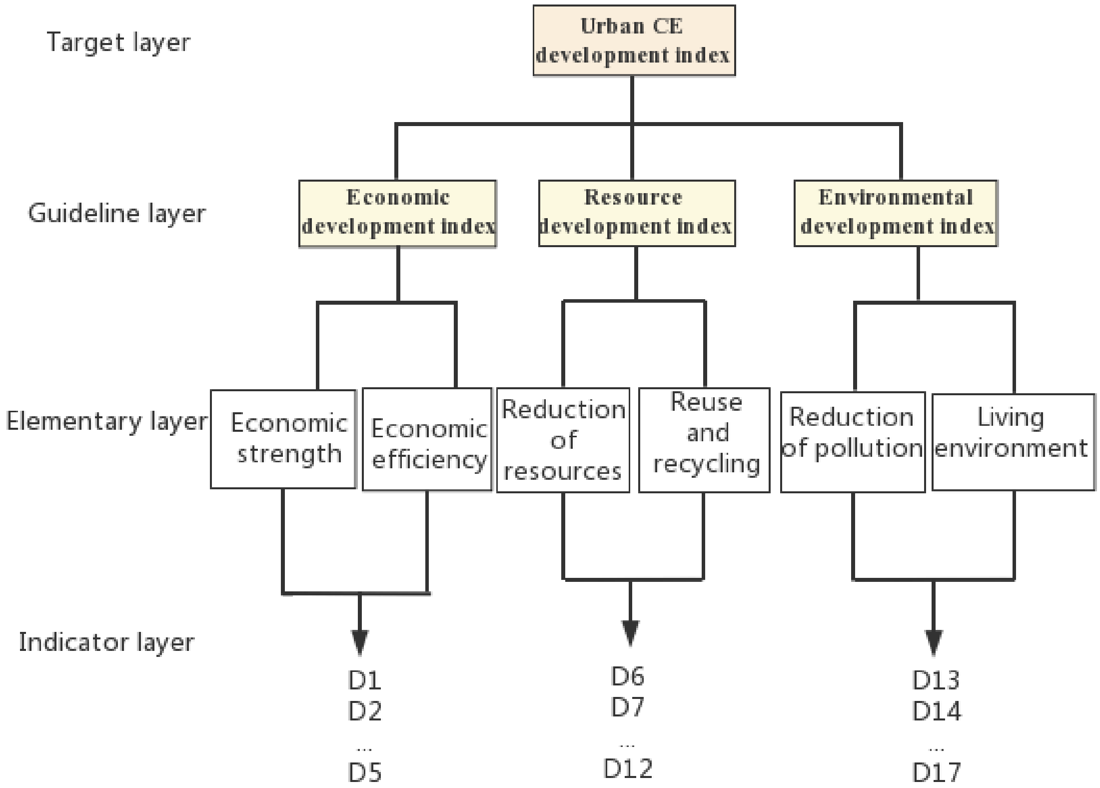

Figure 2.9 – Hierarchy of urban CE development evaluation system

Source: prepared by the author

This method is based on the construction of a judgment matrix. On this basis, the consistency ratio (CR) is used to assess the consistency of hierarchical ranking calculation results. Saaty et al. believed that when the random consistency ratio meets C.R. < 0.10, the calculation results of the hierarchical total ranking have satisfactory consistency. Otherwise, the judgment matrices of this level must be re-determined. The weight values of D1-D17 calculated by AHP are shown in the Table 2.4.

Table 2.4 – The weight values of each indicator in urban CE evaluation.

Wight (w_j)	Value	Wight (w_j)	Value	Wight (w_j)	Value
w_1	0.070523	w_7	0.0474289	w_{13}	0.0313513
w_2	0.1078862	w_8	0.0632386	w_{14}	0.013398
w_3	0.0551107	w_9	0.0345668	w_{15}	0.1134242
w_4	0.1243822	w_{10}	0.0409979	w_{16}	0.0459395
w_5	0.0620978	w_{11}	0.0286717	w_{17}	0.0186963
w_6	0.1227257	w_{12}	0.0195611		

Source: Raw data are from China City Statistical Yearbook and City Annual Statistical Bulletin, and the table is prepared by the author

(4) Comprehensive evaluation of urban CE development based on the linear weighted sum approach

After determining the evaluation index system of urban CE development and the weights of the indicators, the next step is to conduct a comprehensive evaluation of urban CE development. According to the comprehensive evaluation objectives and evaluation requirements of the CE, and considering the convenience of guiding practical operation, this thesis adopts the linear weighted sum method to establish the comprehensive evaluation model of urban CE with multiple indicators. This method is simple in operation and clear in meaning, easy to calculate, can simultaneously find out the comprehensive index of the whole system, the evaluation result is objective and reasonable, meets the comparability in time, and is easy to popularize in practice, and it is a commonly used to carry out the evaluation of the program in the multi-objective decision-making.

We use the composite index as a measure of urban CE, and the variable CEI_i to represent the evaluation index of urban CE, which is calculated by the following formula:

$$CEI_i = \sum_{j=1}^{n} w_j \cdot D_{ij} \tag{3}$$

The formula can be used to calculate the development index of the CE of each city, and the significance represented by this development index is the overall situation of the development of the CE of the city. Through the calculation, we can obtain the trend of the city's CE development index in different years.

2.3 Assessing the development of an urban circular economy through digital technology innovations

Theoretical basis and hypothesis

Urban environmental pollution is becoming more and more serious, and the construction of smart cities has become an important trend to reduce environmental pollution and build an urban CE. The extensive economic growth mode of high consumption, high emissions and high pollution is still relatively obvious, and serious resource and environmental problems restrict the development of urban CE. According to World Bank data, the number of people living in urban areas increased from 14% to 54% between 1990 and 2015, and is predicted to reach 66% by 2050. Urban greenhouse gas emissions account for 60% to 80% of the global. Moreover, according to the data compiled by the National Bureau of Statistics of China, it is found that in 2021, the total amount of wastewater discharge in China has reached 596.985 million tons, and the total amount of exhaust gas discharge has reached 35.4076 million tons. Excessive consumption of resources and serious damage to the environment and ecology have constrained the development of urban CE. Therefore, to reduce the impact of environmental pollution on economic development, the construction of smart cities came into being. Smart city is a new type of urban innovation model emerging with the development of information technologies such as the IoT, cloud computing, and 5G networks, and has become an important trend of future urban development. Although the concept of "smart city" was officially proposed in 2010, the practice of smart cities was much earlier than 2010. In 2006, Singapore launched the "Smart Nation 2015" program, which is based on IT such as the IoT and strives to build Singapore into a first-class international city in terms of economic and social development. Now Singapore has made achievements in e-government, smart cities, and interconnectivity. In 2009, the city of Dubuque cooperated with IBM to establish the first smart city in the United States, digitize urban resources (water, electricity, transportation, etc.), and use IoT technology to connect them. In order to promote the process of smart city construction, the Chinese government has issued policies and regulations related to "smart cities", including "National New Urbanization Plan (2014-2020)", "Urbanization Plan (2016-2020)", "Smart City Development Action Plan (2016-2020)", which are aimed at promoting urban digitalization and intelligence, and put forward the development goals and key areas of smart cities, such as smart transportation, smart healthcare, and smart environmental protection. The construction of smart cities can improve the utilization efficiency and management level of urban resources through digital IT, thereby having a positive impact on the development of urban CE. For example, smart cities can realize the resource utilization of waste and reduce waste and pollution through intelligent waste classification, recycling, and treatment systems. Smart cities can also optimize urban traffic and energy consumption through intelligent transportation systems and energy-saving and environmental protection technologies, thereby promoting the sustainable development of cities. In conclusion, smart cities, environmental pollution, and urban CE development interact with each other and should be considered comprehensively in urban planning and construction to achieve sustainable urban development.

Smart city refers to the transformation and upgrading of all aspects of the city by means of advanced technologies such as IoT and other information technologies, to improve the operational efficiency of the city, optimize the allocation of resources in the city, enhance the quality of service in the city, and achieve sustainable development of the urban form. First, the development of smart cities needs to rely on IT. The development of IT provides strong support for the construction of smart cities, including the application of technologies such as IoT, cloud computing, big data, AI, and other technologies, which can realize the intelligent and digital management of cities. Second, the development of smart cities requires government support. The government plays an important role in the construction of smart cities. It needs to formulate relevant policies and plans, provide financial and technical support, and promote the development of smart cities. Thirdly, the development of smart cities requires the participation of all sectors of society, including enterprises, academia, and social organizations. Finally, the development of smart cities needs to pay attention to privacy protection and strengthen data security and privacy protection measures to safeguard the legitimate rights and interests of citizens. In summary, the development of smart city is a complex and long-term process, which requires the joint efforts of the government, enterprises, academia, and society, supported by IT and focusing on privacy protection, to promote the intelligent and sustainable development of the city.

The CE is a sustainable economic model whose core concept is to maximize the utilization of resources and reduce waste and pollution. The CE converts waste into resources, maximizes the life cycle of products, and realizes the reuse and recycling of resources, to achieve sustainable economic, social, and environmental development. The CE's implementation is primarily the lack of information, so digital transformation becomes the ideal enabler of the CE. It can be mitigated by improving the availability of information. The development of DTs will improve the coordination of information and material flows, which will speed up the shift to a CE. A vast amount of information about products, their quantities, especially the quality of the raw materials they contain, their usage patterns, and their location in the waste system can be stored and tracked digitally, all of which provide the necessary conditions for the implementation of a CE. The CE is the optimal point of sustainability, because it provides a set of practices that can produce more sustainable operations, making sustainability possible in organizations. To measure the changes of the urban CE caused by smart cities construction which is driven by digital technology innovation, this study formulated a multi-dimensional index to measure the development level of urban circularity, and then put forward and verified the hypothesis through the econometric model. The results demonstrate that the growth of the smart cities reduces urban pollutants and encourages the development of the urban CE.

The accelerated integration of the development of digital technology and the field of CE can make a breakthrough of digital CE in cities, and DTs are widely used in urban sustainability management practice. Through digital techniques, computer simulations provide a quick and effective approach for forecasting energy consumption and carbon emissions throughout a building's lifecycle. Çetin S. et al. identified ten DTs that support the transition of the construction industry to a CE, and they find that additive manufacturing has a prominent role in enabling the use of bio-based materials in the construction industry. Robotics can be used in workplace settings for the sorting of mixed waste that are hazardous to human health. Magrini, C. et al. deemed that the application of IoT/blockchain system helps manufacturers to control their electronic products throughout their life cycle, innovate business models, and go beyond traditional methods that only focus on manufacturing or waste management. Digital twins can promote circular supply chain management and resource circularity. Big data was used for life cycle assessment and microstructural analysis of materials. Integrating small and medium-sized enterprises into the ecology of digital platforms can reduce the cost of digital transformation of industrial enterprises. Chinese organizations have a strong desire to use digital technology to improve the efficiency of production operations. With the development of a 5G networks, AI, the IoT, and other new technologies, all countries in the world need to seize opportunities to vigorously develop DTs such as digital governance, digital education, digital medical care, and digital industries, and promote the application of DTs in a sustainable CE.

Overview of smart cities

This study found that researches on smart cities mainly focuses on three aspects: the definition, technological innovation, and impact effects of smart cities. In terms of the definition of smart cities, Hasija and Teo (2022) believe that smart cities refer to the use of advanced technical means such as ICT and the IoT to manage cities comprehensively, multi-level, and efficiently, and to improve the sustainable development capacity and citizens' quality of life in cities. Moreover, Reis et al. (2022) found that the intelligence of cities is not only reflected in the automation of daily functions of individuals, buildings, and transportation systems, but also enables us to monitor, understand, analyze, and plan cities in real-time to improve efficiency, fairness, and the quality of life. In short, smart city is a new urban development model, derived from IBM's new social development model "Smart Earth". The concept of a smart city is defined as a city that improves urban services through technology, such as civil, commercial, transportation, communication, water affairs, and other urban core systems, and maximizes payment with limited resource input. In terms of technological innovation of smart cities, Putra (2018) found that ICT technologies (big data, IoT, AI, and so on) is completely altering our way of life, enabling managers to use new tools to manage urban processes. Big data analysis approaches can enable industrial symbiosis in metropolitan areas. Ali et al. (2020) believes that the IoT and AI realize smart waste bin monitoring and intelligent Municipal Solid Waste Management. Chen (2022) discovered that machine learning algorithm classifies and separates the materials in mixed waste to realize urban waste recycling. Meanwhile, Almalki et al. (2021) believe that electronic devices are used to collect data, which is processed and used to effectively manage resources, assets, and services. In return, this data is used to solve problems in the city and enhance the operations of the city. The overall performance of the urban system is optimized and maintained through new technological innovation, and the adaptability of urban society, ecology, engineering, and organization is also enhanced. Zhang et al. (2021) argued that industry 4.0 technology increased CE efficiency by smart waste management in the reverse supply chain. In short, urban management requires technological innovation to establish a new sustainable economic model and solve the city's core problems in an innovative manner. Smart cities utilize IT to change the mode of urban governance and improve the efficiency of urban resource allocation and utilization.

In terms of the impact effects of smart cities, Winters (2011) believed that smart cities are service-oriented, so it is necessary to build an integrated system rather than a single terminal, with the goal of improving the overall quality of urban services through service supply mechanisms and information sharing. Angelidou et al. (2022) considered that smart cities use strategic emerging industries and clean energy to help the IT industry develop healthily, innovate the social management model, and ultimately achieve the win-win goal of efficiency and fairness in economic and social development. According to Harrison and Donnelly (2011), IT is an effective tool for smart cities. Through continuous analysis and guidance of public services and management measures, smart cities could achieve a state of expedite information and comprehensive services. Moreover, the research of Angelidou et al. (2011) suggest that smart city construction can also promote the development of CE. Intelligent management and services in smart cities can improve resource utilization efficiency and reduce the waste of resources. For example, the intelligent garbage classification system realizes recycling of recyclable waste, and reduces the impact of landfill and incineration on the environment. In brief, smart city construction can reduce environmental pollution, and promote the development of CE.

Overview of urban environmental pollution

Urban environmental pollution is one of the important society issues facing today. To solve this problem, many countries and regions have adopted various measures, including policy formulation, technological innovation, and public education. First, the policy formulation of smart cities is one of the important means of urban environmental pollution control. The government can strengthen urban environmental pollution management by formulating environmental protection laws and regulations, establishing an environmental monitoring system, and implementing environmental taxes. In 2015, the Chinese government issued a newly revised "Environmental Protection Law", which strengthened the punishment for environmental violations and promoted the development of environmental protection work. Secondly, the digital technology innovation of smart cities is also one of the important means of urban environmental pollution control. The application of new technologies can effectively reduce pollution emissions, and the application of clean energy such as electric vehicles, solar energy and wind energy can reduce the use of fossil fuels, thereby reducing air pollution. In addition, the research on pollutant control technology is also one of the important directions of urban environmental pollution control. For example, research on new waste gas purification technology and sewage treatment technology can effectively reduce pollutant emissions. Finally, public education is also one of the important means of urban environmental pollution control. The public's environmental awareness and behavior are crucial to urban environmental pollution control. The government can raise the public's awareness of environmental protection through publicity and education, media publicity, and social organizations. In 2018, the Chinese government formulated a three-year action plan to win the blue-sky defense war. Through various publicity and education activities, the public's awareness of air pollution has been improved, and environmental protection work has been promoted. In summary, urban environmental pollution control requires efforts in policy formulation, digital technology innovation, and public education. The construction of smart cities can improve the efficiency of environmental pollution control. By using intelligent system to monitor environmental indicators such as air and water quality in real-time, environmental pollution problems can be detected and addressed in a timely manner. The construction of smart cities can effectively reduce environmental pollution such as air pollution and water pollution. In addition, smart cities can also optimize traffic flow through intelligent transportation systems, reduce traffic congestion and emissions, and further reduce environmental pollution.

Fundamental theories

Theoretical basis of smart city

Smart city is a new type of urban innovation model, which has emerged with the development of information technologies such as the IoT, cloud computing, and 5G networks, and has become an important trend in future urban development. In November 2012, the Ministry of Housing and Urban-Rural Development of the People's Republic of China issued the "Notice on Carrying out National Smart City Pilot Work", and decided to carry out national smart city pilot program, aiming to comprehensively apply information communication and technology, integrate information resources, and coordinate business application system to strengthen urban planning, construction, and management.

Urban issues such as pollution, resource shortage, and traffic congestion have become increasingly serious for urban management and development. smart cities have been proposed as an effective approach to better urban management, which is shown as Figure 2.10. With the rapid development of ICT, countries all over the world, including China, have begun to build smart cities. The National New Urbanization Planning of China from 2014 to 2020 explicitly requests to promote the development of smart city, with objectives including broadband network access, information planning and management, smart infrastructures, convenient provision of public service, modernized industrial development, elaborate social governance, and unification of material, informational and intellectual resources for urban development. It is proposed that the IoT, cloud computing, big data, and other new ICT to be innovatively integrated for the social and economic development of cities.

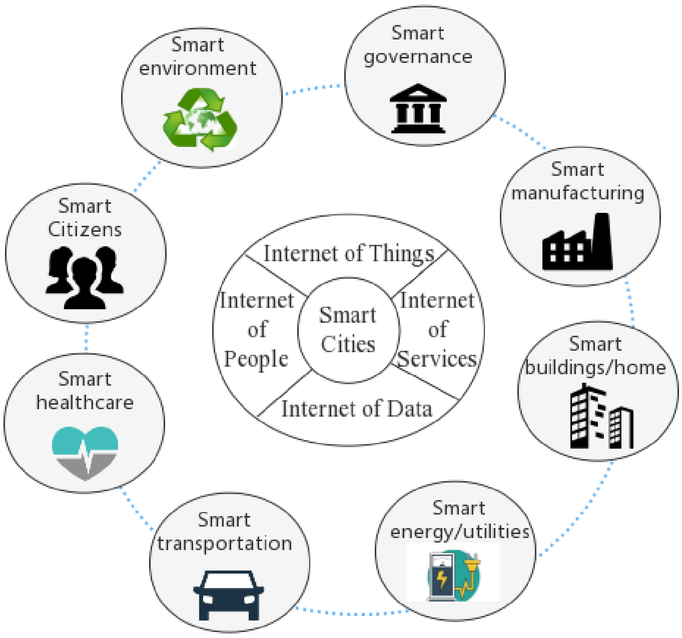

Figure 2.10 – The components of smart cities

Source: prepared by the author

In 2013, China's Ministry of Industry and Information Technology (MIIT) established the Smart City Industry Alliance to implement smart city programs by providing US$8 billion in funding for smart city research and projects. The study shows that the investment on smart city in China reached to US$147 billion by the end of December 2015, and it would remain growing at the rate of about 19% for 2016-2018. Eight Chinese government departments jointly issued the policy "Guidance on Promoting the Healthy Development of Smart Cities" in 2014. In line with this trend, an increasing number of Chinese cities are putting smart city principles into practice. According to the Telecommunication Research Institute of China's Ministry of Industry and Information Technology (2014), all cities at the provincial or higher level, 89% of prefecture-level cities, and approximately 40% of county-level cities have smart city development plans. Low energy use, low emissions, and low pollution are three main objectives of the creation of smart cities, and they are accomplished by utilizing technological innovation to protect the environment. On the one hand, by promoting the advancement of manufacturing technology, energy-saving technology, and environmental protection technology, we can reduce energy consumption, improve energy utilization, and reduce environmental pollution. On the other hand, technological innovation promotes enterprises' research of a variety of clean energy, changes the energy use structure, improves production efficiency, and reduces GDP energy consumption and pollutant emissions while promoting economic growth.

Smart cities use IT, IoT, cloud computing and other modern scientific and technological means to integrate and share data in various fields of the city to achieve intelligence, efficiency and convenience of urban management and public services. The development of smart cities can be divided into the following stages: (1) Infrastructure construction stage, this stage is mainly to build the city's information infrastructure, including the construction of urban broadband networks, intelligent transportation systems, intelligent lighting systems, etc.; (2) Data integration stage, this stage is mainly to integrate and share data in various fields of the city, and establish urban data centers to realize the interconnection of urban data; (3) Application service stage, this stage is mainly to apply urban data to urban management and public services, such as intelligent transportation, intelligent medical care, intelligent environmental protection, etc.; (4) Intelligent upgrade stage, this stage is mainly to realize the intelligent upgrade of city management and public services through AI, big data and other technological means, and improve the efficiency and quality of city management. In general, the development of smart cities is characterized by informatization, intelligence, efficiency, and convenience, which is an important direction for the development of future cities.

Theoretical basis of CE evaluation system

The thought of CE can be traced back to the era of environmental protection, in the 1960s American economist bowdine "earth spacecraft theory" can be used as the early representative of the CE his earth than do spacecraft highlights the earth's narrow, crowded, and limited resources human want to survive on the earth for a longer time must strive to improve the earth's recycling ability of resources. The 1970s was the brewing stage of the thought of CE. In the organized environmental remediation movement of the international community, the concern of all countries in the world was how to reduce the harm of pollutants after their generation, that is, the so-called terminal governance mode of environmental protection. In the 1980s, people realized the limitations of terminal treatment and began to recycle waste resources, which was sublimated both in thought and in policy. People's understanding has experienced the process from "discharge waste" to "clean waste" to "waste utilization". However, most countries still lack ideological insights and policy measures on the fundamental question of whether pollutants are reasonable and whether they should prevent pollution from the source of production and consumption. In the 1990s, especially with the human ecological environment protection and sustainable development theory and further development of understanding, people realize the original economic development model is unsustainable, and began to actively explore the sustainable development of economic model, people on the basis of continuous exploration and summary, put forward to maximize resource utilization and pollution emissions as the main line, the clean production, comprehensive utilization of resources, ecological design and sustainable consumption of CE development strategy. Since the 1990s, CE in developed countries has become a trend and trend, some countries in the form of legislation, many developed countries are developing CE, establish a circular society as an important way to implement the strategy of sustainable development, CE got more and more attention and rapid development.

So-called CE, its essence is a kind of ecological economy, is a kind of efficient utilization of resources and recycling as the core, to reduce (Reduce), reuse (Reuse), recycling (Recycle) as the principle, with low consumption, low emissions, high efficiency as the basic characteristics, conform to the concept of sustainable development of economic growth model, CE is to "mass production, large consumption, a large number of wastes" the fundamental change of the traditional way of growth. It is in the large system of population, resources, environment, economy, society and science and technology, studying the economic principles in line with the objective law, balancing the economy, social and ecological benefits. Based on the combination of CE index system is scientific and practical, systematic, and hierarchical, dynamic and stability, measurable and comparability, completeness and simplicity, efficiency, and benefit of combining six basic design principles, combining with the characteristics of urban CE development, from the perspective of CE system, using stratification, the analysis method of "purpose tree", starting from the nature of CE design CE evaluation index system.

Based on the theoretical basis at home and abroad, although the foreign research on CE began earlier, the theoretical study of this economic development model itself is still in the exploratory stage. China's research on CE has just started, and its research mainly focuses on the discussion of the basic theory and realization mode of CE. There are few research results on the evaluation index system and evaluation methods of CE system, and there is a lack of a widely applicable CE evaluation index system, which is closely related to the differences in the evaluator's knowledge level, background. In addition, the evaluation method of CE development mainly focuses on the use of the analytic hierarchy process. This method is very suitable for decision-making and evaluation of complex systems with multiple objectives, multiple factors, and multiple levels. However, because the indicator weight determines the selection, it is a combination of qualitative and quantitative methods, so its accuracy is affected by human subjective factors to a certain extent. How to build an organic, reasonable, simple, and easy index system, so that it can fully reflect the requirements of CE, and how to choose appropriate evaluation methods, and make an objective evaluation of the development degree of CE in a region and even a country is a problem that needs to be solved, which is also a hot spot in the research on CE at present.

The hypothesis of the relationship mechanism

Smart city refers to the use of modern IT and the IoT to intelligently manage all kinds of resources in the city, improve the operational efficiency of the city and the quality of life. Environmental pollution refers to the increase of pollutants in the natural environment, such as air, water, and soil, caused by human activities, which causes harm to human health and the natural ecosystem. On the one hand, Jiang et al. (2022) showed that, there is a close mutual relationship between smart city and environmental pollution. The construction of smart city can conduct real-time monitoring and early warning of the urban environment through intelligent management and monitoring means, and take timely measures to reduce environmental pollution. For example, the intelligent traffic management system can reduce urban traffic congestion, reduce automobile exhaust emissions, and thus reduce air pollution. Through the intelligent garbage classification and treatment system, the garbage landfill and incineration can be reduced, and the pollution to the environment can be reduced. On the other hand, Liu et al. (2021) showed that, environmental pollution will also have an impact on the construction of smart cities. Environmental pollution will affect the urban ecological environment and the health of residents, and reduce the livability and attractiveness of cities, thus affecting the development of smart cities. Therefore, in the process of smart city construction, it is necessary to fully consider the problems of environmental protection and ecological balance, take effective measures to reduce environmental pollution, and protect the ecological environment of the city and the health of residents. To sum up, there is a close relationship between smart city and environmental pollution. In the process of smart city construction, it is necessary to fully consider environmental protection and ecological balance, take effective measures to reduce environmental pollution, and protect the urban ecological environment and the health of residents.

CE refers to an economic mode that realizes the sustainable eco-nomic development through the reuse and reproduction of resources. Smart city refers to the use of IT, IoT and other technical means to improve the intelligent level of urban management and service, and realize the sustainable development of cities (Saw et al., 2021). On the one hand, Caputo et al. (2023) showed that, the construction of smart city can promote the development of CE. Smart city can improve the efficiency of resource utilization, reduce resource waste and pollution, and promote the development of CE through the intelligent management and supervision of real resources by means of IT. For example, through the intelligent garbage classification system, it can realize the classification and recycling of resources, and promote the recycling of waste. On the other hand, Soo et al. (2023) showed that, the development of CE can also promote the construction of smart cities. CE needs to rely on IT means to realize the intelligent management and monitoring of resources, and smart city just provides the technological innovation support. For example, through the IoT technology, it can realize the intelligent recycling and reuse of waste, and promote the development of CE. To sum up, there is a close relationship between smart city and CE. The construction of smart cities can promote the development of CE, and the development of CE can also promote the construction of smart cities.

Based on the above analysis, this study proposes:

Theoretical Hypothesis 1 (H1): Smart cities are closely related to environmental pollution and urban CE. This study was verified by the benchmark regression evaluation model of urban CE development. If the standard error $p < 0.1$, the hypothesis is valid; otherwise, if $p > 0.1$, the hypothesis is not valid.

The hypothesis of the mediation mechanism

The construction of smart cities can have a direct impact on the management of environmental pollution. Through the intelligent urban management system, real-time monitoring and early warning of urban environmental pollution can be realized, and timely measures can be taken to manage it. For example, through intelligent transportation systems, traffic flow can be optimized to reduce congestion and exhaust emissions, thus reducing air pollution. The intelligent waste sorting system can effectively reduce the amount of waste. In addition, smart cities can also realize the efficient use of energy and reduce energy waste through intelligent energy management, thereby reducing the impact of energy consumption on the environment. In short, the construction of smart cities provides more scientific and efficient means for environmental pollution control (Han, 2021a).

DTs can not only be used to solve the complexity of industrial processes, optimize manufacturing processes, and improve the material efficiency of manufacturing enterprises, but also can be used in the field of construction to improve the efficiency and cost-effectiveness of construction. IoT is a critical component in enabling smart environments and better urban planning (Perera et al., 2014; Whitmore et al., 2014). Atzori et al. (2010) redefined urban planning as a city information model that enables continuous monitoring of urban facilities such as railways, transportation corridors, energy distribution and management, sewerage, and waste disposal. Digital technology will ensure that every building and component works with the best efficiency, thus ensuring the sound management of all resources of urban environmental characteristics (Runaghan, 2019). The attention of community designers to these technologies can ensure the immediate benefits of promoting circular solutions in urban residential environments. The open building management platform can realize integrated management and optimization of the building's heating, ventilation, and air conditioning systems, as well as provide key building operation data to the energy management system, making the building facilities more comfortable, safe, and efficient. Users can use energy management software to analyze building energy consumption and identify potential energy-saving spaces to reduce energy consumption and carbon emissions.

Intelligent technologies are being used in smart city construction to manage municipal waste and realize product and material recycling. DTs innovation can solve the problem of informal collection and improper disposal of urban waste through smart waste management. The development of Internet technology and e-commerce platforms has led to the emergence of many Internet-based recycling platforms. The platforms are based on the online to offline e-commerce model, which can track user information, monetary information, and logistics information to manage reverse recycling chain and generate statistical information. Internet-based recycling platforms combine new technologies such as IoT and big data to build a complete recycling ecosystem.

The smart waste collection system based on IoT, including RFID tags, near-field communication sensors, and GPS sensors, can obtain real-time data on the status of smart recycling bins and on the users involved in recycling to optimize the recycling process. The recycling platforms consist of a smartphone–based application through which users can find the nearest or most suitable smart recycling bin and are rewarded with money or points for participating in recycling.

AI technologies used in waste recycling systems can identify the types of recyclable products and materials through image recognition technology and analyze users' behavior data. Machine learning-based optimization techniques are already being used in IoT-based smart waste collection systems. These methods facilitate the analysis of incoming waste material, the size of waste bins and the type of waste collection vehicle required for action Overall, DTs can promote urban CE by closing the material loop.

Through DTs, smart cities have many links with the CE. Smart cities collect data through advanced technologies to monitor and optimize the use of resources, which is the basic concept of CE principles. Advances in digital technology have encouraged the development of new business models. Some enterprises have tried to apply CE principles beyond product sales to provide various types of services, such as life-cycle services for tangible assets, leasing services for tangible assets, and functional delivery of shared products. DTs such as the IoT, big data analysis, and AI can effectively support CE implementation. Viglioglia et al. (2021) investigate the emerging design of ICT solutions that promote CE in urban settings, optimize smart city management, and achieve sustainable urban development model. The urban context is divided into three urban systems: construction, transportation, and products. It is demonstrated that ICT solutions can promote smart cities to realize CE principles through nine case studies. In the face of global development's enormous pressure on the environment and resources, how to implement the construction of smart cities to promote the development of CE. Alcayaga et al. (2019) proposed a conceptual framework of smart circulation system, describing the interrelationship among smart circulation, smart PSS, and circular PSS. Khawngern et al. (2021) investigated the role of digital technology in addressing the complexity of the CE and its function in circular business models by three case studies. The results show that digital technology is an effective enabler of a CE, which can benefit both the economy and the environment.

Smart cities should have a smart economic structure and industrial system, as well as an efficient urban economic system. Smart cities fully consider the urban ecosystem's carrying capacity, saves urban resources, continuously improves the utilization efficiency of existing resources, recycles resources, and creates benign social wealth. CE reduces waste, replaces non-renewable resources with recyclable renewable resources as much as possible, and uses ICT as a beneficial tool to achieve a harmonious and unified economy, society, and ecology. Enterprises and industries can manage their product value chain more effectively with the help of DTs, narrow the loop with increased resource efficiency, and slow down the loop by extending product life, thereby promoting the CE. DTs are effective enablers for transitioning to a CE, which can provide economic and environmental benefits such as increasing raw material efficiency, reducing resource extraction, stimulating innovative design, promoting production and remanufacturing, ensuring better distribution, consumption, reuse, and repair, and reducing waste.

Based on the above analysis, this study proposes:

Theoretical Hypothesis 2 (H2): Smart cities have a direct impact on environmental pollution and an indirect impact on the development of urban CE through the intermediary role of technological innovation. This study introduced the intermediary variable (technological innovation index Inn) for verification. The larger the correlation coefficient of Difference in difference method (DID) and Inn, the greater the mediation effect of the mediator variable; and the larger the correlation coefficient between DID and CE, the greater the indirect impact of smart city construction on the development of urban CE.

The hypothesis of the timeliness mechanism

The evaluation of urban CE evaluation system refers to the use of a specific methodology through a series of calculations to obtain a comprehensive index that reflects all aspects of economy circularity. To verify hypotheses, the evaluation of urban CE is crucial. The evaluation indicators and methods for urban CE have difficulty such as large scale, numerous aspects, and complicated linkages between elements. Currently, there are still no recognized or generally accepted evaluation indicators and methods. The implementation of urban CE is a dynamic and all-encompassing process. As a result, evaluation CE performance at urban level is actually a process of comprehensive evaluation of multiple indicators. Through literature review, this paper determines and selects the indicators for evaluating urban CE.

To assess regional CE, there are many different approaches available, such as material flow accounting or analysis. The EU indicator system used material flow analysis that is made up of three groups of indicators: input, consumption, and output and balance. Similarly, there are three kinds of indicators in Japanese CE assessment system: resource productivity (RP), recycling rate and rate of final waste disposal. Meanwhile, the EU used GDP generated per unit of net primary finite material input as measurement of resource efficiency. China have improved the evaluation index system of CE development and issued the Circular Economy Development Evaluation Index System (EIS, 2017). The indicator system of China is divided into three categories: comprehensive indicators, special indicators, and reference indicators, including 17 specific indicators. It is being used at a national level, while it has not been implemented at the urban level. Due to the lack of sufficient statistical data at the city level, there is no other universal indicator system for evaluating urban CE development currently. There are many academic studies on CE in different contexts, but criteria for measuring urban CE are still lacking.

Based on the above analysis, this study proposes:

Theoretical Hypothesis 3 (H3): Driven by long-term digital innovation technology, smart cities can reduce environmental pollution and promote the development of urban CE. In this study, the time point of smart policy was tested three years in advance and three years later. If the standard error of DID and CE $p > 0.01$, or $p < 0.01$, there is no time effect, and the assumption is not valid; If the standard error of DID and CE three years in advance $p > 0.1$, but the standard error of DID and CE three years in delay $p < 0.01$, indicating that there is a timeliness effect, and the assumption is valid.

Data and methods

Data source

Based on the first batch of smart city pilot list published by the Chinese government in 2012, this paper determines the treatment group and the control group, uses 253 prefecture-level cities in China from 2003 to 2018 as the research object, and makes the following processing in the selection: (a) In order to maximize the estimated time interval of the policy, this paper chose the pilot smart cities in 2012 as the treatment group, and perform a tentative regression analysis. The new pilot cities in 2013 and 2014 are excluded to ensure that the estimated result of this study is the net effect of the policy in 2012. Prefecture-level cities with only one district or county in the city as a pilot are excluded to avoid underestimating the impact of smart city hypothesis on pollution reduction performance and urban CE. (b) Eliminate the newly established prefecture-level cities after the abolition of counties. (c) Exclude the prefecture-level cities with serious data shortages, such as Tibet, Qinghai, Xinjiang, and others. Excluding prefecture-level cities with severe data shortage, such as Tibet, Qinghai, and Xinjiang. (d) The balance panel data of 185 prefecture-level cities from 2003 to 2018 are obtained. Among them, 32 prefecture-level cities belong to the treatment group. The data comes from the "China City Statistical Yearbook" and the annual statistical bulletins of cities.

Regression model

Regression model construction

The “quasi-natural experiment” attribute of smart city policy implementation provides an opportunity for this paper to study whether the implementation of smart city policy will have an impact on the environment and the development of CE. This study uses difference-in-differences method to evaluate the impact of the policy. According to the conditions created by the “quasi-natural experiment”, the pilot cities can be set as the treatment group, that is, treated=1, the non-pilot cities are set as the control group, i.e., treated=0. At the same time, the first batch of the smart cities were announced in 2012, which has been more than ten years, so 2012 was determined as the policy year. In 2012 and later, post=1, prior to 2012, post=0. On this basis, referring to the design of Shi et al. (2018) and Wu (2021), the econometric regression model 1 (equation 4) and model 2 (equation 5) is set up as follows:

$$Pollution_{it} = \alpha_0 + \alpha_1 DID_{it} + \sum X_{it} + \mu_i + year_t + \varepsilon_{it} \quad (4)$$

$$CE_{it} = \beta_0 + \beta_1 DID_{it} + \sum Z_{it} + \mu_i + year_t + \varepsilon_{it} \quad (5)$$

In the model 1, $Pollution_{it}$ represents environmental pollution, measured by industrial pollutant emissions. In the model 2, CE_{it} represents the development of the city's CE, which is measured by urban CE evaluation index system. DID_{it} is a policy dummy variable, represents the treatment status of individual i at t stage, which is set as 1 when receiving treatment and 0 when not receiving treatment. X_{it} and Z_{it} represent control variables. μ_i and $year_t$ are city and time fixed effects, respectively. ε_{it} is a random disturbance team. The regression coefficient α_1 and β_1 are the main regression coefficient of this study and reflect the net impact of the implementation of smart city policies on environmental pollution and urban CE development.

The definition of each variable in formula (5) and (6) is shown in the Table 2.5 DID_{it} is the key explanatory variable, $Pollution_{it}$ and CE_{it} are dependent variables.

Table 2.5 – The definition of each variable in the models.

VarName	Content	Values range
i	City	$\{1,2,3,\cdots,192\}$
t	Year	$\{2003,2004,2005,\cdots,2018\}$
$Pollution_{it}$	Discharged industrial waste amount of i city in year t	
CE_{it}	Development level of urban CE	
T_i	Grouping dummy variable	$\{0,1\}$
P_t	Policy implementation time dummy variable	$\{0,1\}$
DID_{it}	Whether i city was set up as a smart city pilot in year t	$\{0,1\}$

Source: Raw data are from China City Statistical Yearbook and City Annual Statistical Bulletin, and the table is prepared by the author

Regression model variables

(1) Interpretive variables

Model 1 (equation 4) uses $Pollution_{it}$ to measure industrial pollution in smart cities represented by industrial sulfur dioxide, industrial wastewater, and industrial solid waste as the explained variable. Since there is no statistical data on industrial solid waste in prefecture-level cities, we chose the first two items to describe environmental pollution.

Model 2 (equation 5) takes CEI_i as the explained variable to measure the level of urban CE, and calculate it according to formula (3).

(2) Core explanatory variables

The smart city policy is expressed by DID_{it}, DID_{it} = 1 if city i has carried out the smart city policy at time t, and 0 in other cases.

(3) Control variables

In model 1 (equation 4), the variables affecting industrial pollution are selected as control variables: (a) Economic development level. Measured by the logarithm of urban per capita GDP. (b) Urbanization. Expressed as the ratio of non-agricultural population to total population. (c) Market openness. Measured by the proportion of actual foreign investment in regional GDP. (d) Technological innovation level. Measured by the China regional innovation and entrepreneurship index published by the state intellectual property office. (e) Industrial structure. Measured by the proportion of the secondary industry in GDP.

In Model 2 (equation 5), variables affecting the development of urban CE are introduced as control variables: (a) Economic development level. (b) Urbanization. (c) Market openness. (d) Technological innovation level. (e) Human capital level. Measured by the ratio of the number of students in ordinary colleges and universities to the total population. (f) Information basis. Measured by the proportion of Internet users in the total population of the region. (g) Ecological environment level. Measured by the greening rate of urban built-up areas. (h)

Industrial structure upgrading index. Choose the proportion of the tertiary industry in GDP to measure.

Mediator model

Mediator model construction

As stated in the research hypothesis 2, smart city construction mainly relies on technological innovation to influence the urban CE. To verify the effect mechanism, we set the following model 3 (equation 6) and model 4 (equation 7):

$$M_{it} = \beta_0 + \beta_1 DID_{it} + \beta_2 T_i + \beta_3 P_t + \beta_4 Z_{it} + \mu_i + year_t + \varepsilon_{it} \quad (6)$$

$$CE_{it} = \alpha_0 + \alpha_1 DID_{it} + \alpha_2 T_i + \alpha_3 P_t + \alpha_4 M_{it} + \alpha_5 Z_{it} + \mu_i + year_t + \varepsilon_{it} \quad (7)$$

In equation (6) and equation (7), M_{it} represents the intermediary variable, and the others are consistent with the previous model. We performed the mediation effect analysis for models 3 and 4.

Mediator model variables

(1) Mediation variables

The mediation variable in Model 4 (equation 7) is M_{it}. To measure the level of technological innovation, the mediation variable in Model 3 (Equation 6) is Inn (technological innovation level). Among them, the level of technological innovation refers to being measured by the China Regional Innovation and entrepreneurship Index published by the State Intellectual Property Office.

(2) Interpretive variables

For Model 3 (equation 6), the explanatory variable in is M_{it} ,for measuring the level of technological innovation. In model 4 (equation 7), with CE_{it} level of urban CE is measured as the explained variable, and it is calculated according to equation (3).

(3) Core explanatory variables

DID_{it} used to represent the differential effect of smart policies mediated by technological innovation, If the city implements the smart city policy within the time of technological innovation, if the technological innovation is implemented in the smart city policy, t= 1, otherwise t=0.

(4) Control variables

Model 3 (equation 6) selects variables affecting industrial pollution as control variables: (a) level of economic development. Measured by the log of urban GDP per capita. (b) urbanization. Is presented as the ratio of the non-agricultural population to the total population. (c) Market opening. Measured by the proportion of utilized foreign capital in the regional GDP. (d) Industrial structure. Measured by the proportion of the secondary industry in GDP.

Model 4 (equation 7) introduces variables affecting the development of urban CE as control variables: (a) the level of economic development. (b) urbanization. (c) Market opening. (d) Human capital level. Measured as the proportion of regular college students in the total population. (e) Information basis. Measured as the proportion of Internet users in the total population of the region. (f) Ecological environment level. Measure it by the green rate of urban built-up areas. (g) Industrial structure upgrading index. Choose the proportion of the tertiary industry in GDP to measure.

Timeliness mechanism

Parallel trend detection

The premise of using the difference-in-difference method to identify policy effects is to satisfy the parallel trend assumption. This means that if there is no external policy impact of smart cities, the development of the CE in non-pilot cities and pilot cities should follow the same trend. Otherwise, systematic differences between the two groups could lead to endogenous problems. In general, there are two methods of parallel trend testing: drawing the time trend map and the event study. If the assumption of parallel trends holds, there should be no significant difference between the treatment and control groups until the policy time point. This paper selects time trend chart and event research method to conduct the parallel trend test of DID.

The smart city pilot program began in 2012, and based on model 3, we created interaction terms between the annual dummy variables and the dummy variables of the treatment group. The interaction term's coefficient quantifies the difference between the treatment and control groups each year. Specifically, variable of $current$ represents the effect of the policy in the current period, pre_1, pre_2, and pre_3 represent the effects of the 1-3 periods before the policy, and $post\_1$, $post\_2$, and $post\_3$ represent the effects of the 1-3 periods after the implementation of the policy. We must choose a phase as the reference group; otherwise, full collinearity occurs. 2011 was selected as the reference group for the model, the year prior to the policy implementation.

Anti-factual detection

Based on model 4, referring to the practice of He et al. (2021), the policy implementation time is artificially advanced by three years, creates a virtual policy time point, and then returns to see if the policy effect is significant. China established the first batch of smart city pilot in 2012. When we implemented the counterfactual test, the implementation time were moved to 2011, 2010, and 2009, and then estimated them respectively. The significance of the explanatory variables after changing the policy occurrence time is far from the benchmark regression, indicating that the establishment of the smart city pilot has a great impact on the improvement of the development level of urban CE, and the previous regression results are reliable. Simultaneously, since the impact of smart city construction policy on the urban CE may appear gradually over time, the time dummy variable is estimated by three years in the study.

DID model robustness detection

To further test the robustness of the estimated results in this paper, smart cities from 2013 and 2014 were included in the regression samples to examine the impact of smart city construction on pollutant emissions and CE. If $p < 0.01$, it indicates that the DID model is robust and the empirical results are reliable.

Empirical results and discussion

Descriptive statistics

The descriptive statistics for 2,944 observations from 2003 to 2018 are shown in Table 2.6, including the definition, unit, mean, and standard deviation of each variable. There are great differences in the urban CE evaluation index (CE) (Mean = 0.57, Std. Dev.=0.05). In addition, per capita industrial sulfur dioxide emissions (Sdiox) also fluctuated among the sample cities (Mean = 19.21, Std. Dev.=36.36), which made it possible to study the impact of smart cities on urban CE. In addition, the average value of the technological innovation level (Inn) is relatively large, and the technological innovation level of different smart cities is quite different (Mean = 0.51, Std. Dev.=0.29). Moreover, Std. Dev. of the control variable in the sample city is far less than the mean, which indicates that the external factors of the sample city have controllable influence on environmental pollution and urban CE. Therefore, environmental pollution (Sdiox, Wwater) and urban CE (CE) as the explanatory variables of the DID model, and technological innovation level (Inn) as the intermediary variables of the DID model to study the policy effect of smart city (DID_{it}).

Table 2.6 – Descriptive statistics for all of the variables.

VarName	Definition	Unit	Mean	Std. Dev.
Sdiox	Industrial sulfur dioxide discharge per capita	10000 tons per capita	19.205	36.356
Wwater	Industrial wastewater discharges per capita	1 Ton per capita	0.018	0. 043
Lngdp	Economic development level	1 CNY per capita	10.113	0.822
Urban	Urbanization	%	0.721	0.350
Mopen	Market openness	%	0.030	0.117
Inn	Technological innovation level	1	0.511	0.291
Industr	Industrial structure	%	0.485	0.109
CE	The urban CE development index	1	0.573	0.049
HuCap	Human capital level	%	0.016	0.023
Infor	Informatization basis	%	0.132	0.132
Envir	Ecological environment level	%	37.006	8.907

Indup	Upgrading degree of industrial structure	%	36.910	8.814

Source: Raw data comes from China City Statistical Yearbook and City Annual Statistical Bulletin, and the table is prepared by the author

The DID empirical results

Regression relationship

Changing the urban governance mode to advanced IT will undoubtedly improve the efficiency of urban resource allocation, thus providing material and technical support for solving environmental problems and encouraging resource recycling. This study analyzed benchmark regression using DID and robust standard errors at the urban level. According to the estimation models 1 and 2, the results of Table 2.7 and Table 2.8, it shows the impact of smart city construction on environmental pollution and urban CE.

Based on model 1 (equation 4), (a) and (b) of Table 2.7 are estimated results without control variables, and (c) and (d) are estimated results with control variables. They represent the impact of smart cities on industrial sulfur dioxide and wastewater discharge per capita. The results of Model 1 showed that the regression coefficient of the interaction term DID was significant when the amount of wastewater per capita is the dependent variable. Without external effects, smart cities are usually closely related to environmental pollution reduction ((a) $\alpha_1 = -0.0221, p < 0.01$;(b) $\alpha_1 = -0.0886, p < 0.01$). Under the influence of external effects, the construction of smart city still has a policy effect on pollution reduction ((c) $\alpha_1 = -0.0174, p < 0.01$; (d) $\alpha_1 = -0.0375, p < 0.01$). Among them, the construction of smart city has significantly reduced the per capita exhaust gas emission by about 1.74% and the per capita industrial wastewater discharge by about 3.75%.

Table 2.7 – The DID estimation results of environmental pollution.

	(a)	(b)	(c)	(d)
	Sdiox	Wwater	Sdiox	Wwater
DID	-0.0221***	-.0886***	-.0174***	-.0375***

	(0.0033)	(0.0265)	(0.0042)	(0.0137)
Control	N	N	Y	Y
City	Y	Y	Y	Y
Year	Y	Y	Y	Y
N	2944	2944	2944	2944

*Note: Standard errors in parentheses, *p < 0.1, **p < 0.05, and ***p < 0.01. The following Tables are the same. Source: Raw data comes from China City Statistical Yearbook and annual statistical bulletin. The table is prepared by the author*

Based on model 2 (equation 5), Table 2.8 shows the estimation results of smart city construction and urban CE development index. First, (e) of Table 2.8 is the estimation result without adding any control variables and fixed effects. The estimated coefficient of DID is significantly valid at a confidence level of 0.01 ($\beta_1 = 0.6866, p < 0.01$), indicating that smart city construction can significantly improve the level of urban CE. Second, conclusions may be disturbed due to the omission of relevant explanatory variables. In this process, the net effect of smart city policy was tested by introducing control variables. List (f) of Table 2.8 added the control variables, and the fixed effect was not controlled. The results of list (f) confirmed that the coefficient of DID is significantly established under the premise that the confidence level is 0.01 ($\beta_1 = 0.7796, p < 0.01$). Third, control variables and fixed city effect were added to the model (g). The regression results show that the DID estimation coefficient decreased slightly, but were still significantly positive ($\beta_1 = 0.7150, p < 0.01$). Fourth, the fixed city effect and time effect were set in model (h). The estimated coefficient is positive and significant, with no fundamental change ($\beta_1 = 0.7459, p < 0.01$).

In short, the results of table 4 show that smart city construction has a significant positive impact on the improvement of the development index of urban CE, and there is a significant relationship between the improvement of smart city construction and the development of CE. According to the coefficient value, after the implementation of the smart city policy, the development index of CE in the pilot cities increased by 74.89%.

Table 2.8 - The DID estimation results of urban CE.

	(e)	(f)	(g)	(h)
	CE	CE	CE	CE
DID	0.6866*** (0.3281)	0.7796*** (0.2827)	0.7150*** (0.2465)	0.7459*** (0.2514)
Control	No	Yes	Yes	Yes
City	No	No	Yes	Yes
Year	No	No	No	Yes
adj. R^2	0.0649	0.5357	0.5942	0.7979
N	2944	2347	2347	2347

*Note: Standard errors in parentheses, *p < 0.1, **p < 0.05, and ***p < 0.01. The following Tables are the same. Source: Raw data comes from China City Statistical Yearbook and annual statistical bulletin. The table is prepared by the author*

In conclusion, the empirical results of Table 2.7 show that smart city construction is significantly correlated with environmental pollution reduction, and the research results of Table 2.8 show that smart city construction is significantly associated with the development of urban CE. The hypothesis H1 of this study is established at the empirical level.

Mediation mechanism

The above verification results show that the construction of smart city can significantly reduce environmental pollution and improve the development level of urban CE. However, what is the specific mechanism of smart cities affecting urban CE? This requires further introduction of the mediation variable Inn of technological innovation for analysis.

The regression results are shown in Table 2.9. The estimated coefficient DID in model 3 is significantly positive with a confidence level of 0.01 ($\beta_1 = 0.0619, p < 0.01$). This indicates that smart cities have a direct impact on the level of technological innovation; the Inn in Model 4 is significantly positive with a confidence level of 0.1 ($\alpha_1 = 0.6541, p < 0.1$). This indicates that technological innovation has a direct effect on the development of urban CE; the estimated coefficient of DID in Model 4 is significantly positive at a confidence level of 0.01 ($\alpha_4 = 0.7211, p < 0.01$). This shows that under the intermediary effect of technological innovation, smart city has an indirect effect on urban CE and environmental pollution emission reduction.

To sum up, the research results of Table 6. show that the technological innovation brought by the construction of smart city is the promotion mechanism affecting the urban CE. Under the intermediary effect of technological innovation, the effect of smart city on environmental pollution reduction and CE is more obvious. Therefore, the hypothesis H2 of this study was validated at the empirical level.

Table 2.9 – The intermediary effect of technological innovation

	Inn	CE
DID	0.0619*** (0.0015)	0.7211*** (0.0025)
Inn		0.6541* (0.0354)
Control	Y	Y
City	Y	Y
Year	Y	Y
N	2944	2944

*Note: Standard errors in parentheses, *p < 0.1, **p < 0.05, and ***p < 0.01. The following Tables are the same. Source: Raw data comes from China City Statistical Yearbook and annual statistical bulletin. The table is prepared by the author*

Timeliness Mechanism

To study the timeliness of smart city construction on the development of CE, this study takes 2012 as the time point of smart city policy pilot, and studies the policy effect of smart city construction on the development of CE in the sample city in the three years around 2012.

To solve the problem of the endogeneity of the DID model and verify whether the CE development of the treatment group and the treatment group in the smart city were consistent under the influence of external factors, the following parallel trends were drawn based on the results in model 4.

Show as Figure 2.11, the dynamic effect test chart of the DID parallel trend test is depicted, showing the dynamic economic effect of smart city policies in different years. In Figure 5, the short line perpendicular to the horizontal axis is the 95% confidence interval of the cross-product regression coefficient of the year and the virtual variables of the treatment group. As can be seen from Figure 5, the interaction term coefficient of the DID policy effect pre_1, pre_2, pre_3 were no significant difference (95% confidence interval, $\beta_1 = 0.05, p < 0.01$). In summary, the coefficients are consistent with theoretical assumptions indicating that there were no significant differences between treatment and control groups before the smart city policy pilot, implying that the hypothesis of parallel trends was met.

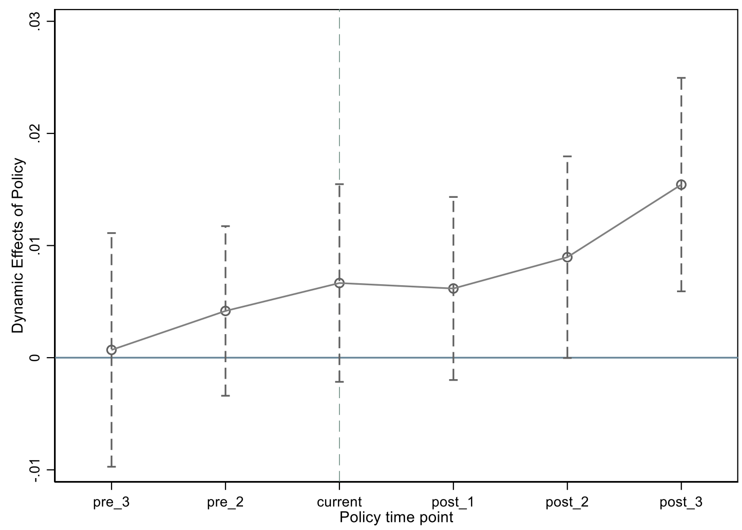

Figure 2.11 – Parallel trend detection map (Source: original data is from China City Statistical Yearbook and City Annual Statistical Bulletin)

Source: prepared by the author

To compare the policy effect of smart city pilot on the development of urban CE, the counterfactual detection method is adopted for a comparative study. In this study, 2012 moved forward to 2009, 2010, 2011, and backward to 2013, 2014, 2015. The estimated results are as follows:

Show as Table 2.10, first, the estimated coefficient of DID one year earlier is not significantly positive at the confidence level of 0.1 ($\alpha_4 = 0.5193, p > 0.1$), the estimated coefficient of DID two years earlier is not significantly positive at the confidence level of 0.1 ($\alpha_4 = 0.4452, p > 0.1$), the estimated coefficient of DID three years earlier is not significantly positive at a confidence level of 0.1 ($\alpha_4 = 0.3848, p > 0.1$), this shows that under the influence of the policy of smart city without technological innovation, the improvement of the development level of urban CE is not obvious; Second, the estimated coefficient of DID lagging one year is significantly positive at a confidence level of 0.01 ($\alpha_4 = 0.7746, p < 0.01$), the estimated coefficient of DID lagging two years is significantly positive at a confidence level of 0.01 ($\alpha_4 = 0.9108, p < 0.01$), the estimated coefficient of DID lagging three years is significantly positive at a confidence level of 0.01 ($\alpha_4 = 0.9557, p < 0.01$), this shows that under the premise of the gradual improvement of the technological innovation level of smart city, the policy pilot of smart city can promote the development of urban CE, and the policy effect is lasting and significant.

Moreover, the significance of the explanatory variables after the change of the policy is far from the benchmark regression, indicating that the establishment of smart city pilot has a great impact on the improvement of the development level of urban CE, while the previous regression results are reliable. At the same time, since the impact of smart city construction policy on urban CE may gradually appear over time, the time virtual variable is estimated by three years in this study. As shown in Table 2.10, the significant performance of the test results based on the lag of policy implementation is basically consistent with the benchmark estimates, indicating that the study results are credible. In conclusion, the hypothesis H3 of this study is established, that is, driven by digital innovation technology, smart city variables are integrated to evaluate the sustainable development ability of urban CE development, and smart city can promote the development of urban CE for a long time.

Table 2.10 - The Counterfactual test results

	CE (one year ahead)	CE (two years ahead)	CE (three years ahead)	CE (one year lag)	CE (two years lag)	CE (three years lag)
DID	0.5193 （0.24）	0.4452 （0.24）	0.3848 （0.25）	0.7746*** （0.27）	0.9108*** （0.29）	0.9557*** （0.34）
Control	YES	YES	YES	YES	YES	YES
City	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
R^2	0.6095	0.6093	0.6091	0.6102	0.6104	0.6101
N	2347	2347	2347	2347	2347	2347

*Note: Standard errors in parentheses, *p < 0.1, **p < 0.05, and ***p < 0.01. The following Tables are the same. Source: Raw data comes from China City Statistical Yearbook and City Annual Statistical Bulletin, and the table is prepared by the author*

DID robustness detection result

To further test the robustness of the estimated results in this paper, smart cities from 2013 and 2014 are included in the regression sample to examine the impact of smart city construction on the discharge of pollutants and the CE. According to the calculation results in Table 2.11, the construction of smart cities still significantly reduces environmental pollution and is conducive to improving the development level of urban CE. There is no significant difference from the previous conclusions, indicating that this paper's conclusions are relatively stable.

Table 2.11 – Results of the robustness test for varying sample size

	sdiox	wwater	CE
DID	-2.5175*** (0.8877)	-0.01496*** (0.0031)	0.58397*** (0.2046)
Control	Yes	Yes	Yes
N	3760	3760	3760
Cities	235	235	235

*Note: Standard errors are shown in parentheses, *p < 0.1, **p < 0.05, and ***p < 0.01. Source: The original data is from China City Statistical Yearbook and City Annual Statistical Bulletin, and the table is compared by the author*

Discussion based on the regression relations

According to the DID results of Model 1, the relationship between smart city and environmental pollution was negatively correlated from 2012 to 2018 ((a) $\alpha_1 = -0.0221, p < 0.01$; (b) $\alpha_1 = -0.0886, p < 0.01$; (c) $\alpha_1 = -0.0174, p < 0.01$; (d) $\alpha_1 = -0.0375, p < 0.01$). According to the DID results of Model 2, the relationship between smart city and the development of urban CE was positively correlated from 2012 to 2018 ((e) $\beta_1 = 0.6866, p < 0.01$; (f) $\beta_1 = 0.7796, p < 0.01$; (g) $\beta_1 = 0.7150, p < 0.01$; (h) $\beta_1 = 0.7459, p < 0.01$). Based on this, hypothesis H1 is established: that is, there is a close correlation between smart cities and environmental pollution, smart cities, and urban CE.

Xu et al. (2021) based on the panel data of 251 cities in China from 2004 to 2015, used DID method to evaluate the establishment of innovative pilot cities on urban environmental pollution, and used the propensity score matching (PSM-DID) further verifies that the establishment of innovative pilot cities significantly reduced urban environmental pollution, which can reduce urban environmental pollution by 8.74% on average. The establishment of innovative pilot cities promotes urban green development and reduces urban environmental pollution mainly through technological effects and environmental regulation effects. Therefore, when implementing smart city pilot policies, it is also necessary to continuously optimize digital innovation technology, cultivate excellent IT talents to promote the development of IT, and improve the development level of urban CE. At the same time, it can also further lead to the improvement of the urban environmental quality.

To summarize, there is a close relationship between smart cities and environmental pollution, smart cities, and CE development. The construction of smart cities can realize the monitoring, early warning, and management of environmental pollution through intelligent technology and management methods, so as to improve the urban environmental quality. Meanwhile, the development of smart cities also needs to rely on the support of CE. Through the utilization and reuse of resources, it can reduce environmental pollution and waste of resources and achieve sustainable development. Therefore, smart cities, environmental pollution control and the development of CE should promote each other and form a favorable relationship mechanism.

Discussion based on the mediator effect

The estimated coefficient DID in Model 3 is significantly positive at a confidence level of 0.01 ($\beta_1 = 0.0619, p < 0.01$), this indicates that smart cities have a direct impact on the level of technological innovation; the Inn in Model 4 is significantly positive with a confidence level of 0.1 ($\alpha_1 = 0.6541, p < 0.1$), this indicates that technological innovation has a direct effect on the development of urban CE; the estimated coefficient of DID in Model 4 is significantly positive at a confidence level of 0.01 ($\alpha_4 = 0.7211, p < 0.01$), this shows that under the intermediary effect of technological innovation, smart city has an indirect effect on urban CE and environmental pollution emission reduction. Moreover, according to the test model 3 and model 4, under the intermediary role of technological innovation, the construction of smart city has an indirect impact on the development of urban CE. Based on this, the hypothesis H2 is established: that is, smart cities have a direct impact on environmental pollution, and have an indirect impact on the development of urban CE through the intermediary variable of technological innovation.

Xuan and Zhang (2021) based on smart city pilot policy from 2012 to 2014, using the panel data of China's prefecture-level cities from 2009 to 2018, calculated and decomposed the green total factor productivity according to the SBM-Malmquist-Luenberger method. The relationship between smart cities and green total factor productivity is analyzed by propensity score matching method and DID model. By studying the impact mechanism of economic agglomeration variables such as specialization and diversification, and finally introducing regional and city-scale heterogeneity, the results show that smart cities significantly enhance regional green total factor productivity, technical efficiency, and scale efficiency. The positive mediation effect of economic agglomeration in the eastern region is significant, while that in the central and western regions is less significant; the larger the city size, the more significant the positive mediation effect of economic agglomeration. Fan and Mi (2022) based on the literature and theories related to smart city and green economic development, put forward the research hypothesis of smart city construction on green economic development. The green total factor productivity measured by the EBM-ML index model was analyzed, and then further based on the panel data of prefecture-level cities in China from 2004 to 2016, a multi-period DID model was built to empirically test the relationship between smart city construction and green economic development. The results show that the construction of smart cities can significantly promote the development of green economy, and this promotion is mainly caused by the progress of green technology. The construction of smart cities can realize the development of urban green economy through three paths: technological innovation, industrial structure upgrading and resource allocation optimization. Based on the premise that the research results of scholars are consistent with this study, we concluded that in the implementation of smart city construction, the production factor of technological innovation should be introduced to improve the level of urban governance, and promote the development of urban CE while improving environmental pollution.

In summary, driven by technological innovation, the impact of smart cities on the CE can be analyzed from the following aspects: firstly, smart cities can promote the efficient use and reuse of urban resources. For example, an intelligent waste classification system can classify recyclables, hazardous waste, wet waste, and other types of waste, realize the resource utilization of waste, reduce landfill and incineration of waste, and realize the development of CE. Secondly, smart cities can achieve intelligent energy management and savings through the application of digital technology. For example, through technical means such as smart grid and energy home, real-time monitoring and management of sources can be realized, energy use can be optimized, energy waste can be reduced, and the goal of CE can be achieved. Secondly, smart cities can realize energy saving management through the application of digital technology. For example, through smart grid, smart home and other technical means, real-time monitoring and management of sources can be achieved to optimize the use of energy and reduce energy waste, thus realizing the goal of a CE. Finally, through the application of digital technology, smart cities can promote the transformation and upgrading of urban industries and realize sustainable development. For example, through the application of digital technology, the intelligent management of urban transportation can be realized, reducing the pollution of urban transportation and the waste of energy. It can promote the transformation and upgrading of urban industry and realize the goal of sustainable development. Therefore, driven by technological innovation, smart cities have a multifaceted impact on the CE. They can promote the efficient use of urban resources in the direction of digitization, networking, and intelligence, achieve intelligent management and conservation of energy, and promote the transformation and upgrading of urban industries to achieve sustainable development.

Discussion based on the timeliness mechanism

According to the time effect model of DID, before 2012, before smart city was launched, the effect of digital technology innovation in driving the development of urban CE was not significant, and the influence of smart city on the development of CE was consistent (95% confidence interval, $\beta_1 = 0.05, p < 0.01$); After 2012, after the launch of smart cities nationwide, the effect of digital technology innovation in driving the development of urban CE is significant. And the estimated coefficient of DID lagging by one year is significantly positive under the premise that the confidence level is 0.01 ($\alpha_4 = 0.7746, p < 0.01$), The estimated coefficient of DID lagging two years is significantly positive at a confidence level of 0.01 ($\alpha_4 = 0.9108, p < 0.01$), The estimated coefficient of DID lagging three years is significantly positive at a confidence level of 0.01 ($\alpha_4 = 0.9557, p < 0.01$). Therefore, hypothesis H3 is established: that is, driven by long-term digital innovation technology, smart city can reduce environmental pollution and promote the development of urban CE.

Shi et al. (2018) assessed the impact of smart city construction on urban environmental pollution based on panel data from 197 prefecture-level cities in China from 2005 to 2015 using the DID under the framework of Schumpeter's theory of innovation and Porter's innovation-driven theory, and further verification was carried out using the difference in difference propensity score matching method (PSM- DID). The results showed that smart city construction has significantly reduced urban environmental pollution, which can be reduced by 9%-24% on average, the estimation results based on the PSM-DID method art not significant different from the above conclusions. Based on the premise that the research results of scholars are consistent with this study, we argue that cities with a better development foundation in terms of technological innovation, human capital level, financial development and information infrastructure can reduce urban environmental pollution in the long term, and the technological innovation element plays the greatest role in the pollution reduction effect of smart cities. It is of great significance to improve the urban environment and ecology, upgrade the urban construction form to create a good urban living and production environment.

Therefore, smart cities reduce environmental pollution and promote the development of urban CE, and the effect mechanism mainly includes the following aspects: (1) The efficiency of resource utilization is improved. The smart cities realize the intelligent management and optimize the use of various urban resources by means of digital technology and the IoT, which improves the efficiency of resource utilization and reduces the waste of resources. (2) Environmental protection benefits increased. Smart cities can improve the sustainability of urban CE by monitoring, predicting, and controlling urban environmental pollution, and increasing the benefits of environmental protection. (3) Promote industrial upgrading and transformation. Smart cities can promote the upgrading and transformation of urban industries from a traditional production-oriented economy to a service-oriented economy, to achieve a more rational use and recycling of resources. (4) Increase social engagement. Smart cities can improve the participation and innovation of citizens through DTs and social media, thereby promoting the development of urban environmental protection and CE.

Conclusions to section 2

In section 2 “CE-related construction and evaluation: urban e-waste management system”, the conceptual framework of DTs in CE is explored from the perspective of product life cycle, and DTs in promoting CE business model innovation is elucidated. The application of DTs in the business model of AB-PSS is further discussed by analyzing the role of digital IT, and using a real-world bike-sharing platform as an example. Based on the CE theory of urban, this study designed the evaluation index system of urban CE development according to the relevant evaluation principles, and conducted a comprehensive evaluation of the city's CE development. The way in which digital technology innovations can contribute to urban CE is explored. The following conclusions are obtained.

1. Based on our analysis of the extant literature, we proposed a conceptual framework in which DTs, such as the Internet, IoT, cloud computing, big data, and AI, play important roles in each stage of the product lifecycle (i.e., design, use, and end of life). By working on the three performance objectives of CE: increasing resource efficiency, extending product lifespan, and closing the loop, we argued that DTs potentially enable radical improvements to the CE model, provided that the environmental and economic costs of DTs are assessed and balanced with benefits. New technologies and innovations provided by Industry 4.0 have been used for various circular product designs, such as design for long life, design for lease or service, design for reuse in manufacturing, and design for material recycling. In addition, non-materialization design should also be considered to reduce the amount

of material required while the core functionality is continuously delivered. From the beginning of the product lifecycle, we considered slowing down the resource flow of products and by entering the closed-loop cycle. New PSS business models have emerged to satisfy customer needs for personalized, experiential, and other professional services. PSSs are divided into three categories according to the degree of service and ownership transfer of product in the transaction process: product-oriented PSSs, usage-oriented PSSs, and result-oriented PSSs. This study abstractly analyzed the consumer–service–product interaction process in the PSS business model that provides professional services to consumers through the Internet, IoT, cloud platforms, and digital twin technology. When the product reaches EoL, the loop through reuse, remanufacturing, and recycling should be closed. DTs are conducive to the improvement of the management of reverse supply chains and to the reduction of transportation flows. With the help of the Internet, IoT, cloud computing, big data analytics, and AI, Internet-based recycling platforms and smart recycling bins have established direct and effective connections for consumers, recyclers, and manufacturers.

2. DTs can support both CE and PSSs to enable circular business models that support our theoretical framework. In recent years, many popular AB-PSSs based on smartphone apps, such as the bike-sharing system studied here as an example of DTs driving the transition toward a CE, have been developed. The development of the Internet and the IoT provided the foundations for the use of shared bicycles based on an AB-PSS. The IoT technology ensures bike data collection and networking. The information collected through the IoT helps provide better technical support for on-site maintenance technicians, thereby extending the service life of the bicycles. The positioning technology provided by the IoT enables reverse recycling activities, such as refurbishment and remanufacturing of bicycles, to close the loop. The cloud platform offers data storage and management for shared bicycles, and AI provides technical support for smart operations through big data analysis. To achieve the transition from a linear economy to CE, we must integrate DTs across all stages of the product lifecycle and operate a transition from a

traditional "product-centric" focus to a "service-centric" focus on solutions and product services to achieve whole lifecycle management.

3. By analyzing the existing evaluation methods for the development of CE, an evaluation system based on the city level was established. The design of the evaluation index system follows the principles of systematicity, scientific, comparability and dynamism. The whole urban CE evaluation system is divided into three subsystems of economy, environment and resources, and the hierarchical structure of the evaluation index system is determined: the target layer, criterion layer, element layer and the index layer, constituting the multi-objective and multi-level structure of the evaluation model. The evaluation indicators are selected through literature analysis, and the weights are calculated using the AHP method, and finally the urban CE index is calculated, which is used to make a comprehensive evaluation of the development of urban CE.

4. Based on the panel data of prefecture-level cities from 2003 to 2018, this study empirically testifies the impact of smart city policy implementation on the environment and urban CE using the difference-in-difference method. The empirical results of this study show that there is a significant relationship between smart city construction and environmental pollution reduction and the development of urban CE. On the one hand, the implementation of smart city policy reduces environmental pollution and realizes environmental protection, and on the other hand, it promotes the development of urban CE. This study explores the mediation mechanism of smart city policy on promoting CE, and the results show that driven by the development of ICT innovation, smart cities contribute to the development of the urban CE. This study further proves the timeliness of CE with the support of technological innovation by counterfactual test, and the results show that smart city can promote the development of urban CE for a long time. The robustness of the findings was further verified through a series of robustness tests such as parallel trend detection and varying the sample size.

SECTION 3. DEVELOPMENT OF ECONOMIC MECHANISM AND RECOMMENDATIONS FOR URBAN ELECTRONIC WASTE MANAGEMENT IN XINXIANG CITY

3.1 Framework for building an intelligent electronic waste collection service platform in Xinxiang city

Municipal e-waste management system is a huge project, and this study chose to build an advanced, efficient, and intelligent recycling and management project for waste electronic products in Xinxiang city for case study, attempt to achieve the enlightenment effect of drawing inferential conclusions in practice. Xinxiang city is selected as the target city for this study because the economic development level and scale of Xinxiang city is at the middle level in China, and it is representative to conduct a case study on it. Xinxiang city is in the northern part of Henan province, and it is a prefecture-level city, with a total area of 8,249 square kilometers. There are four municipal districts in Xinxiang city, and the resident population of Xinxiang city is 6,166,000 at the end of 2022. Xinxiang city is a national civilized city, national sanitary city, national garden city, national forest city, national intellectual property demonstration city, and national CE demonstration city. As of December 2022, Xinxiang city has 9 counties and districts under its jurisdiction, 1 urban-rural integration demonstration zone, 2 state-level development zones, and 3 county-level cities under its administration. This study focuses on four municipal districts in Xinxiang city to understand the status of its e-waste management, and the survey was conducted from May to July 2023. The sources of e-waste are scattered and widely distributed, so how to achieve efficient recycling of all types of used appliances is a key step in the large-scale treatment of used appliances. At present, the peddler can collect a certain number of used appliances, but the peddler collection has problems such as supervision difficulties and low efficiency. Therefore, this chapter mainly discusses how to build an efficient and intelligent collection system for e-waste, which provides references for the efficient recycling of e-waste.

Key DTs and devices

Waste home appliances are of various types and huge quantities, and can be categorized into large-sized waste home appliances and small-sized waste home appliances according to the difference in their size or quality. Large-sized used home appliances mainly include cathode ray tube televisions, refrigerators, washing machines, air conditioners, etc., which are large and heavy in quality, and are not easy for residents to handle and dispose of, but they contain more recyclable resources and have a higher recycling value. Small-sized used home appliances include used cell phones, telephones, plug-in boards, chargers, etc., which are small and light in weight, and are easy for residents to handle and dispose of, but due to the large number of wastes and their wide distribution, it is not economically feasible to collect them through door-to-door collection.

Based on the different characteristics of large and small-sized used home appliance products, this study puts forward a targeted approach to build an intelligent recycling system for used home appliances based on IoT technology. On the one hand, for large-sized used household appliances, online methods such as websites, hotlines and mobile apps can be used to make reservations in advance, and door-to-door quotes, settlements and deliveries of large-sized recycled resources can be realized for residents by integrating the traditional recycling system. On the other hand, for small-sized used home appliances, the IoT smart recycling bins set up in communities and major commercial districts are used as recycling carriers, giving full play to the advantages of the smart recycling bins, which integrate the functions of waste delivery and smart and convenient living, and encouraging residents to make real-time deliveries, so that residents can directly realize the quotation, settlement and delivery of small-sized renewable resources through the smart recycling bins. Through the infrared full box alarm system set up in the smart recycling boxes of each recycling outlet, the background data is analyzed in real time to plan the optimized logistics and recycling routes. In addition, after the delivery of large and small used home appliances is completed, the value of the delivered waste will be exchanged through the backstage settlement system in the first time, thus motivating more residents to participate in the delivery of used home appliances for recycling (Han & Shevchenko, 2023).

The key to building an intelligent recycling system for used home appliances is IoT technology. IoT technology is a network that connects objects to the IoT through information sensing devices such as RFID, infrared sensors, GPS, laser scanners, etc., in accordance with predetermined protocols, to exchange information and communicate to realize intelligent identification, localization, tracking, monitoring, and management of objects.

The related application of IoT technology has become more and more common, but the construction of the management platform for the recycling system of end-of-life household appliances is still to be improved. For the construction of IoT management platform for used and waste household appliances, the author analyzes Xinxiang city as a case study and proposes an intelligent service platform with IoT intelligent bins and waste household appliances recycling information collection, and the platform construction framework is shown in Figure 3.1. The platform can revolutionize the traditional, low-tech, and unordered information collection mode of all kinds of renewable resources industry including used appliances, and initially establish an urban sensing network of used appliances with comprehensive sensing, reliable transmission, and intelligent processing. It will change the situation of low level of information collection and excessive labor consumption in the industry, greatly improve the efficiency of information collection on end-of-life household appliances, and provide a reliable and efficient data source for the recycling of used and end-of-life household appliances.

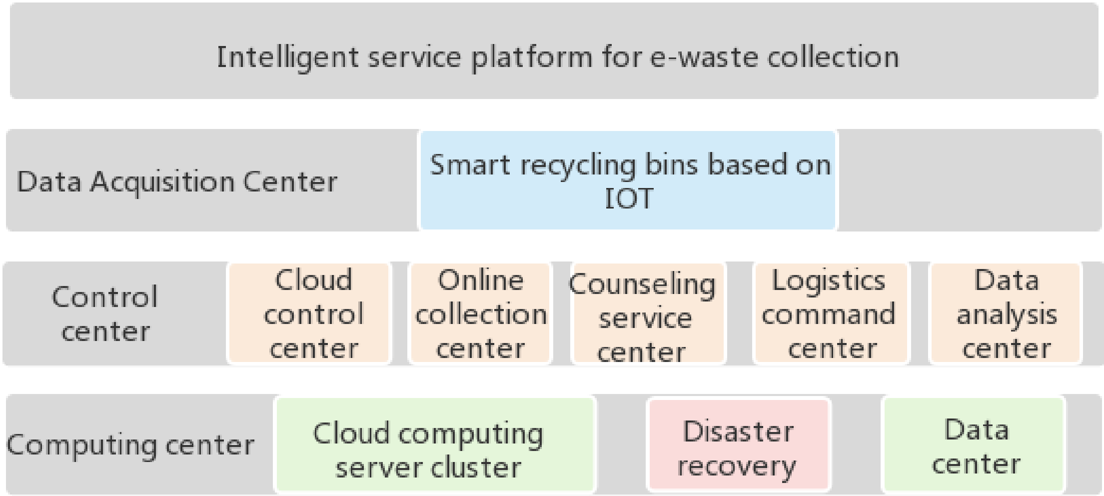

Figure 3.1 – Framework for building an intelligent e-waste collection service platform

Source: prepared by the author

Intelligent service platform for e-waste collection can collect data information and obtain attribute information on end-of-life household appliances distributed in cities anytime and anywhere by means of RFID, QR code, GPS, cameras, sensors, networks and other technical means of sensing, capturing and measuring; and the attribute information on end-of-life household appliances can be accessed to the information network through the convergence of various communication networks and the Internet, and the information can be shared and interacted at anytime and anywhere through the network. Through the integration of various communication networks and the Internet, the attribute information of used and end-of-life appliances is connected to the information network, and the information can be shared and interacted at any time and any place. At the same time, by utilizing information technologies, such as cloud computing and intelligent identification, the massive and cross-regional stock and attribute information of end-of-life appliances can be analyzed and processed to enhance the insight into the consumption activities of urban electronic products, the stock of used and end-of-life appliances and the related changes, and to realize the intelligent decision-making and control.

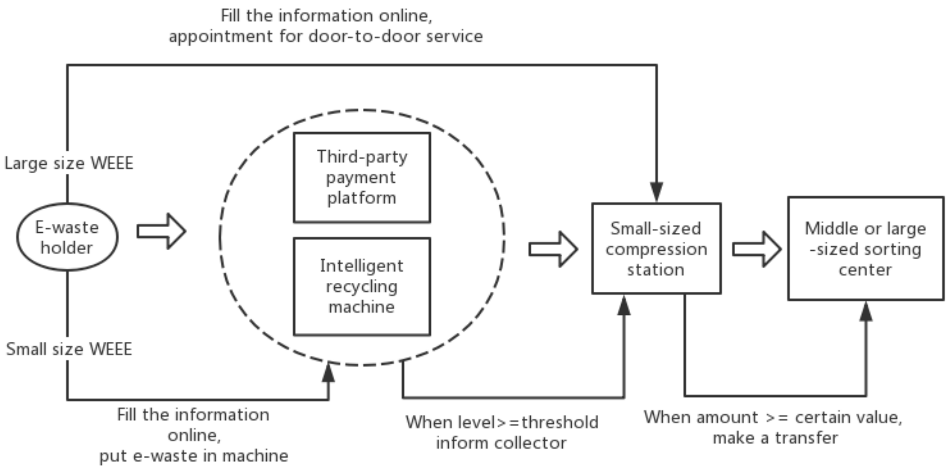

Figure 3.2 – The e-waste collection process based on IoT platform

Source: prepared by the author

The current infrastructure of the IoT system includes smart recycling bins, IoT recycling mobile terminals, a WeChat platform, an environmental protection website, a logistics scheduling system, a financial settlement system, a traceability system, a POS management system, a call center, and the infrastructure of each recycling site.

The system is based on the IoT, and the construction of the renewable resources recycling network system strictly follows the principle of "reduce, reuse and recycle" of the CE in the process of operation, and through the integration of various types of renewable resources chain, it generates economic benefits and becomes a demonstration base for fostering a new type of economic growth point. At the same time, through market-oriented and professional operation, the formation of the CE industry chain is driven by the goal of minimizing the pollution emission and maximizing the utilization of resources in the process of recycling and treatment of e-waste renewable resources. Through the IoT technology, the logistics cost of the whole recycling system has been greatly reduced, and the recycling volume has increased.

The IoT Smart Recycling Bin is a customized IoT terminal device that contains two parts: the collection terminal and the cloud control center. The device is oriented to residents, enterprises, and organizations with the service goal of recycling waste home appliances, and is a set of intelligent collection and sensing equipment deployed in buildings, commercial districts, and communities. Its core function is to serve as an information collection terminal for e-waste, providing residents with information and delivery services. Based on this, we have developed other value-added services for it, including open advertising services, ticket distribution services, online redemption services, and social public welfare services, considering the needs of the community and the commercial district.

The IoT has two meanings: first, its core and foundation are the Internet, which is a network that extends and expands on the Internet, and second, the user side extends and expands to any object to object to exchange information and communicate. The technologies and devices required for the construction of IoT mainly include information sensing devices such as RFID, infrared sensors, GPS, laser scanners, gas sensors, and so on.

RFID technology is the basis of the IoT, through the emission of radio frequency signals, the use of alternating magnetic fields and electromagnetic fields of spatial coupling, the information in a non-contact way to pass out and identify. The key to RFID technology is the RFID chip, also known as RFID tags, which are divided into passive tags and active tags, the main principle is as follows:

Passive tags, also known as passive tags, when the passive tags into the alternating magnetic field or electromagnetic field, if the corresponding identifier/reader to receive a specific radio frequency signals sent out, you can use the energy obtained from the inductive current will be stored in the passive tags stored in the chip of the goods or other related information sent out; active tags, also known as active tags, it can actively send a specific frequency signal, identifier/reader to read the information actively sent out after decoding and related data analysis and processing work. Reader in reading active tags actively send information, decoding and related data analysis and processing work.

RFID technology in practical application, to suit the actual business operations, the data collection mode is more flexible, both fixed equipment can be used, but also portable data collection system. The use of fixed equipment RFID reader to signal full coverage as a principle, according to the environment of the deployment site for decentralized layout, the reader through WIFI or other network methods and information management systems to connect and carry out the next step in the data operation. Portable data collection device is mainly a handheld data collector, data collection personnel carrying data collector active scanning RFID tags on the data information, data can be temporarily stored in the RFID reader, and then batch to the background information system to transmit data, but also through the portable data collector using WIFI or other wireless communication means of real-time data transmission to the backstage information management system to store, analyze and process. This kind of handheld data collector for data collection has great flexibility, especially suitable for places where it is not suitable to install fixed RFID readers, and can greatly improve the efficiency of using RFID readers.

Logistics and warehouse management is the main application field of bar code technology, it can be said that the warehouse is not competitive and vitality away from bar code technology, in the commercial goods inventory management, factory products and raw materials inventory management, bar code technology has been widely used. Through the bar code warehouse management, products, raw materials, information resources to achieve information sharing, improve warehouse utilization and turnover rate. Warehouse management is a dynamic management process, through the warehouse bar code management system, managers can timely grasp each product and raw materials in the warehouse real-time quantity and its dynamic changes, and can accurately predict and analyze each product and raw materials inventory, sales, and production. Through accurate prediction and analysis, managers can make timely judgments on the dynamic changes in the number of incoming goods, and then adjust the procurement and production and sales plans to ensure optimal inventory and improve the inventory structure, improve the turnover rate of funds, and realize the comprehensive management and control of products and raw materials.

Logistics traceability technology, also known as logistics tracking technology, is an important means of tracking and visualization management in the whole process of logistics, and is one of the ways to realize value-added logistics services.

The tracking technology of transportation vehicles and their loaded cargoes was firstly generated by logistics service providers and cargo owners in the multimodal transportation process tracking demand. In multimodal transportation, since multiple modes of logistics and transportation are in the process of conversion, logistics errors are very easy to occur, and logistics service providers and cargo owners hope to have a comprehensive control of the whole process of logistics through logistics tracking technology. In the logistics tracking technology application is becoming more and more extensive today, the technology is further extended to warehousing as well as in-plant logistics, and the in-depth application of barcode technology also makes the barcode-based cargo identification capabilities have been further developed. At the same time, the application of logistics tracking technology has also been deepened to warehousing, production, transportation, distribution, and other aspects of the entire supply chain, to achieve the whole process of real-time tracking of the whole business and visualization, traceability management. At present, the research on logistics tracking technology mainly focuses on effectively integrating multiple tracking technologies, improving tracking capability, and realizing multi-system sharing, backtracking and data analysis of tracking data.

GPS/GIS and barcode technology is the basis of the current logistics tracking technology, and the increasingly wide application of Bluetooth technology, wireless radio frequency technology, etc. is also playing an increasingly large role in logistics tracking, while the tracking technology is also being widely used in the process of Informa ionization of the enterprise with the ERP system, warehousing management system, transportation scheduling system, distribution and picking system and other information management systems continue to merge and integrate the application.

In the modularization and integration of enterprise information management system, logistics tracking data no longer comes from a single system, but from each business management system, which leads to the data in the format, content and other aspects of the larger structural differences, the current solution to this structural difference is mainly the use of XML technology, which adopts the standardized data structure standard to convert heterogeneous data into a unified structured data format to achieve data sharing, so that the data from each business system can be further applied. XML technology adopts a standardized data structure standard to convert heterogeneous data into a unified structured data format, realize data sharing, and enable further application of data obtained from various business systems.

Data back will be in the logistics process of multiple database data to realize the link and query at the database level, the current main realization includes the same system with the platform data chain query and different systems between the cross-platform chain query.

Data retrospective will be in the logistics process of multiple database data to realize the link and query at the database level, the current main realization includes the same system with the platform data chain query and different systems between the cross-platform chain query.

Intelligent Recycling Logistics System for e-Waste

The intelligent logistics and recycling system for e-waste in city Xinxiang consists of four parts: coverage of e-waste logistics and recycling network, tracking of e-waste logistics and recycling process, intelligent recommendation of e-waste logistics and recycling routes, and e-waste inventory management.

The logistics and recycling network for e-waste will be combined with intelligent recycling bins of the IoT, and a three-layer logistics and recycling system will be constructed with the core of "points, stations and centers", which will be operated based on the data and information obtained from the urban perception network, and designed in accordance with the principle of "unified planning, fixed-point operation and centralized management". It forms a new intelligent integrated recycling system with reasonable layout and comprehensive coverage by setting up community collection points (collection kiosks or mobile collection vehicles), regional collection stations (collection stores) and regional collection centers (processing and utilization centers).

Community collection points are generally deployed in the form of collection kiosks, which are responsible for the recovery of renewable resources surrendered by the community and its neighboring residential areas and community commercial outlets. In residential communities with limited conditions, mobile recycling vehicles can be set up to provide the community with regular collection services at regular intervals.

The basic principle of setting up community collection points is to build recycling points in accordance with the requirements of convenience for the residents, with one collection point (kiosk) for every 2,000-2,500 residents in urban areas and one collection point (kiosk) for every 3,000-3,500 residents in rural area. Institutions and enterprises are required to designate special persons or points for collection according to the declaration system.

The regional collection station is the key node of the infrastructure. The regional collection station requires a relatively large sorting site and a fixed location for centralized sorting, simple processing, and resource distribution of recycled resources other than hazardous waste. Regional collection stations are required to realize the following functions: (1) Collection. Collecting renewable resources centrally collected from community collection stations and mobile collection vehicles, as well as renewable resources submitted by enterprises, institutions, government agencies and schools. (2) Classification. Based on the principle of maximizing value, formulate classification standards for renewable resources, and carry out sorting and simple processing; (3) Storage. The regional collection stations also must take on the function of temporary storage of small used home appliances and toxic and hazardous waste. The regional collection stations will sort various types of renewable resources and then distribute them to various specialized collection centers as needed.

The regional collection center is also a renewable resources processing and utilization center, which is the end of the renewable resources recycling and utilization system. Based on the centralized sorting and simple processing of the regional recycling stations, the regional collection center forms an organic whole of the resources recycling chain and combines it with the operation network, which is the greatest point of interest in the development of the recycling industry chain. It integrates resource collection, processing, reuse, information, service, and environmental protection, and is characterized by scale, ecology, and industrialization.

The tracking of the reverse logistics recycling process of waste home appliances will utilize logistics tracking technology and adopt the fusion of multiple tracking technologies to realize the heterogeneous sharing and the chain query of waste home appliances reverse logistics recycling data. The tracking technologies will integrate the application of barcode identification technology, GPS/GIS technology, Bluetooth technology, RFID and other logistics tracking technology, and further integrate with the ERP system, warehousing management system, transportation scheduling system, distribution and picking system and other information management systems. The data of the reverse logistics come from many recycling business links, and the format and content of the data have strong heterogeneity, we will mainly use XML technology (Extensible Markup Language) to achieve the sharing and analysis of different structural data processing. XML technology adopts a standardized data structure standard to convert heterogeneous data into a unified structured data format.

The data traceability of the recycling process of the reverse logistics of used and end-of-life appliances will adopt the cross-platform chain query technology between different systems to track all the links of the reverse logistics in the whole process, and through the multi-database data level connection between the systems, it can realize the chain query of the tracking data, and at the same time, it also facilitates real-time querying on the current links and status of the waste home appliances.

The source of waste household appliances is scattered in all corners of the city, optimize the recycling logistics mode of used and waste household appliances, with the help of GPS/GIS, integrating Bluetooth, barcode, RFID and wireless communication and other advanced technical means, through the construction of cross-platform logistics information platform, the closed recycling logistics information is converted into an open recycling logistics information platform, and recycling logistics information is changed from single-direction and single-channel transmission to multi-direction and multi-channel transmission, so that the recycling logistics information can be further optimized and utilized on the basis of sharing. By building a cross-platform logistics information platform, the closed recycling logistics information will be converted into an open recycling logistics information platform, and the recycling logistics information will be changed from single-direction and single-channel transmission to multi-direction and multi-channel transmission, which will make the recycling logistics information of the waste household appliances further optimized and utilized on the basis of sharing, and the efficiency of the recycling logistics will be greatly improved by the coordinated calculation of the recycling routes and the optimization of recycling routes of the waste household appliances, which will effectively reduce the consumption of the logistics, lower the cost, and achieve the dynamic control of the whole recycling logistics and transportation.

The information on the recycling of waste household appliances mainly comes from the urban waste household appliance perception network established in the early stage; through wireless communication network and technology to obtain comprehensive road traffic information, using GPS/GIS control center to obtain the road traffic status and logistics vehicle status on the recycling logistics network, the whole process of dynamic tracking of the vehicle, to achieve the comprehensive management and control of the recycling logistics status. Establishment of a visual management platform is to visualize the utilization plan of recycling vehicles, the optimization of transportation schemes and the dynamic control of vehicles and goods within the scope of the platform. We need to establish warehousing management, financial management and customer service supporting systems, the recycling of waste home appliances information to implement the whole supply chain management, combined with the transportation scheduling function, constituting a complete intelligent logistics and transportation system.

Reverse logistics inventory management. The waste appliance logistics inventory management is built based on logistics and recycling information data management, providing daily management and decision-making support for used and end-of-life appliance inventory. The completed logistics inventory management system can effectively reduce the fragmentation of data and information and the resulting loss of data in substance, establish appropriate decision-making models through the mining and utilization of logistics data, apply the theory of decision-making knowledge, and form solutions to help managers make correct decisions on the problems exposed in recycling logistics.

Among them, to effectively control and manage the inventory of waste electronic products means to do a good job in the daily management of the warehouse inventory, in accordance with the standard requirements and procedures of the work of the warehouse, the collection of all the data in the inventory processing work, such as records of entry and exit of the warehouse, bills, bills and so on, and to realize the all-around management of the waste electronic products into the warehouse, out of the warehouse, and the inventory. Inventory decision support mainly realizes decision support for the formulation of inventory management programs. (1) The system collects information on inventory, raw materials, and prices, makes forecasts on the price trend and market trend of inventory items, and puts forward decision-making plans on the recycling and sales strategies of waste electronic products as well as the optimization of inventory. (2) Management of basic database, decision-making model library and knowledge database. The basic database system is responsible for adding, modifying, deleting, storing, and querying various basic data, forecasting data and decision-making data. The decision model library system is responsible for generating various models and methods for prediction and decision-making, and finding the optimal solution through the continuous combination of decision models. The knowledge database is responsible for storing all kinds of knowledge rules, knowledge reasoning and all kinds of decision-making models, and can use knowledge rules to carry out knowledge reasoning, providing theoretical basis and practical basis for decision-making.

So far, the city Xinxiang is in the process of building an Internet and IoT based e-waste recycling system, and volunteers are often recruited and organized to carry out a series of environmental protection publicity activities, such as "going into institutions, enterprises, schools and communities". Through the implementation of a variety of ways to standardize the recycling of waste home appliances, the residents' environmental protection concepts have been cultivated, and the recycling rate of used home appliances has been improved by the residents' correct delivery. Taking going into the community as an example, through the deployment of points in the community, the establishment of publicity strongholds and recycling logistics points, the formation of effective publicity channels to enhance the enthusiasm of the residents to participate, and at the same time to strengthen the linkage between the community to form the active participation of the residents of various regions. Several community-specific waste separation and recycling activities were carried out, and established a trusting and interactive relationship between the model system and consumers through this regular community activity. Waste home appliance recycling bins are placed at each site, and regular maintenance of recycling bins and collection and transportation of waste home appliances is carried out. The original scattered and disorderly recycling system has gradually moved towards standardization and rationalization, greatly improving the quality of recycling services and gradually replacing illegal peddler traders.

3.2 Exploring the electronic waste recycling behavior: case study of Xinxiang city in China

The main research content of this chapter: questionnaire design and data sources, theoretical model and research hypotheses, empirical evidence of residents' behavioral attitudes toward e-waste recycling and discussion of the results, and finally laying an empirical foundation for the study of the status quo, problems, and countermeasures of residents' behavioral attitudes toward e-waste recycling.

Questionnaire design and data sources

This study is mainly based on the theory of planned behavior, with reference to Ajzen (1991), and designed the questionnaire as shown to conduct the empirical study of structural equation modeling, with the following index system:

(1) In terms of structural variables, this study mainly includes seven structural variables: B_Base Situation, X_Intention, Y_Behavior, I_Internal Environment, E_External Environment, P_Promote Factors, and D_Disorder Factors. Factors, D_Disorder Factors". Moreover, in this study, the five indicators of the general situation of the questionnaire survey were used as the control variables (B_Base Situation), residents' willingness to recycle e-waste as the independent variable (X_Intention), residents' e-waste recycling behaviors as the dependent variable (Y_Behaviour), residents' e-waste recycling internal environment as the internal moderating variables (I_Internal Environment), and residents' e-waste recycling internal environment as the internal moderating variables (I_Internal Environment), the external environment of residential e-waste recycling as an external regulating variable (E_External Environment), incentives for residential e-waste recycling as a mediating variable (P_Promote Factors), and barriers to residential e-waste recycling as a mediating variable (D_Disorder Factors). Disorder Factors), thus constructing the indicator system of structural variables of the behavioral attitude model of residential e-waste recycling as shown below.

(2) In terms of latent variables: there are mainly 45 latent variables. In terms of the latent variables of residents' general situation, the questionnaire survey on gender, age, educational background, occupational background, and income level is mainly included; in terms of the latent variables of residents' willingness to recycle e-waste, the survey on seven aspects, namely, consciousness, values, common sense, specialty, social responsibility, civil obligation, and governmental responsibility, is mainly included. In the questionnaire survey, the seven aspects of residents' willingness to recycle e-waste mainly include Consciousness, Values, Common Sense, Specialty, Social Responsibility, Civil Obligation, and Governmental Responsibility, and the seven aspects of residents' willingness to recycle e-waste

mainly include Personal Recycling, Circle Promotion, Social Publicity and Education, Institutional Recycling, Market Contracting Recovery, and Attention, Trust, Cooperation, Expectation, and Excitation are the five aspects of the survey, while Attention, Trust, Cooperation, and Excitation are the seven aspects of the survey, Expectation, Excitation, and Bylaw, Cultural Atmosphere, Infrastructure, Publicity and Education, and Technical Recovery. In terms of the latent variables of the external environment of e-waste recycling, the survey mainly includes Bylaw, Cultural Atmosphere, Infrastructure, Publicity and Education, and Technical Innovation; in terms of the latent variables of the promotion measures of e-waste recycling, the survey mainly includes nine measures; in terms of the latent variables of the obstacles to e-waste recycling, the survey mainly includes nine factors, as shown in the Table 3.1.

Table 3.1 – Latent variables of residents' willingness to recycle e-waste

Target	Structure Variables	Latent Variables	Item and Definition
Conventional Variables	B_ Base Situation	B1:Gender	1. Your gender
		B2:Age	2. Your age group.
		B3:Education	3. Your education background.
		B4:Occupation	4. Your current occupation.
		B5:Income	5. Your current monthly income level (RMB)
Independent Variables	X_ Intention	X1:Consciousness	1. Do you think that formal e-waste recycling is a meaningful act to protect the environment?
		X2:Values	2. Do you think that the unreasonable disposal of e-waste will have a negative impact on your life and health?
		X3:Common Sense	3. Do you agree that formal e-waste recycling can provide a better living environment for future generations to some extent?
		X4:Specialty	4. Do you agree that formal e-waste recycling can solve the problem of resource scarcity and environmental problems?
		X5: Social Responsibility	5. Do you agree that your personal participation in formal e-waste recycling is making a contribution to the society?
		X6: Civil Obligation	6. Do you agree that every citizen has a responsibility to participate in formal e-waste recycling?

		X7: Governmental Responsibility	7. Do you agree that e-waste recycling is the responsibility of the government, which has little to do with it?
Dependent Variables	Y_ Behaviour	Y1: Personal Recycling	8. Do you participate in formal e-waste recycling, although with only little monetary compensation?
		Y2:Circle Promotion	9. Will you tell your family and friends about the formal recycling and disposal of e-waste, so that more people can know about this?
		Y3: Social Publicity and Education	10. Have you ever participated in any publicity and education activities related to e-waste recycling?
		Y4: Institutional Recycling	11. In the future, I am willing to contact professional recycling agencies.
		Y5: Market Contracting Recovery	12. I tend to buy electronic products that promise formal recycling in the future.
Internal Variables	I_ Internal Environment	I1:Attention	13. The e-waste recycling campaign will give you attention to the formal e-waste recycling behavior.
		I2:Trust	14. Do you believe that a regular disposal company can properly handle e-waste?
		I3: Cooperation	15. Do you agree to sell e-waste to small vendors is also a kind of recycling.
		I4: Expectation	16. Do you think that small traders can properly dispose of e-waste?
		I5: Excitation	17. If formal e-waste recycling can receive substantial material rewards or cash subsidies, you will participate in formal e-waste recycling.
External Variables	E_ External Environment	E1:Bylaw	18. If Chinese laws or urban rules and regulations explicitly require residents to take responsibility for e-waste recycling, you will participate in formal e-waste recycling. formal e-waste recycling.
		E2: Cultural Atmosphere	19. If your family or friends participate in formal e-waste recycling, you will also participate in formal e-waste recycling.
		E3:Infrastructure	20. If there is a regular e-waste recycling site or recycling facility near the community, I will do regular e-waste recycling.
		E4: Publicity and Education	21. The promotion and promotion of formal e-waste recycling methods will make you more keen to participate in formal e-waste recycling activities.
		E5: Technical Innovation	22. Intelligent recycling based on the Internet and the IoT facilitates e-waste recycling, and you will use this new way for formal e-waste recycling. Intelligent recycling based on the Internet and the IoT

			facilitates e-waste recycling, and you will use this new way for formal e-waste recycling.
Regulated Variable	P_ Promote Factors	P1:Promote Measure	23 (Regular publicity and education activities on e-waste recycling)
		P2:Promote Measure	23 (Set up banners in the community to promote regular e-waste recycling)
		P3: Promote Measure	23 (Regular recycling sites and infrastructure for e-waste in the community)
		P4: Promote Measure	23 (Arrange volunteers to remind them at the community e-waste recycling site)
		P5: Promote Measure	23 (Establish clear laws and regulations for e-waste recycling management)
		P6: Promote Measure	23 (Establish clear rewards and punishment measures for e-waste recycling)
		P7:Promote Measure	23 (Create a cultural and environmental atmosphere for formal e-waste recycling in the community)
		P8: Promote Measure	23 (Add a special staff to supervise the community e-waste recycling behavior)
		P9: Promote Measure	23 (Other (please specify))
Regulated Variable	D_ Disorder Factors	D1:Disorder Factor	24 (Insufficient publicity and education on formal e-waste recycling channels)
		D2:Disorder Factor	24 (No sites and infrastructure for formal e-waste recycling near the community)
		D3:Disorder Factor	24 (Participating in formal e-waste recycling takes up a lot of personal time and energy)
		D4:Disorder Factor	24 (No rules and regulations for mandatory e-waste recycling)
		D5:Disorder Factor	24 (Insufficient material rewards for participants who properly recycle e-waste)
		D6:Disorder Factor	24 (Lack of penalties and supervision for informal e-waste recycling)
		D7: Disorder Factor	24 (Insufficient cultural and environmental atmosphere for formal e-waste recycling)
		D8: Disorder Factor	24 (Residents are not aware of the importance of formal e-waste recycling)
		D9: Disorder Factor	24 (Other (please specify))

Source: prepared by the author

Research sample. This study takes the behavioral attitudes of Chinese residents toward e-waste recycling as the research object, with a total of 500 research samples. Moreover, this study mainly discusses the rationality and scientific of the research sample for the model study of residents' behavioral attitudes toward e-waste recycling from the five aspects of gender, age, educational background, occupational background, and income level of the residents in the sample survey:

(1) Gender: As shown below, this study mainly distributed the questionnaire of "Current Situation Survey on Residents' Attitude towards Electronic Waste Recycling Behavior" to 59.2% of females and 40.80% of males, and the recovered data showed that there were 296 females and 204 males. In terms of e-waste recycling, males and females have the same opportunities, only that females are more focused on the recycling of electronic resources by nature. Asking and investigating females' views on the willingness to recycle e-waste can more accurately explore the value of recycling e-waste, and asking and investigating males' views on the willingness to recycle e-waste can more accurately locate the reasons why residents are unwilling to recycle e-waste, to promote the sustainable development of recycling electronic resources.

(2) Age: As shown below, this study mainly distributed questionnaires to young people over the age of 18-25, and the recovered data showed that there were mainly 452 data, accounting for 90.40%. Among them, young people aged 18-25 are the ones who are most frequently exposed to electronic resources, and a survey related to e-waste recycling for them can more accurately reflect the current situation of the behavioral willingness of Chinese residents to recycle e-waste.

(3) Educational background: As shown below, this study mainly distributes questionnaires to college students, and the recovered data show that there are mainly 431 data, accounting for 86.20%. Among them, young people aged 18-25 are mainly undergraduates, specialists, and postgraduates, which also side by side reflects that people with education background of specialties and above pay more attention to the recycling of electronic resources, and launching a survey to these highly educated people is more capable of clarifying the direction of the development of behavioral willingness to recycle e-waste.

(4) Occupational background: as shown below, this study mainly distributes questionnaires to students, and the recovered data show that there are mainly 445

data, accounting for 89.00%. Among them, the youth aged 18-25 is mainly a student group with higher education, more interested in the recycling of electronic resources, more willing to cooperate with the status quo survey on the attitude of residents' e-waste recycling behavior, the data is more authentic and more reliable.

(5) Income level: As shown in the Table 3.2, this study mainly distributes questionnaires to low-income groups, and there are mainly 425 data, accounting for 85.00%. Among them, the low-income level is mainly students, because they are still studying, not yet oriented to social work, mainly part-time and internship income. Therefore, their behavioral willingness to e-waste recycling of the status quo survey, more inclined to the nature of electronic resources, the results of the survey is more reliable.

Table 3.2 – Statistical indicators of the research sample

Index	Type	Number	Percent(%)
B1:Gender	Female	296	59.20
	Male	204	40.80
B2:Age	18-25	452	90.40
	Under18	17	3.40
	26-30	13	2.60
	31-40	9	1.80
	Up 50	6	1.20
	41-50	3	0.60
B3:Education	Bachelor's Degree	431	86.20
	High/Technical Secondary school	23	4.60
	Master's degree or above	22	4.40
	Junior College	15	3.00
	Under Junior	9	1.80
B4:Occupation	Student	445	89.00
	Teacher	8	1.60
	Manager	6	1.20
	Marketing	5	1.00
	purchaser	4	0.80
	Personnel of Party and government organs	4	0.80
	Engineer	4	0.80
	Accountants	3	0.60
	HR	3	0.60
	Operations personnel	2	0.40

	Worker	2	0.40
	lawer	2	0.40
	Medical staff	2	0.40
	Self-employed	2	0.40
	Freelance	2	0.40
	Scientific research personnel	2	0.40
	Designer	1	0.20
	Waiter	1	0.20
	Retiree	1	0.20
	Administrative personnel	1	0.20
B5:Income	Under 2500	425	85.00
	2500-4000	23	4.60
	> 10000	19	3.80
	4000-6000	18	3.60
	6000-8000	9	1.80
	8000-10000	6	1.20
Total		500	100.00

Source: prepared by the author

Research variables and their descriptive statistics:

(1) Control variables: this study mainly carries out the related research of structural equations under the premise of controlling the five aspects of gender, age, educational background, occupational background, and income level, and the data comes from the questionnaire survey on the general situation of the residents.

(2) Independent variables: the independent variables in this study are mainly residents' willingness to recycle e-waste, which mainly contains seven latent variables: consciousness, Values, Common Sense, Specialty, Social Responsibility, Civil Obligation, Governmental Responsibility, Social Responsibility, Civil Obligation, and Governmental Responsibility. As shown in Table 3.3, the CV coefficient of variation of each latent variable data is greater than 0.15, the mean is greater than the median, the standard deviation is greater than 0.8, and the variance is greater than 0.6, which indicates that each resident's willingness to recycle e-waste varies greatly, and the tendency degree of the residents' willingness to expect the government to lead the recycling of e-waste is high.

Table 3.3 – Descriptive statistics of independent variables

Index	Mean	Std.	Median	Cor.	CV
X1: consciousness	1.42	0.83	1	0.69	0.59
X2:Values	1.50	0.87	1	0.76	0.58
X3:Common Sense	1.43	0.81	1	0.65	0.56
X4:Specialty	1.48	0.82	1	0.68	0.56
X5: Social Responsibility	1.45	0.80	1	0.64	0.55
X6: Civil Obligation	1.46	0.82	1	0.67	0.56
X7: Governmental Responsibility	2.53	1.59	2	2.53	0.63

Source: prepared by the author

(3) Dependent variable: The dependent variable of this study is mainly residents' e-waste recycling behavior, which mainly contains five latent variables: Personal Recycling, Cycle Promotion, Social Publicity and Education, Institutional Recycling, and Market Contracting Recovery. As shown in Table 3.4, the CV coefficient of variation of the data of each latent variable is greater than 0.15, and except for the series of Social Publicity and Education, the means of the series of other latent variables are greater than the median, the standard deviation is greater than 0.8, and the variance is greater than 0.6, which suggests that the behavior of each resident's e-waste recycling is more varied, but the practices of the social promotion and education are basically the same, indicating that the residents' e-waste recycling behavior is more varied, but in social promotion and education practices are basically the same, indicating that the residents' willingness to e-waste recycling behavior is high, but the behavior still fails to be implemented concretely.

Table 3.4 – Descriptive statistics of dependent variables

Index	Mean	Std.	Median	Cor.	CV
Y1: Personal Recycling	1.62	0.95	1	0.89	0.58
Y2: Circle Promotion	1.50	0.84	1	0.70	0.56
Y3: Social Publicity and Education	2.70	1.34	3	1.79	0.50
Y4: Institutional Recycling	1.75	0.97	1	0.94	0.55
Y5: Market Contracting Recovery	1.66	0.90	1	0.80	0.54

Source: prepared by the author

(4) Intrinsic moderating variables: the intrinsic moderating variables in this study are mainly the intrinsic environment of residents' e-waste recycling, which mainly contains five latent variables, namely Attention, Trust, Cooperation, Expectation, and Excitation. As shown in Table 3.5, the CV coefficients of variation of the data of each latent variable are all greater than 0.15, the means of the series of latent variables are all greater than the median, the standard deviations are all greater than 0.8 and the variances are all greater than 0.6, and the standard deviations and variances of the two latent variables of Cooperation and Expectation are all greater than 1, which indicates that, at the level of personal willingness, the residents are still more looking forward to the e-recycling buyers and the foreign trade buyers to recycle electronic waste. foreign trade buyers to purchase e-waste in a comprehensive manner to enhance the income of residents and ultimately realize the value of electronic resources.

Table 3.5 – Descriptive statistics of intrinsic moderating variables

Index	Mean	Std.	Median	Cor.	CV
I1:Attention	1.60	0.88	1	0.77	0.55
I2:Trust	1.70	0.89	1	0.79	0.52
I3: Cooperation	2.26	1.28	2	1.63	0.57
I4: Expectation	2.45	1.30	2	1.69	0.53
I5: Excitation	1.60	0.86	1	0.74	0.54

Source: prepared by the author

(5) Extrinsic moderating variables: The extrinsic moderating variables of this study are mainly the extrinsic environment of residents' e-waste recycling, which mainly contains five latent variables: Bylaw, Cultural Atmosphere, Infrastructure, Publicity and Education, and Technical Innovation. As shown in Table 3.6, the coefficient of variation of each latent variable is greater than 0.15, the mean of the series of latent variables is greater than the median, the standard deviation is greater than 0.8, and the variance is greater than 0.6, which suggests that the construction of the external environment of residents' e-waste recycling is relatively low, and that

the supporting regulations, cultural atmosphere, infrastructure, publicity and education, and technological innovation have not yet been popularized nationwide, and that the residents are less aware of the policies related to e-waste recycling than they were before. There is a big difference in the degree of understanding of the related policies of e-waste recycling.

Table 3.6 – Descriptive statistics of extrinsic moderating variables

Index	Mean	Std.	Median	Cor.	CV
E1:Bylaw	1.59	0.84	1	0.71	0.53
E2: Cultural Atmosphere	1.62	0.87	1	0.75	0.54
E3:Infrastructure	1.58	0.85	1	0.72	0.54
E4: Publicity and Education	1.64	0.89	1	0.79	0.54
E5: Technical Innovation	1.60	0.84	1	0.71	0.53

Source: prepared by the author

(6) Incentive mediator variables: the incentive mediating variables in this study are mainly the incentives for residents' e-waste recycling, which mainly contain nine latent variables of nine incentives for e-waste consumption, recycling, treatment, and utilization. Among them, except for the ninth incentive, the CV coefficients of variation of the data of the other latent variables are all greater than 0.15, which indicates that the incentives for e-waste recycling preferred by residents vary widely. Except for incentives 1, 2, and 9, the means of the series of data for the other latent variables are smaller than the median value, which indicates that e-waste recycling has more uncertainties at the incentive level. The standard deviation and variance of each latent variable is greater than 1, which indicates that there is a greater degree of variation in the incentives residents have for recycling e-waste.

Table 3.7 - Descriptive statistics of incentive mediator variables

Index	Mean	Std.	Median	Cor.	CV
P1: Promote Measure	2.43	2.43	1	5.88	1.00
P2: Promote Measure	3.02	2.73	2	7.48	0.91

P3: Promote Measure	2.78	2.08	3	4.32	0.75
P4: Promote Measure	3.63	2.60	4	6.77	0.72
P5: Promote Measure	3.28	2.61	4	6.81	0.80
P6: Promote Measure	4.12	3.08	5	9.49	0.75
P7: Promote Measure	4.99	3.12	6	9.70	0.63
P8: Promote Measure	5.18	3.57	7	12.75	0.69
P9: Promote Measure	-0.05	4.05	-2	16.44	-75.08

Source: prepared by the author

(7) Barrier mediator variables: the barrier mediator variables in this study are mainly the barrier factors to residents' e-waste recycling, which mainly contain nine latent variables, such as the policy restriction of e-waste recycling, the imperfect system, the unclear process, and the lack of technological basis. Among them, except for the ninth incentive, the CV coefficients of variation of the data of the other latent variables are all greater than 0.15, which indicates that residents perceive more obstacles to e-waste recycling. Except for barrier factors 4-8, the means of the series data of other latent variables are smaller than the median value, which indicates that there are more uncertainties in the technical difficulties and institutional environment of e-waste recycling. The standard deviation and variance of each latent variable are greater than 1, which indicates that there is a greater degree of variation in the problems encountered by residents in e-waste recycling.

Table 3.8 – Descriptive statistics of barrier mediator variables

Index	**Mean**	**Std.**	**Median**	**Cor.**	**CV**
D1: Disorder Factor	2.24	2.44	1	5.94	1.09
D2: Disorder Factor	2.46	2.00	2	4.01	0.81
D3: Disorder Factor	3.22	2.56	3	6.54	0.79
D4: Disorder Factor	3.23	2.56	4	6.56	0.79
D5: Disorder Factor	4.03	2.67	5	7.11	0.66
D6: Disorder Factor	4.33	2.82	5	7.92	0.65
D7: Disorder Factor	4.97	3.15	6.5	9.94	0.63
D8: Disorder Factor	5.15	3.55	7	12.57	0.69

D9: Disorder Factor	-0.14	3.97	-2	15.76	-29.19

Source: prepared by the author

Data validity:

(1) Questionnaire pre-processing:

The first step, pre-survey. The author issued 100 questionnaires to complete the pre-survey, in which the author chose the residents in the author's location and took the form of random distribution, a total of 100 questionnaires were issued, and the final valid questionnaires were 68. The main purpose of the pre-survey is to check whether there is any ambiguity in the questionnaire, questionnaire question items are wrong, and we hope that the interviewees can easily understand the meaning of the questions and give accurate and heartfelt answers. In this study, the pre-survey was utilized to adjust the questionnaire question items to improve the reliability and validity of the questionnaire and to remove inappropriate and unreasonable options.

The second step, the questionnaire recovery. In the formal questionnaire research, the author issued a sample of 1,000 research, of which, the author recovered 678 questionnaires, 500 valid, to determine the validity of the questionnaire based on two main principles: 1) all answered the questions; 2) all the answers to the questions to choose a different option; 3) the residents of the general situation of the five indicators are true.

The third step is the questionnaire items. This questionnaire consists of two parts in total, the general situation of the residents and the current situation of the residents' behavioral willingness to recycle e-waste: 1) the general situation investigates the information of the respondents' gender, age, education, occupation, and monthly income level; 2) the current situation of the residents' behavioral willingness to recycle e-waste investigates the residents' willingness to recycle e-waste, behaviors, intrinsic environment, extrinsic environment, incentives, and obstacles in the six main The data of these six aspects were investigated. The questionnaire items are the measurement items for each latent variable in this paper, and the questions are all based on the internationally recognized Likert 5-point scale, with the question options in the order of "Strongly Disagree (1), Disagree (2), Generally Agree (3), Agree (4), and Strongly Agree (5)".

(2) Questionnaire reliability test:

Reliability refers to the reliability of a questionnaire, and the reliability meets a certain standard that indicates that several question items can work together to explain a concept. This paper focuses on analyzing the internal reliability of the scale, and the widely used internal reliability coefficient is the Cronbach coefficient. The Cronbach's coefficient of the reliability test results of the six models in this study are all above 0.9, which indicates that the reliability of this study is strong, and the specific test steps are as follows:

(i) There is no uniform standard for analyzing Cronbach's alpha coefficient (or folding coefficient), but according to most scholars, generally speaking, if Cronb's alpha coefficient (or folding coefficient) is above 0.9, then the reliability of the test or scale is very good, between 0.8-0.9 indicates good reliability, between 0.7-0.8 indicates acceptable reliability, between 0.6-0.7 indicates average reliability, and between 0.5-0.6 indicates less than ideal reliability, and if it is below 0.5, we should consider rearranging the questionnaire. 0.6-0.7, 0.5-0.6 indicates fair reliability, 0.5-0.6 indicates less than satisfactory reliability, and if it is below 0.5, the questionnaire should be considered for reformatting.

(ii) Further analyze the item total statistical table to see which topics have led to a decline in the overall reliability, reliability if the value of "Corrected item-total correlation" is lower than 0.3, or the value of "alpha coefficient after deletion of the item" is significantly higher than the alpha coefficient, then consider the removal of the topic. If the value of "Correlation between corrected item and total" is lower than 0.3, or the value of "Alpha coefficient after deletion of item" is significantly higher than the alpha coefficient, then the topic can be excluded.

(3) Questionnaire validity test:

Validity refers to the validity of the questionnaire data, and the validity reaches a certain standard, which indicates that the factors can be factor analyzed with a strong correlation between the factors, indicating that the results of the research and analysis of the questionnaire are valid. This study mainly uses KMO and Bartlett to carry out the validity test of the questionnaire, and the results of the six models are all greater than 0.9, which indicates that the empirical results of this study are valid. The steps of questionnaire validity test are as follows:

(i) First of all, KMO and Bartlett's test: for KMO test, 0.9 is very suitable for factor analysis: between 0.8-0.9 is more suitable: between 0.7-0.8 is suitable: between 0.6-0.7 is OK: between 0.5-0.6 indicates poor: under 0.5 should be given up, through the KMO value of the test explains that there is a correlation between the variables of the question items. It meets the requirements of factor analysis. For Bartlett's test, if the significance is less than 0.05, the original hypothesis is rejected, indicating that the factor analysis can be done, if the original hypothesis is not rejected, indicating that these variables may provide some information independently, and it is not suitable for factor analysis.

(ii) Analyze the total variance of the explanation and the gravel plot, the total variance of the explanation is mainly to see the contribution of the factor to the explanation of the variable (can be interpreted as how many factors are needed to express the variable as 100%), and generally must be expressed to more than 80%, or else have to adjust the factor data. The function of the gravel plot is to confirm the number of factor principal components to be selected according to the slope of the eigenvalue decline, and the combination of these two can be used to confirm or adjust the number of factor principal components.

Analysis process of empirical results:

(1) Data source: the data of this study mainly comes from the results of 500 questionnaires, and the data recovered from the questionnaires are mainly analyzed and organized by using SPSS19.0 and Amos17.0 to verify the theoretical model and research hypotheses proposed in this chapter.

(2) Construct structural equation model: mainly to include 7 structural variables, 45 latent variables, according to the structural model of the weighted path diagram, analyze the factor path influence relationship situation, you can understand the path composition and relationship of each factor node from the global.

(3) Analyze the factor loading coefficient table: through the factor loading coefficients to screen the quantitative variables within the factor, in general, the measurement variables through the significance test (P<0.05), and the standardized loading coefficient value is greater than 0.6, it can be shown that the measurement variables are in line with the requirements of the factor downscaling, and if the gap between the conditions is too large, you can consider deleting the variables (variable settings are not reasonable) (PS: Structural Equation Modeling) (Essentially the same way with the path analysis, just more this step, for the conversion of multiple variables into a factor (variable), this step is used to explore the variable composition of the factor is on the same principal component).

(4) Analysis of model path coefficients: the model path coefficients of the paired features can be seen through the model path coefficients table, according to the significance test to analyze (P<0.05) whether there is an impact relationship between the model variables, if there is a significance, it indicates that there is an impact relationship between the variables, which can be analyzed in-depth through the standardized path coefficients of the impact of the efficiency of the amount.

(5) Model validation: the model fit indicator can analyze the model fit, usually do not require all the test passed.

(6) Analysis summary: The main analysis of the covariance table does not enter the degree of the node, used to analyze the correlation between the path nodes, the analysis is summarized.

Theoretical model and research hypothesis

This chapter focuses on the Theory of Planned Behavior and its extensions as the theoretical foundation, constructs a relevant theoretical model, and proposes six major research hypotheses, which are analyzed as described below.

(1) Behavioral attitude model and assumptions under general regression

The Theory of Planned Behavior (TPB) was developed by Icek Ajzen (1988,1991), and is the successor to the Theory of Reasoned Action (TRA), which was developed by Ajzen and Fishbein (1975,1980), because Ajzen found that human behavior is not 100% voluntary, but under control. He expanded TRA by adding a new concept of perceived behavior control, which developed into a new model of behavioral theory - Theory of Planned Behavior (TPB). Therefore, this study argues that residents' e-waste recycling behavior is not 100% voluntary, but rather under the control of behavioral intention and driven by some intentional factors.

Residents' e-waste recycling attitude (Intention) refers to the positive or negative feelings individuals hold towards e-waste recycling behaviors, that is, the attitude formed after conceptualization of the individual's evaluation of e-waste recycling behaviors, so the components of the attitude are often regarded as a function of the individual's salient beliefs about the outcome of e-waste recycling behaviors. E-waste recycling is a non-negligible problem in cities. With the development of technology, the use of electronic products is becoming more and more common, and the amount of e-waste is increasing. Residents' attitudes toward e-waste recycling refer to the positive or negative feelings individuals hold toward e-waste recycling behaviors, i.e., attitudes formed by conceptualizing individuals' evaluations of e-waste recycling behaviors. Therefore, residents' attitudes toward e-waste recycling are crucial to solving the e-waste recycling problem. According to relevant research, the components of attitudes are often viewed as a function of an individual's salient beliefs about the outcomes of e-waste recycling behavior. These beliefs include evaluations of the value of e-waste recycling behavior, expectations of the possible consequences of e-waste recycling behavior, expectations of the possible benefits of e-waste recycling behavior, and perceptions of the possible costs of e-waste recycling behavior. For some residents, they believe that e-waste recycling is a valuable and necessary thing to do to protect the environment, avoid pollution, and facilitate the recycling of resources. They had a positive attitude towards e-waste recycling and actively participated in e-waste recycling activities. However, there are some residents who have negative attitude towards e-waste recycling. They think that e-waste is a kind of waste, which is troublesome and dangerous to handle, and they are not willing to pay any price for such behavior. Therefore, they are often reluctant to participate in e-waste recycling activities.

When analyzing the influencing factors of residents' attitudes toward e-waste recycling, a variety of factors need to be considered. First, education level is one of the factors influencing residents' e-waste recycling attitude. Well-educated residents usually have higher environmental awareness and are more inclined to view e-waste recycling behavior positively. Second, income level also affects residents' e-waste recycling attitude. Residents with higher income levels have more choices and better conditions to dispose of their e-waste, and are therefore more likely to view e-waste recycling behavior positively. Finally, community environment also influences residents' e-waste recycling attitudes. In a community that supports and encourages e-waste recycling, residents are more likely to view e-waste recycling behavior positively. In summary, residents' attitudes toward e-waste recycling are critical to solving the e-waste recycling problem. We need to change residents' attitudes toward e-waste recycling by raising their environmental awareness, improving the community environment, and providing better disposal conditions to better solve the e-waste recycling problem.

Moreover, the Theory of Planned Behavior suggests that behaviors that are not fully controlled by individual will are not only affected by behavioral intention, but also constrained by the actual control conditions such as personal ability to perform the behavior, opportunities, and resources, etc. Under the conditions of the general situation of the residents, the behavioral intention of the residents' e-waste recycling directly determines the behavior of the residents' e-waste recycling. E-waste recycling is a complex task that requires residents to have certain electronic knowledge and skills to correctly identify and handle different types of e-waste. If residents lack such knowledge and skills, they may choose not to recycle e-waste because they perceive the recycling process to be too complicated or dangerous. Therefore, residents' behavioral intention to recycle e-waste directly affects their actual recycling behavior, which is an important point of the theory of planned behavior. In addition, opportunities and resources are also factors that influence residents' e-waste recycling behavior. For example, if the community lacks recycling facilities or the recycling price is too low, residents may choose not to recycle e-waste. Therefore, governments and businesses should provide appropriate recycling facilities and reasonable recycling prices to encourage residents to recycle e-waste. Overall, the theory of planned behavior suggests that residents' behavioral intention to recycle e-waste directly determines residents' e-waste recycling behavior. In addition to behavioral intention, factors such as personal ability to perform the behavior, opportunities and resources also affect residents' recycling behavior. Therefore, the government and enterprises should provide appropriate support to encourage residents to recycle e-waste to protect the environment and reduce environmental pollution.

Therefore, this study proposes hypothesis **H1: under the premise that the general situation of residents is basically unchanged, residents' willingness to recycle e-waste will have a direct impact on residents' e-waste recycling behavior.** In summary, this study constructs the following theoretical model 1 based on hypothesis H1. At the level of structural path, residents' willingness to recycle e-waste will have a direct impact on behavior, and the hypothesis is valid if the standardized coefficient of the path is greater than 0 and the significance test analysis ($P<0.05$) is passed.

Figure 3.3 – Theoretical model 1 based on hypothesis H1

Source: prepared by the author

(2) Models and assumptions of behavioral attitudes in endogenous environments

The intrinsic environment of this study is mainly measured through the subjective norms of individuals, and the theory of planned behavior suggests that subjective norms (Subjective Norm) refers to the degree of social concern, social trust, merchant participation, degree of promotion, and the degree of need for material incentives faced by an individual regarding whether or not to adopt e-waste recycling behaviors, i.e., when predicting the e-waste recycling behaviors of other people, the extent to which those In other words, when predicting the e-waste recycling behavior of others, those individuals or groups that have influence on the individual's behavioral decisions play a significant role in influencing whether or not the individual engages in e-waste recycling behavior. Nowadays e-waste recycling has become a global problem. With the continuous progress of science and technology and the improvement of people's living standards, the replacement speed of electronic products is getting faster and faster, and the quantity of e-waste also shows a rapid growth trend. E-waste contains many toxic and hazardous substances, if not properly handled, will cause serious harm to the environment and human health. Therefore, the issue of e-waste recycling has attracted widespread attention and focus. The subjective norms of individuals play an important role in e-waste recycling. First, social concern has a significant effect on individuals' e-waste recycling behavior. When individuals perceive that society is more concerned about e-waste recycling issues, they are more likely to adopt e-waste recycling behaviors. Second, social trust is also an important factor. Individuals are more likely to participate in e-waste recycling if they have sufficient trust in the e-waste recycling process, disposal methods and related policies. Further, the degree of merchant participation and promotion will also affect individuals' e-waste recycling behavior. If merchants are actively involved in e-waste recycling and the degree of promotion of e-waste recycling is high, individuals are more likely to participate in e-waste recycling. In addition, the degree of need for material incentives is also a factor that should not be ignored. Individuals are more likely to adopt e-waste recycling behaviors if they believe that e-waste recycling can bring them substantial material incentives. In conclusion, individuals' subjective norms play a crucial role in e-waste recycling. Only when factors such as social concern, social trust, merchant participation, degree of promotion and material incentives are improved can individuals participate more actively in e-waste recycling, thus effectively solving the e-waste recycling problem.

Therefore, this study proposes the hypothesis **H2: under the premise that the general situation of the residents is basically unchanged, as well as based on theoretical model 1, the residents' willingness to recycle e-waste will be affected by the changes in the intrinsic environment, thus adjusting the residents' e-waste recycling behavior.** In summary, this study constructs the following theoretical model 2 based on hypothesis H2, at the level of structural path, residents' willingness to recycle e-waste will be affected by changes in the intrinsic environment to adjust e-waste recycling behavior, and the hypothesis is valid if the standardized coefficient of the path is greater than 0 and the analysis of the test of significance (P<0.05) is passed.

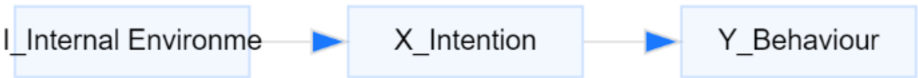

Figure 3.4 – Theoretical model 2 based on hypothesis H2

Source: prepared by the author

(3) Models and assumptions of behavioral attitudes in the external environment

Perceived Behavioral Control (PBC) refers to the external environment that reflects an individual's past experiences and expectations of e-waste recycling behavior. When an individual believes that the more external resources and opportunities he or she has at his or her disposal, and the better the external environment, the stronger the perceptual behavioral control of e-waste recycling behavior will be. Accurate perceptual behavioral control reflects the state of external environmental conditions, so it can be used as an alternative measure of external environmental conditions, directly predicting the likelihood of behavioral occurrence, and the accuracy of the prediction of e-waste recycling behavior relies on the true degree of perceptual behavioral control. With the continuous development of science and technology, electronic products are being updated more and more rapidly, and people's demand for electronic products is also increasing.

However, along with it comes a large amount of electronic waste, which brings serious pollution and harm to the environment. Therefore, e-waste recycling has become an important issue. Perceptual behavioral control refers to an individual's ability to perceive and control the external environment. In e-waste recycling behavior, the strength of perceptual behavioral control directly affects the individual's behavioral decisions. If an individual believes that the more external resources he has, and the better the policy and technical environment, the stronger his perceptual behavioral control over e-waste recycling behavior will be. Conversely, if an individual believes that the fewer external resources he has at his disposal and the worse the policy and technological environment, the weaker his perceived behavioral control over e-waste recycling behavior will be. Accurate perceived behavioral control reflects the state of external environmental conditions, and thus it serves as a proxy measure of external environmental conditions that directly predicts the likelihood of the behavior occurring. If an individual's perceived behavioral control over e-waste recycling behavior is stronger, then he is more likely to take positive action to recycle e-waste. Conversely, if the weaker the individual's perceived behavioral control over e-waste recycling behavior, then the more likely he is to abandon the act of recycling e-waste. The accuracy of e-waste recycling behavior predictions depends on the true level of perceived behavioral control. If an individual's perceptual-behavioral control over e-waste recycling behavior is consistent with the actual situation, then his behavioral prediction will be more accurate. On the contrary, if an individual's perceptual-behavioral control over e-waste recycling behavior does not match the actual situation, then his behavioral prediction will be biased. Therefore, to improve the accuracy of the prediction of e-waste recycling behavior, we need to strengthen the research on the individual's perceptual behavioral control. First, we need to understand the true extent of individuals' perceptual behavioral control over e-waste recycling behavior. Second, we need to investigate the factors that influence individuals' perceived behavioral control, such as policy and technological environments. Finally, we need to take measures to improve individuals' perceived behavioral control over e-waste recycling, such as strengthening publicity and education and providing convenient recycling channels. In conclusion, perceived behavioral control plays an important role in e-waste recycling behavior. Only by strengthening the research on individual perceptual behavioral control and improving individual perceptual behavioral control over e-waste recycling behavior can we better promote the development of e-waste recycling behavior, protect the environment, and promote sustainable development.

Therefore, this study proposes hypothesis **H3: under the premise that the general situation of the residents is basically unchanged, and on the basis of theoretical model 1, the residents' willingness to recycle e-waste will be affected by changes in the external environment, thus adjusting the residents' e-waste recycling behavior.** In summary, this study constructs the following theoretical model 3 based on hypothesis H3. At the level of structural path, residents' willingness to recycle e-waste will be affected by changes in the external environment to adjust e-waste recycling behavior, and the hypothesis is valid if the standardized coefficient of the path is greater than 0 and if the significance test analysis ($P<0.05$) is passed.

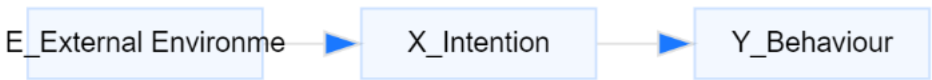

Figure 3.5 - Theoretical model 3 based on hypothesis H3

Source: prepared by the author

(4) Behavioral attitude models and assumptions under incentive interventions

The extended theory of the theory of planned behavior suggests that the incentive intervention of residents' e-waste recycling behavior mainly refers to a series of incentives, such as publicity and education, promotional activities, e-waste recycling cultural atmosphere, recycling supervision and other incentives at the spiritual level, which will have an indirect impact on the subjective norms of residents' e-waste recycling behavior. Moreover, material incentives, such as reward and punishment systems, educational rewards, and commercial promotion, will have a direct impact on the perceived behavioral control of residents' e-waste recycling practices, thus changing the social environment of e-waste recycling, and promoting the sustainable development of residents' e-waste recycling.

With the continuous development of science and technology, electronic products are being updated more and more rapidly, and people's lives cannot be separated from electronic products. However, the service life of electronic products is limited, and once they are scrapped, they will become garbage, which contains many hazardous substances, causing great harm to the environment and human health. Therefore, the recycling of electronic waste has become one of the important issues nowadays. However, the difficulty of e-waste recycling lies in how to motivate residents to participate in recycling behavior. In China, although the government has introduced a series of laws, regulations and policy measures, the residents' awareness and behavior of e-waste recycling still have certain problems due to the lack of effective incentives. Therefore, incentive interventions for residents' e-waste recycling behavior are particularly important. First, publicity and education is one of the important incentives for residents' e-waste recycling behavior. Through various forms of publicity and education, such as TV advertisements, publicity posters, and community lectures, the importance and methods of e-waste recycling can be popularized among residents to raise their awareness and cognitive level, to promote residents' participation in e-waste recycling behavior. In addition, voluntary work and volunteer services for e-waste recycling can be carried out through channels such as community volunteers and environmental protection organizations to further strengthen the strength of publicity and education. Secondly, promotion activities are also one of the important incentives for residents' e-waste recycling behavior. Through various forms of promotional activities, such as e-waste recycling contests, redemption activities and lucky draws, residents can be attracted to participate in e-waste recycling behaviors and increase their participation and recycling volume. At the same time, recycling preferential policies can also be introduced through cooperation with enterprises to encourage residents to hand over their e-waste to designated recycling enterprises, thus improving the efficiency and quality of recycling. In addition, the creation of a cultural atmosphere for e-waste recycling is also one of the important incentives for residents' e-waste recycling behavior. Through the establishment of an e-waste recycling culture, a good social atmosphere and values are formed, so that residents will regard e-waste recycling as a social responsibility and obligation, thus improving their recycling awareness and behavior. For example, a recycling culture can be created by setting up e-waste recycling boxes and publicity columns in public places such as communities and schools to guide residents to form good recycling habits. Finally, recycling supervision is also one of the important incentives for residents' e-waste recycling behavior. Through the establishment of a recycling supervision mechanism, the supervision and evaluation of recycling enterprises can be strengthened, and the service quality and credibility of recycling enterprises can be improved, to enhance residents' trust in recycling enterprises and their willingness to participate. At the same time, the supervision and management of recycling behavior can also be strengthened through the establishment of recycling complaint hotlines, reporting platforms, etc., to protect the legitimate rights and interests of residents and environmental safety. In conclusion, the incentive intervention of residents' e-waste recycling behavior is a complex and long-term work, which requires the joint participation and efforts of the government, enterprises, social organizations, and residents. Only through the comprehensive use of multiple incentives can we effectively promote the sustainable development of residents' e-waste recycling behavior and achieve the goals of environmental protection and sustainable development.

Therefore, this study proposes Hypothesis **H4: Under the premise that the general situation of residents is basically unchanged, as well as based on Theoretical Models 1, 2, and 3, the incentives for residents' e-waste recycling will intervene in residents' behaviors by adjusting residents' willingness to recycle their e-waste, thus promoting the sustainable development of e-waste recycling.** In summary, this study constructs the following theoretical model 4 based on hypothesis H4. At the level of structural path, residents' e-waste recycling behavior will be influenced by incentives to adjust residents' attitudes, thus promoting the sustainable development of residents' e-waste recycling behavior, and the hypothesis is valid if the standardized coefficient of the path is greater than 0 and the significance test analysis (P<0.05) is passed.

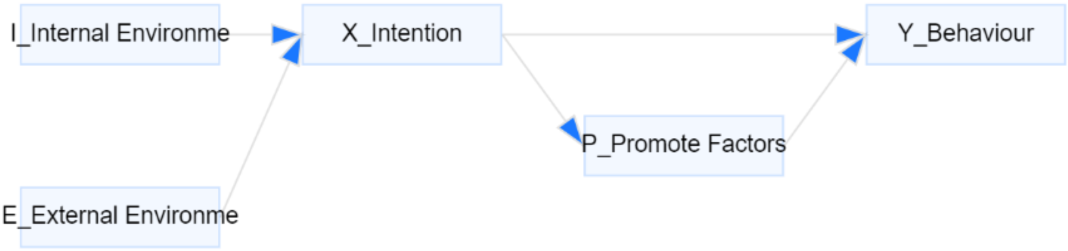

Figure 3.6 – Theoretical model 4 based on hypothesis H4

Source: prepared by the author

(5) Behavioral-attitudinal models and assumptions under the barrier mechanism

The extended theory of the Theory of Planned Behavior argues that the barrier intervention of residents' e-waste recycling behavior mainly refers to the solution of problems caused by a series of obstacles, such as solving the problems of e-waste recycling in terms of recycling channels, infrastructure, human resources, laws and regulations, rewards and punishment system, penalty and supervision measures, atmosphere construction, and residents' awareness, in order to enhance the degree of residents' willingness to recycle e-waste and make the residents' e-waste recycling behavior is sustainable.

In the extended theory of the Theory of Planned Behavior (TPB), the intervention of barriers to residents' e-waste recycling behavior is regarded as a key strategy aimed at solving the problems caused by a series of barriers to enhance the degree of residents' willingness to recycle e-waste and to make residents' e-waste recycling behavior sustainable. This theory has important guiding significance in the field of environmental protection, providing new ideas and methods for policy makers, enterprises and the public. First, the problem of recycling channels for e-waste recycling is an important obstacle in residents' e-waste recycling behavior. As e-waste contains hazardous substances, it will cause serious impacts on the environment and human health if not handled properly. Therefore, establishing an effective recycling channel is the key to solving this problem. This includes building recycling stations, setting up recycling points and promoting door-to-door recycling services. Only in this way can residents conveniently surrender their e-waste to professional recycling enterprises, avoiding waste accumulation and environmental pollution. Secondly, the construction of infrastructure is crucial to e-waste recycling. Without a sound infrastructure, the behavior of residents in recycling e-waste will be greatly restricted. Therefore, funds and resources need to be invested in the establishment of facilities for handling e-waste, such as crushers, sorting equipment, harmless treatment equipment, and so on. At the same time, supporting transportation systems need to be established to ensure that e-waste can be transported to treatment plants in a timely and safe manner. Again, the investment in human resources cannot be ignored. Professional recycling enterprises need to have enough technicians and managers to ensure that the recycling and treatment process of e-waste is effectively managed and controlled. At the same time, the government also needs to strengthen the training and guidance for recycling personnel to improve their professional quality and technical level. In addition, the formulation and improvement of laws and regulations is also an important means to ensure the sustainability of e-waste recycling behavior. The government needs to formulate relevant laws and regulations to clarify the classification, collection, transportation, and disposal of e-waste, and penalize those who violate the regulations. At the same time, it also needs to strengthen the supervision of enterprises to ensure that they carry out recycling and disposal work in accordance with the regulations. The reward and punishment systems are also one of the important means to enhance residents' willingness to recycle e-waste. The government can recognize and reward residents and enterprises that actively participate in e-waste recycling by setting up a reward mechanism to encourage more people and enterprises to participate in e-waste recycling behavior. At the same time, the government can also set up a penalty mechanism to penalize the violation of regulations to curb the occurrence of undesirable behaviors. Penalty monitoring measures are also one of the important means to ensure the sustainability of e-waste recycling behavior. The government needs to strengthen the supervision of e-waste recycling behavior and establish a perfect supervision mechanism to detect and deal with violations in a timely manner. At the same time, the government also needs to strengthen the supervision of e-waste recycling enterprises to ensure that they carry out the recycling and disposal work in accordance with the regulations. Atmosphere construction is also one of the important means to enhance the willingness of residents to recycle e-waste. The government can raise residents' awareness of and attention to e-waste recycling behavior through publicity and education, public welfare activities and other means to create a good social atmosphere. At the same time, the government can also improve the residents' awareness of and attention to e-waste recycling behavior through publicity and education and other ways to create a good social atmosphere. In conclusion, the extended theory of planned behavior provides us with a new perspective to examine the problem of residents' e-waste recycling behavior. By solving the problems caused by a series of obstacles, we are expected to increase the level of residents' recycling willingness and make residents' e-waste recycling behavior sustainable. This will be of great significance in protecting the environment and promoting sustainable development (Han, 2021b).

Therefore, this study proposes hypothesis **H5: Under the premise that the general situation of residents remains basically unchanged, and based on theoretical models 1, 2, and 3, residents will adjust residents' e-waste recycling willingness to intervene in residents' behaviors by solving the problems caused by the obstacle factors of e-waste recycling to promote the sustainable development of e-waste recycling.** In summary, this study constructs the following theoretical model 5 based on hypothesis H5. At the level of structural path, residents' e-waste recycling behavior will be affected by obstacle factors and adjust residents' willingness to intervene in residents' behavior to promote the sustainable development of residents' e-waste recycling behavior in solving the problems caused by e-waste recycling, and if the standardized coefficient of the path is greater than 0, and the analysis of the test of significance ($P<0.05$) is passed, then the hypothesis is established.

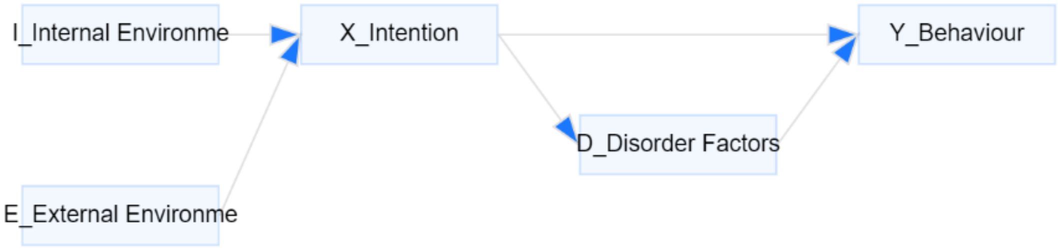

Figure 3.7 – Theoretical model 5 based on hypothesis H5

Source: prepared by the author

(6) Behavioral Attitude Model and Assumptions under Integrated Practice

In an extension of the Theory of Planned Behavior, Ajzen argues that all factors that may influence behavior are indirectly influenced by behavioral intentions. Behavioral intention is influenced by three related factors: first, the attitude of the individual himself, i.e., the "attitude" toward e-waste recycling behavior; second, the "subjective norms" originating from the internal environment, i.e., the "subjective norms" that will influence the individual to adopt e-waste recycling behavior; and finally, the "subjective norms" originating from the external environment, i.e., the "subjective norms" originating from the external environment. The second is the "subjective norms" originating from the internal environment, i.e., the "subjective norms" that influence individuals to adopt e-waste recycling behaviors; and the last is the "perceived behavioral control" originating from the external environment. Therefore, under the control of the internal and external environments, this study concludes that residents' willingness to recycle e-waste will influence the development of their e-waste recycling behavior. In past research, scholars have identified the effects of attitudes, subjective norms, and perceived behavioral control on behavioral intentions, but in this study, we will focus on how attitudes affect e-waste recycling intentions and behaviors by influencing subjective norms and perceived behavioral control. In addition, we will analyze the level of residents' awareness of e-waste recycling policies and whether these policies help to increase residents' e-waste recycling intentions and behaviors. At the theoretical level, the Theory of Planned Behavior (TPB) emphasizes the influence of personal factors, environmental factors, and behavioral experiences on behavioral intentions and behaviors. In this study, we will use the TPB model to analyze the relationship between attitudes, subjective norms, perceived behavioral control, and e-waste recycling intentions and behaviors. At the same time, external environmental factors such as policy, education, and community support will be considered to better understand residents' e-waste recycling behavior. At the methodological level, this study will use a questionnaire survey to collect real data on residents' attitudes, subjective norms, perceived behavioral control, and e-waste recycling willingness and behavior towards e-waste recycling. Based on the collected data, we will use statistical analysis to verify the relationship between attitude, subjective norms, perceived behavioral control, and e-waste recycling willingness and behavior. At the conclusion level, this study will summarize the relationship between attitude, subjective norms, perceived behavioral control, and e-waste recycling willingness and behavior. If the TPB model is supported, we will conclude that there is a significant positive relationship between attitude, subjective norms, perceived behavioral control, and e-waste recycling willingness and behavior. This will help us better understand residents' e-waste recycling behavior and provide policy makers with suggestions on how to improve residents' e-waste recycling willingness and behavior. This study will also focus on the level of residents' awareness of e-waste recycling policies. If it is found that the higher the level of awareness of the policy, the higher the willingness and behavior of residents to recycle e-waste, we will suggest policy makers to strengthen the publicity and education of the e-waste recycling policy to increase the environmental awareness and participation of residents. In addition, this study will analyze the impact of community support on residents' e-waste recycling willingness and behavior. If it is found that community support can increase residents' e-waste recycling willingness and behavior, we will suggest policy makers to strengthen community environmental protection activities to increase community residents' environmental awareness and participation. In conclusion, this study will help us better understand residents' e-waste recycling willingness and behavior, and provide policy makers with suggestions on how to improve residents' e-waste recycling willingness and behavior. At the same time, this study will also provide a reference for future research to further expand and improve the application of the theory of planned behavior in the field of environmental protection.

Moreover, individual as well as socio-cultural incentives and barriers will indirectly affect behavioral attitudes, subjective norms, and perceived behavioral control by influencing behavioral beliefs, and ultimately influence residents' e-waste recycling behavioral intentions and behaviors. Behavioral attitudes, subjective norms and perceived behavioral control of residents' e-waste recycling can be completely distinguished from each other conceptually, but sometimes they may share a common belief base, so they are both independent of each other and related to each other. With the progress of society and the development of science and technology, the quantity and types of e-waste are increasing. Residents' e-waste recycling behavior not only affects the environment, but also relates to the effective use of resources. Therefore, understanding the influencing factors of residents' e-waste recycling behavior is of great significance in promoting environmental protection and sustainable development. Behavioral beliefs are one of the important factors influencing residents' e-waste recycling behavioral intentions and behaviors. Individuals as well as socio-cultural and other factors such as incentives and barriers will indirectly affect behavioral attitudes, subjective norms, and perceptual behavioral control by influencing behavioral beliefs, and ultimately affect residents' e-waste recycling behavioral intentions and behaviors. Behavioral attitude refers to the individual's view and evaluation of a certain behavior, which is an important factor influencing behavioral intention. If individuals believe that e-waste recycling behavior is valuable and beneficial, they are more likely to adopt recycling behavior.

Conversely, if individuals perceive e-waste recycling behavior as meaningless and harmful, then they are less likely to adopt recycling behavior. Subjective norms refer to individuals' perceptions and expectations of their surroundings and others, which affect their behavioral decisions. If individuals believe that the people and environment around them are supportive of e-waste recycling behaviors, then they are more likely to adopt recycling behaviors. Conversely, if individuals perceive that people and the environment around them are not supportive of e-waste recycling behaviors, then they are less likely to adopt recycling behaviors. Perceived behavioral control refers to an individual's perception of and confidence in his or her ability to successfully implement a behavior, and it similarly affects an individual's behavioral decisions. If individuals believe they can successfully implement e-waste recycling behaviors, then they are more likely to adopt recycling behaviors. Conversely, if individuals believe they cannot successfully implement e-waste recycling behaviors, then they are less likely to adopt recycling behaviors. Behavioral attitudes, subjective norms, and perceived behavioral control of residential e-waste recycling can be fully distinguished conceptually, but at times they may share a common basis of beliefs, making them both independent of each other and related. Residents' e-waste recycling behavioral intentions and behaviors are influenced by a variety of factors, including personal characteristics, social culture, incentives, and barriers. These factors influence residents' behavioral beliefs by influencing their behavioral attitudes, subjective norms, and perceived behavioral control. Personal characteristics are one of the factors that influence residents' e-waste recycling behavior. For example, age, gender, education level, etc. will have an impact on residents' e-waste recycling behavior. Young people are more aware of environmental protection and are more likely to participate in e-waste recycling behaviors; women tend to be more concerned about environmental protection issues than men and are therefore more likely to participate in e-waste recycling behaviors; residents with higher education levels usually understand and accept environmental protection knowledge more easily and are also more likely to participate in e-waste recycling behaviors. Socio-cultural factors are also one of the factors influencing residents' e-waste recycling behavior. Cultural values and social expectations have an important impact on residents' behavioral decisions. In some areas, where waste separation and disposal are seen as a social norm, residents are more likely to participate in e-waste recycling behaviors; while in some areas, people are more inclined to consider discarded items as garbage and throw them away casually, so relatively few residents participate in e-waste recycling behaviors. Incentives can also influence e-waste recycling behavior. The government can encourage residents to participate in e-waste recycling by providing incentives and subsidies. For example, cash incentives or point incentives can be provided to motivate residents to participate in e-waste recycling. These incentives can increase residents' willingness to participate in e-waste recycling, which in turn increases their recycling rate.

Therefore, this study proposes hypothesis **H6: under the premise that the general situation of residents is basically unchanged, as well as based on theoretical models 1, 2, and 3, residents will adopt relevant incentives by solving the problems caused by the obstacle factors of e-waste recycling, so as to promote the residents' willingness to recycle e-waste to intervene in the residents' behaviors, and to promote the sustainable development of e-waste recycling.** In summary, this study constructs the following theoretical model 6 based on hypothesis H6, at the level of structural path, residents' e-waste recycling behavior will be affected by incentives and obstacle factors to adjust residents' willingness to intervene in residents' e-waste recycling behavior to promote the sustainable development of residents' e-waste recycling behavior in solving e-waste recycling problems, if the standardized coefficient of the path is greater than 0, and the significance test analysis ($P< 0.05$) is passed, then the hypothesis is valid.

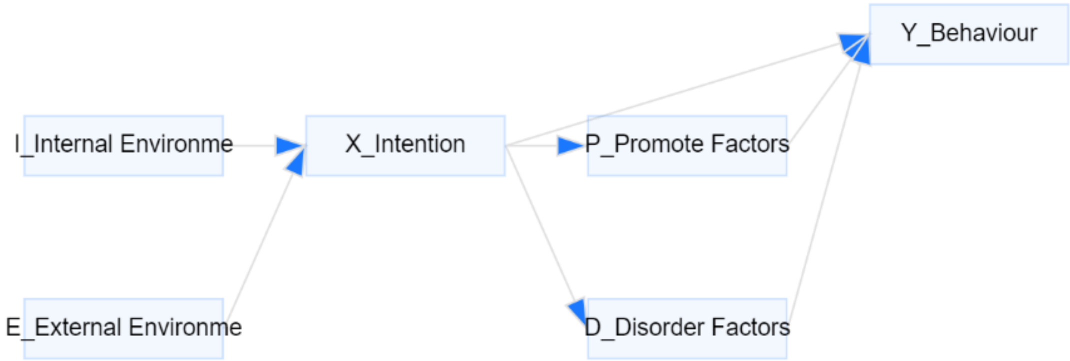

Figure 3.8 – Theoretical model 6 based on hypothesis H6

Source: prepared by the author

Empirical results and discussion

Regression of behavioral attitudes towards e-waste recycling

(1) Reliability and validity test: the results of the reliability and validity test of the questionnaire in model 1 in this study: 1) Normalized Cronbach's alpha coefficient=0.93, then it shows that the data of this questionnaire meets the reliability standard of model 1; 2) KMO=0.93, P=0.00***, then it shows that the structural equation analysis of the data of the questionnaire of model 1 is valid.

Table 3.9 – The results of the reliability and validity test in model 1

Cronbach's α coefficient	Normalized Cronbach's α coefficient	Index	N
0.90	0.93	12	500
KMO			0.93
Bartlett Sphelicity test		Approximate chi square	4409.07
		df	66
		P	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.			

Source: prepared by the author

(2) Analysis of factor loading coefficients: as shown below, the anomalies of the factor loading coefficients of residents' attitudes toward e-waste recycling behaviors in Model 1 are shown in Table 3.10: 1) In the factor loading coefficients of residents' general situation, B2:Age and B5:Income are -0.18 and -0.19, respectively, which indicates that the residents' ages and incomes are more different, which negatively affects the control variables of Model 1 which may affect the direction of residents' e-waste recycling behavior; 2) In the factor loading coefficients of residents' e-waste recycling attitudes, each latent variable positively affects residents' e-waste recycling attitudes, and the Standard load coefficient of the latent variable (X7:Governmental Responsibility) is = 0.15, which positively affects residents' e-waste recycling attitudes. 0.15, contributing the least to residents' e-waste recycling attitudes, which indicates that all 500 respondents believe that governmental responsibility has a stable influence on residents' e-waste recycling attitudes; 3) In the factor loading coefficients of residents' e-waste recycling behaviors, all latent variables have a positive influence on residents' e-waste recycling behaviors, and the Standard load coefficient for the latent variable (Y3:Social Publicity and Education) has a Standard load coefficient=0.44, which contributes the least to residents' e-waste recycling behavior, which indicates that there is still a need to strengthen publicity and education within the society to promote the process of residents' e-waste recycling.

Table 3.10 – The results of factor loading coefficient analysis in model 1

Index	Variables	Non-standard load coefficient	Standard load coefficient	z	S.E.	P
B_Base Situation	B1:Gender	1.00	0.08	-	-	-
	B2:Age	-3.31	-0.18	-1.59	2.08	0.11
	B3: Education	2.62	0.16	1.55	1.69	0.12
	B4: Occupation	13.22	0.17	1.56	8.45	0.12
	B5: Income	-5.84	-0.19	-1.61	3.64	0.11
X_Intention	X1: consciousness	1.00	0.81	-	-	-
	X2:Values	1.00	0.77	19.79	0.05	0.00***
	X3:Common Sense	1.06	0.88	24.15	0.04	0.00***

	X4:Specialty	1.03	0.85	22.63	0.05	0.00***
	X5: Social Responsibility	1.07	0.90	25.04	0.04	0.00***
	X6: Civil Obligation	1.04	0.86	23.04	0.05	0.00***
	X7: Governmental Responsibility	0.35	0.15	3.25	0.11	0.00***
Y_Behaviour	Y1: Personal Recycling	1.00	0.74	-	-	0.00***
	Y2:Circle Promotion	1.02	0.86	19.94	0.05	0.00***
	Y3: Social Publicity and Education	0.83	0.44	9.63	0.09	0.00***
	Y4: Institutional Recycling	1.09	0.79	18.26	0.06	0.00***
	Y5: Market Contracting Recovery	1.07	0.84	19.47	0.06	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.						

Source: prepared by the author

(3) Model path coefficient analysis: as shown in Table 3.11, the trend of the model path coefficients of Model 1's attitudes toward residents' e-waste recycling behaviors is as follows: 1) the general situation of residents does not have a significant impact on residents' e-waste recycling behaviors (Standard coefficient=2.20, P=0.25), which suggests that with the control variables, residents' e-waste recycling behaviors are development is more fixed; 2) residents' e-waste recycling attitude has a significant positive effect on residents' e-waste recycling behavior (Standard coefficient=3.03, P=0.037**), which indicates that residents' e-waste recycling attitude has a significant direct effect on recycling behavior.

Table 3.11 – The results of model path coefficient analysis in model 1

Factor (Subactive variable)	→	Analysis items (explicit variables)	Non-standard coefficient	Standard coefficient	SEx	Z	P
B_Base Situation	→	Y_Behaviour	40.42	2.20	35.09	1.15	0.25
X_Intention	→	Y_Behaviour	3.16	3.03	1.52	2.08	0.037**
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.							

Source: prepared by the author

(4) Analysis of model fitting effect: as shown in Table 3.12, the fitting effect of model 1 is better, and the fitting effect of model path coefficients is significant (χ^2=4461.31, P=0.00***), which indicates that the empirical results of structural equations of model 1 are valid, and the prediction of model path coefficients is more in line with reality.

Table 3.12 – The results of model fitting effect analysis in model 1

χ^2	df	P
-	-	>0.05
4461.31	928	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(5) Summary analysis of Model 1: Based on the above analysis, the hypothesis H1 of this study about Model 1 is valid, i.e., under the premise that the general situation of the residents is basically unchanged, the residents' willingness to recycle e-waste will have a direct impact on the residents' e-waste recycling behavior. Moreover, personal consciousness and values, social responsibility, and government obligations determine the attitude of residents' e-waste recycling, which will have a direct impact on e-waste recycling behavior.

Endogenous regulation of behavioral attitudes towards e-waste recycling

(1) Reliability and validity test: the results of the reliability and validity test of the questionnaire of model 2 of this study: 1) Normalized Cronbach's alpha coefficient=0.94, then it shows that the data of this questionnaire meets the reliability standard of model 2; 2) KMO=0.93, P=0.00***, then it shows that the structural equation analysis of the data of the questionnaire of model 2 is valid.

Table 3.13 – The results of the reliability and validity test in model 2

Cronbach's αcoefficient	Normalized Cronbach's α coefficient	Index	N
0.92	0.94	17	500
KMO			0.93
Bartlett Sphelicity test		Approximate chi square	6759.67
		df	136
		P	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.			

Source: prepared by the author

(2) Analysis of factor loading coefficients: as shown in Table 3.14, based on the factor loading coefficients of model 1, the abnormalities of the factor loading coefficients of the residents' attitudes towards e-waste recycling behaviors of model 2 are as follows: 1) In the factor loading coefficients of the residents' general situation, B2:Age and B5:Income are -0.01 and -0.26, respectively, which indicates that the residents' age and income have large differences, which may negatively affect the development direction of the control variables of model 2's control variables, which may affect the direction of residents' e-waste recycling behavior; 2) In the factor loading coefficients of residents' e-waste recycling attitudes, each latent variable positively affects residents' e-waste recycling attitudes, and the latent variable (X7:Governmental Responsibility) has a Standard load coefficient=0.15, contributing the least to residents' e-waste recycling attitudes, which indicates that all 500 respondents believe that governmental responsibility has a stable influence on residents' e-waste recycling attitudes; 3) In the factor loading coefficient of residents' e-waste recycling behaviors, each latent variable has a positive influence on residents' e-waste recycling behaviors, and the latent variable (Y3:Social Publicity and Education) has a Standard load coefficient=0.44, which contributes the least to residents' e-waste recycling behavior, which indicates that there is still a need to strengthen publicity and education within the society to promote the process

of residents' e-waste recycling; 4) In the factor load coefficients of the internal environment of residents' e-waste recycling, all the latent variables have a positive effect on residents' e-waste recycling behavior, and the Standard load coefficient of the latent variable (I1:Attention) = 0.89, P>0.05, which contributes insignificantly to residents' e-waste recycling behaviors, which suggests that Attention does not have a significant effect on the internal subjective consciousness of residents' e-waste recycling.

Table 3.14 – The results of factor loading coefficient analysis in model 2

Index	Variables	Non-standard load coefficient	Standard load coefficient	z	S.E.	P
B_Base Situation	B1:Gender	1.00	0.07	-	-	-
	B2:Age	-0.19	-0.01	-0.21	0.90	0.83
	B3: Education	8.80	0.48	1.56	5.64	0.12
	B4: Occupation	88.50	1.00	1.52	58.42	0.13
	B5: Income	-8.75	-0.26	-1.52	5.75	0.13
X_Intention	X1: consciousness	1.00	0.81	-	-	-
	X2:Values	1.00	0.77	19.79	0.05	0.00***
	X3:Common Sense	1.06	0.88	24.03	0.04	0.00***
	X4:Specialty	1.04	0.85	22.60	0.05	0.00***
	X5: Social Responsibility	1.08	0.90	24.95	0.04	0.00***
	X6: Civil Obligation	1.04	0.86	23.02	0.05	0.00***
	X7: Governmental Responsibility	0.36	0.15	3.29	0.11	0.00***
Y_Behaviour	Y1: Personal Recycling	1.00	0.74	-	-	-
	Y2:Circle Promotion	1.02	0.86	20.02	0.05	0.00***
	Y3: Social Publicity and Education	0.83	0.44	9.67	0.09	0.00***
	Y4: Institutional Recycling	1.09	0.79	18.27	0.06	0.00***
	Y5: Market Contracting Recovery	1.07	0.84	19.42	0.06	0.00***
I_Internal Environme	I1:Attention	1.00	0.89	-	-	-
	I2:Trust	0.93	0.81	23.77	0.04	0.00***
	I3: Cooperation	0.69	0.42	9.73	0.07	0.00***
	I4: Expectation	0.61	0.36	8.22	0.07	0.00***
	I5: Excitation	0.86	0.77	21.99	0.04	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.						

Source: prepared by the author

(3) Model path coefficient analysis: as shown in Table 3.15, the trend of the model path coefficients of Model 2's attitudes toward residents' e-waste recycling behavior is as follows: 1) the general situation of residents does not have a significant effect on residents' e-waste recycling behavior (Standard coefficient=-0.87, P=0.11), which suggests that with the control variables, residents' e-waste recycling behavior development is more negative; 2) Residents' e-waste recycling attitude has a significant positive effect on residents' e-waste recycling behavior (Standard coefficient=0.16, P=0.00***), which indicates that residents' e-waste recycling attitude has a significant direct effect on recycling behavior under the regulation of the intrinsic environment; 3) the intrinsic environment of residents' e-waste recycling has a significant positive effect on residents' e-waste recycling attitudes (Standard coefficient=0.80, P=0.00***), which indicates that changes in the factors of the inner environment will positively affect the development of residents' e-waste recycling attitudes.

Table 3.15 – The results of model path coefficient analysis in model 2

Factor (Subactive variable)	→	Analysis items (explicit variables)	Non-standard coefficient	Standard coefficient	SEx	Z	P
B_Base Situation	→	Y_Behaviour	-16.77	-0.87	10.62	-1.58	0.11
X_Intention	→	Y_Behaviour	0.17	0.16	0.05	3.49	0.00***
I_Internal Environme	→	X_Intention	0.70	0.80	0.04	18.00	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.							

Source: prepared by the author

(4) Analysis of model fitting effect: as shown in Table 3.16, the fitting effect of model 2 is better and the fitting effect of model path coefficients is significant

(χ^2=4311.82, P=0.00***), which indicates that the empirical results of structural equations of model 2 are valid and the prediction of model path coefficients is more in line with reality.

Table 3.16 – The results of model fitting effect analysis in model 2

χ^2	df	P
-	-	>0.05
4311.82	927	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(5) Summary analysis of Model 2: Based on the above analysis, the hypothesis H2 of this study on Model 2 is valid, i.e., under the premise that the general situation of the residents is basically unchanged, as well as based on theoretical model 1, the residents' willingness to recycle e-waste will be affected by the changes in the inner environment, which adjusts the residents' e-waste recycling behavior. Moreover, changes in the internal environment mainly change residents' personal consciousness, values, common sense and enhance the sense of social responsibility, thus indirectly affecting e-waste recycling behavior.

External environment of behavioral attitudes towards e-waste recycling

(1) Reliability and validity test: the results of the reliability and validity test of the questionnaire of model 3 in this study: 1) Normalized Cronbach's alpha coefficient=0.95, then it shows that the data of this questionnaire meets the reliability standard of model 3; 2) KMO=0.95, P=0.00***, then it shows that the structural equation analysis of the questionnaire data of model 3 is valid.

Table 3.17 – The results of the reliability and validity test in model 3

Cronbach's αcoefficient	Normalized Cronbach's α coefficient	Index	N
0.94	0.95	17	500

KMO		0.95
Bartlett Sphelicity test	Approximate chi square	7485.22
	df	136
	P	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(2) Analysis of factor loading coefficients: as shown in Table 3.18, based on the factor loading coefficients of Model 1, the abnormalities of the factor loading coefficients of the residents' attitudes towards e-waste recycling behaviors of Model 3 are as follows: 1) In the factor loading coefficients of the residents' general situation, B2:Age and B5:Income are -0.01 and -0.26, respectively, which indicates that the residents' age and income have greater differences, which may negatively affect the development direction of the control variables of Model 2's control variables, which may affect the direction of residents' e-waste recycling behavior; 2) In the factor loading coefficients of residents' e-waste recycling attitudes, each latent variable positively affects residents' e-waste recycling attitudes, and the latent variable (X7:Governmental Responsibility) has a Standard load coefficient=0.15, contributing the least to residents' e-waste recycling attitudes, which indicates that all 500 respondents believe that governmental responsibility has a stable influence on residents' e-waste recycling attitudes; 3) In the factor loading coefficient of residents' e-waste recycling behaviors, each latent variable has a positive influence on residents' e-waste recycling behaviors, and the latent variable (Y3:Social Publicity and Education) has a Standard load coefficient=0.44, which contributes the least to residents' e-waste recycling behavior, which indicates that there is still a need to strengthen publicity and education within the society to promote the process of residents' e-waste recycling; 4) In the factor load coefficients of the external environment of residents' e-waste recycling, each of the latent variables has a positive effect on residents' e-waste recycling behavior. latent variables all positively affect the external environment of residents' e-waste recycling, and the Standard load coefficient of the latent variable (E1: Bylaw) = 0.87, P>0.05, which

contributes insignificantly to residents' e-waste recycling behaviors, which suggests that the construction of laws and regulations does not have a significant impact on the external resources of residents' e-waste recycling.

Table 3.18 – The results of factor loading coefficient analysis in model 3

Index	Variables	Non-standard load coefficient	Standard load coefficient	z	S.E.	P
B_Base Situation	B1: Gender	1.00	0.07	-	-	-
	B2: Age	-0.19	-0.01	-0.21	0.90	0.83
	B3: Education	8.80	0.48	1.56	5.64	0.12
	B4: Occupation	88.50	1.00	1.52	58.42	0.13
	B5: Income	-8.75	-0.26	-1.52	5.75	0.13
X_Intention	X1: consciousness	1.00	0.81	-	-	-
	X2: Values	1.00	0.77	19.79	0.05	0.00***
	X3: Common Sense	1.06	0.88	24.03	0.04	0.00***
	X4: Specialty	1.04	0.85	22.60	0.05	0.00***
	X5: Social Responsibility	1.08	0.90	24.95	0.04	0.00***
	X6: Civil Obligation	1.04	0.86	23.02	0.05	0.00***
	X7: Governmental Responsibility	0.36	0.15	3.29	0.11	0.00***
Y_Behaviour	Y1: Personal Recycling	1.00	0.74	-	-	-
	Y2: Circle Promotion	1.02	0.86	20.02	0.05	0.00***
	Y3: Social Publicity and Education	0.83	0.44	9.67	0.09	0.00***
	Y4: Institutional Recycling	1.09	0.79	18.27	0.06	0.00***
	Y5: Market Contracting Recovery	1.07	0.84	19.42	0.06	0.00***
E_External Environme	E1: Bylaw	1.00	0.87	-	-	-
	E2: Cultural Atmosphere	1.04	0.88	27.78	0.04	0.00***
	E3: Infrastructure	1.09	0.94	31.90	0.03	0.00***
	E4: Publicity and Education	1.04	0.86	26.56	0.04	0.00***
	E5: Technical Innovation	1.03	0.89	28.82	0.04	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.						

Source: prepared by the author

(3) Model path coefficient analysis: as shown in Table 3.19, the trend of the model path coefficients of Model 3's attitudes toward residents' e-waste recycling behavior is as follows: 1) the general situation of residents has a non-significant impact on residents' e-waste recycling behavior (Standard coefficient=-0.77,

P=0.12), which suggests that, with the control variables, residents' e-waste recycling behavior development is more negative; 2) Residents' e-waste recycling attitude has a significant positive effect on residents' e-waste recycling behavior (Standard coefficient=0.33, P=0.00***), which suggests that residents' e-waste recycling attitude has a significant direct effect on recycling behavior under the regulation of the external environment; 3) Residents' e-waste recycling external environment has a significant positive effect on residents' e-waste recycling attitudes (Standard coefficient=0.75, P=0.00***), which indicates that changes in the factors of the external environment will positively affect the development of residents' e-waste recycling attitudes.

Table 3.19 – The results of model path coefficient analysis in model 3

Factor (Subactive variable)	→	Analysis items (explicit variables)	Non-standard coefficient	Standard coefficient	SEx	Z	P
B_Base Situation	→	Y_Behaviour	-14.48	-0.77	9.23	-1.57	0.12
X_Intention	→	Y_Behaviour	0.34	0.33	0.04	8.12	0.00***
E_External Environme	→	X_Intention	0.69	0.75	0.04	17.01	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.							

Source: prepared by the author

(4) Analysis of model fitting effect: as shown in Table 3.20, the fitting effect of model 3 is better and the fitting effect of model path coefficients is significant (χ^2=4417.68, P=0.00***), which indicates that the empirical results of structural equations of model 3 are valid and the prediction of model path coefficients is more in line with reality.

Table 3.20 – The results of model fitting effect analysis in model 3

χ^2	df	P
-	-	>0.05

4417.68	927	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(5) Summary analysis of Model 3: Based on the above analysis, this study's hypothesis H3 about Model 3 holds, that is, under the premise that the general situation of the residents is basically unchanged, as well as based on Theoretical Model 1, the residents' willingness to recycle e-waste will be affected by changes in the external environment, so as to adjust the residents' behavior of e-waste recycling. Moreover, changes in the external environment mainly change the technological basis, cultural atmosphere, and infrastructure construction of residents' e-waste recycling, thus indirectly affecting e-waste recycling behavior.

Motivational interventions for e-waste recycling behavioral attitudes

(1) Reliability and validity test: the results of the reliability and validity test of the questionnaire of model 4 of this study: 1) Normalized Cronbach's alpha coefficient=0.92, then it shows that the data of this questionnaire meets the reliability standard of model 4; 2) KMO=0.93, P=0.00***, then it shows that the structural equation analysis of the data of the questionnaire of model 4 is valid.

Table 3.21 – The results of the reliability and validity test in model 4

Cronbach's αcoefficient	Normalized Cronbach's α coefficient	Index	N
0.82	0.92	31	500
KMO			0.93
Bartlett Sphelicity test		Approximate chi square	12178.07
		df	465
		P	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.			

Source: prepared by the author

(2) Analysis of factor loading coefficients: as shown in Table 3.22, based on the factor loading coefficients of Models 1, 2, 3, the anomalies of the factor loading coefficients of the residents' attitudes towards e-waste recycling behavior of Model 4 are as follows: 1) In the factor loading coefficients of the residents' general situation, B2:Age and B5:Income are -0.01 and -0.26, respectively, which indicates that the differences in the residents' ages and incomes are large, which negatively affects the control variables of Model 2 and may influence the direction of residents' e-waste recycling behavior; 2) In the factor loading coefficients of residents' e-waste recycling attitudes, each latent variable positively affects residents' e-waste recycling attitudes, and the latent variable (X7:Governmental Responsibility) has a Standard load coefficient=0.15, contributing the least to residents' e-waste recycling attitudes, which indicates that all 500 respondents believe that governmental responsibility has a stable influence on residents' e-waste recycling attitudes; 3) In the factor loading coefficients of residents' e-waste recycling behaviors, each latent variable has a positive influence on residents' e-waste recycling behaviors, and the latent variable (Y3:Social Publicity and Education) has a Standard load coefficient=0.44, which contributes the least to residents' e-waste recycling behavior, which indicates that there is still a need to strengthen publicity and education within the society to promote the process of residents' e-waste recycling; 4) In the factor load coefficients of internal environment of residents' e-waste recycling, each latent factor loading coefficients, each latent variable positively affects the internal environment of residents' e-waste recycling, and the Standard loading coefficient of the latent variable (I1:Attention) = 0.89, $P>0.05$, which does not significantly contribute to residents' e-waste recycling behaviors, indicating that precautions do not have a significant effect on residents' internal subjective e-waste recycling awareness; 5) In the factor loading coefficients of the external environment of residents' e-waste recycling, each latent variable positively affects the external environment of residents' e-waste recycling, and the Standard loading coefficient of the latent variable (E1:Bylaw) is 0.87, $P>0.05$, which is not significant on residents' e-waste recycling behavior, which indicates that the construction of laws and

regulations has a significant influence on residents' e-waste recycling behavior, which suggests that the construction of laws and regulations has a significant influence on residents' e-waste recycling behavior. significant, which indicates that the construction of laws and regulations does not have a significant impact on the external resources of residential e-waste recycling; 6) In the factor loading coefficients of the incentives for residential e-waste recycling, each latent variable has a positive impact on the incentives for residential e-waste recycling, and the Standard load coefficient of the latent variable (P1:Promote Measure) = 0.24, p>0.05, which contributes to the behavior of residential e-waste recycling. coefficient=0.24, P>0.05, the intervention effect on residents' e-waste recycling behavior is not significant, which indicates that incentives such as publicity and education do not have a significant intervention effect on residents' e-waste recycling behavior.

Table 3.22 – The results of factor loading coefficient analysis in model 4

Index	Variables	Non-standard load coefficient	Standard load coefficient	z	S.E.	P
B_Base Situation	B1: Gender	1.00	0.07	-	-	-
	B2: Age	-0.19	-0.01	-0.21	0.90	0.83
	B3: Education	8.80	0.48	1.56	5.64	0.12
	B4: Occupation	88.50	1.00	1.52	58.42	0.13
	B5: Income	-8.75	-0.26	-1.52	5.75	0.13
X_Intention	X1: consciousness	1.00	0.81	-	-	-
	X2: Values	1.00	0.77	19.79	0.05	0.00***
	X3: Common Sense	1.06	0.88	24.03	0.04	0.00***
	X4: Specialty	1.04	0.85	22.60	0.05	0.00***
	X5: Social Responsibility	1.08	0.90	24.95	0.04	0.00***
	X6: Civil Obligation	1.04	0.86	23.02	0.05	0.00***
	X7: Governmental Responsibility	0.36	0.15	3.29	0.11	0.00***
Y_Behaviour	Y1: Personal Recycling	1.00	0.74	-	-	-
	Y2: Circle Promotion	1.02	0.86	20.02	0.05	0.00***
	Y3: Social Publicity and Education	0.83	0.44	9.67	0.09	0.00***
	Y4: Institutional Recycling	1.09	0.79	18.27	0.06	0.00***
	Y5: Market Contracting Recovery	1.07	0.84	19.42	0.06	0.00***

I_Internal Environme	I1: Attention	1.00	0.89	-	-	-
	I2: Trust	0.93	0.81	23.77	0.04	0.00***
	I3: Cooperation	0.69	0.42	9.73	0.07	0.00***
	I4: Expectation	0.61	0.36	8.22	0.07	0.00***
	I5: Excitation	0.86	0.77	21.99	0.04	0.00***
E_External Environme	E1: Bylaw	1.00	0.87	-	-	-
	E2: Cultural Atmosphere	1.04	0.88	27.78	0.04	0.00***
	E3: Infrastructure	1.09	0.94	31.90	0.03	0.00***
	E4: Publicity and Education	1.04	0.86	26.56	0.04	0.00***
	E5: Technical Innovation	1.03	0.89	28.82	0.04	0.00***
P_Promote Factors	P1: Promote Measure	1.00	0.24	-	-	-
	P2: Promote Measure	1.71	0.37	4.53	0.38	0.00***
	P3: Promote Measure	1.84	0.52	4.96	0.37	0.00***
	P4: Promote Measure	2.85	0.65	5.14	0.55	0.00***
	P5: Promote Measure	2.90	0.66	5.15	0.56	0.00***
	P6: Promote Measure	4.19	0.80	5.27	0.80	0.00***
	P7: Promote Measure	4.40	0.83	5.29	0.83	0.00***
	P8: Promote Measure	5.08	0.84	5.29	0.96	0.00***
	P9: Promote Measure	1.57	0.23	3.66	0.43	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.						

Source: prepared by the author

(3) Model path coefficient analysis: as shown in Table 3.23, the trend of the model path coefficients of the attitudes of residents' e-waste recycling behaviors in Model 4 is as follows: 1) the general situation of residents has a non-significant impact on residents' e-waste recycling behaviors (Standard coefficient=-0.86, P=0.075), which indicates that, with the control variables, the residents' e-waste recycling behavior is more negative; 2) Residents' e-waste recycling attitude has a significant positive effect on residents' e-waste recycling behavior (Standard coefficient=0.18, P=0.001***), which suggests that residents' e-waste recycling attitude has a significant positive effect on recycling behavior under the regulation of the internal and external environments and the intervention of incentives; and 3) The intrinsic environment of residents' e-waste recycling has a significant positive effect on residents' e-waste recycling attitudes (Standard coefficient=0.05, P=0.037**), which indicates that residents are affected by incentives to change intrinsic subjective behavioral intentions, which positively affects residents' attitudes toward e-waste recycling.4) The extrinsic environment of residents' e-

waste recycling has a significant positive effect on the residents' e-waste recycling attitude is not significant (Standard coefficient=0.06, P=0.57), which indicates that it is mainly difficult for incentives to change the external environment, which does not have a significant effect on residents' e-waste recycling attitude. 5) The effect of residents' e-waste recycling attitude on incentives is not significant (Standard coefficient=-0.07, P=0.15), which indicates that residents' e-waste recycling attitudes are not significantly affected by incentives.

Table 3.23 – The results of model path coefficient analysis in model 4

Factor (Subactive variable)	→	Analysis items (explicit variables)	Non-standard coefficient	Standard coefficient	SEx	Z	P
B_Base Situation	→	Y_Behaviour	-14.69	-0.86	8.26	-1.78	0.075*
X_Intention	→	Y_Behaviour	0.19	0.18	0.06	3.47	0.001***
P_Promote Factors	→	Y_Behaviour	0.07	0.05	0.03	2.08	0.037**
I_Internal Environme	→	X_Intention	0.65	0.74	0.10	6.21	0.00***
E_External Environme	→	X_Intention	0.06	0.06	0.10	0.57	0.57
X_Intention	→	P_Promote Factors	-0.06	-0.07	0.04	-1.45	0.15
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.							

Source: prepared by the author

(4) Analysis of model fitting effect: as shown in Table 3.24, the fitting effect of model 4 is better, and the fitting effect of model path coefficient is significant (χ^2=4304.31, P=0.00***), which indicates that the empirical results of structural equations of model 4 are valid, and the prediction of model path coefficients is more in line with reality.

Table 3.24 – The results of model fitting effect analysis in model 4

χ^2	df	P
-	-	>0.05
4304.31	925.00	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(5) Summary analysis of Model 4: Based on the above analysis, the hypothesis H4 of this study about Model 4 holds, that is, under the premise that the general situation of the residents is basically unchanged, as well as based on theoretical Models 1, 2, and 3, the incentives for residents' e-waste recycling will intervene in the residents' behavior by adjusting the residents' intention to recycle their e-waste, and will promote the sustainable development of e-waste recycling. Moreover, under the joint regulation of the internal and external environment, incentives such as publicity and education, reward and punishment system, and material rewards influence residents' behavioral intention of e-waste recycling to a certain extent, thus positively intervening in the sustainable development of e-waste recycling behavior.

Barriers to behavioral attitudes towards e-waste recycling

(1) Reliability and validity test: the results of the reliability and validity test of the questionnaire of model 5 in this study: 1) Normalized Cronbach's alpha coefficient=0.92, then it shows that the data of this questionnaire meets the reliability standard of model 5; 2) KMO=0.94, P=0.00***, then it shows that the structural equation analysis of the data of the questionnaire of model 5 is valid.

Table 3.25 – The results of the reliability and validity test in model 5

Cronbach's αcoefficient	Normalized Cronbach's α coefficient	Index	N
0.81	0.92	31	500
KMO			0.94

Bartlett Sphelicity test	Approximate chi square	11825.87
	df	465
	P	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(2) Analysis of factor loading coefficients: as shown in Table 3.26, based on the factor loading coefficients of Models 1, 2 and 3, the abnormalities of the factor loading coefficients of the residents' attitudes towards e-waste recycling behavior of Model 5 are as follows: 1) In the factor loading coefficients of the residents' general situation, B2:Age and B5:Income are -0.01 and -0.26, respectively, which indicates that the residents' age and income have large differences and negatively affect the control variables of Model 2, which may influence the direction of residents' e-waste recycling behavior; 2) In the factor loading coefficients of residents' e-waste recycling attitudes, each latent variable positively affects residents' e-waste recycling attitudes, and the latent variable (X7:Governmental Responsibility) has a Standard load coefficient=0.15, which contributes the least to residents' e-waste recycling attitudes, indicating that all 500 respondents believe that governmental responsibility has a stable influence on residents' e-waste recycling attitudes; 3) In the factor load coefficients of residents' e-waste recycling behaviors, each latent variable has a positive influence on residents' e-waste recycling behaviors, and the Stability coefficient of the latent variable (Y3: Social Publicity and Education) has a positive influence on residents' e-waste recycling behaviors. Social Publicity and Education) has a Standard load coefficient=0.44, which contributes the least to residents' e-waste recycling behavior, which indicates that there is still a need to strengthen publicity and education within the society to promote the process of residents' e-waste recycling; 4) In the factor loading coefficients of the internal environment of residents' e-waste recycling, all the latent variables have a positive effect on residents' e-waste recycling behavior. coefficients, each latent variable positively affects the internal environment of residents' e-waste recycling, and the

Standard load coefficient of the latent variable (I1: Attention) = 0.89, P>0.05, which does not significantly contribute to residents' e-waste recycling behaviors, which suggests that Attention does not have a significant impact on residents' internal subjective consciousness of e-waste recycling. significant influence; 5) In the factor loading coefficients of the external environment of residents' e-waste recycling, each latent variable positively influences the external environment of residents' e-waste recycling, and the Standard load coefficient of the latent variable (E1:Bylaw) = 0.87, P>0.05, contributes insignificantly to residents' e-waste recycling behavior, which indicates that the construction of laws and regulations does not have a significant impact on the external resources of residential e-waste recycling; 6) In the factor loading coefficients of the obstacles to residential e-waste recycling, each latent variable has a positive impact on the obstacles to residential e-waste recycling, and the Standard load coefficient of the latent variable (D1:Disorder Factor)= 0.21, P>0.05, is not significant in intervening on the barrier to residential e-waste recycling behavior, which indicates that issues such as punishment and supervision do not have a significant effect on intervening on residential e-waste recycling behavior.

Table 3.26 – The results of factor loading coefficient analysis in model 5

Index	Variables	Non-standard load coefficient	Standard load coefficient	z	S.E.	P
B_Base Situation	B1: Gender	1.00	0.07	-	-	-
	B2: Age	-0.19	-0.01	-0.21	0.90	0.83
	B3: Education	8.80	0.48	1.56	5.64	0.12
	B4: Occupation	88.50	1.00	1.52	58.42	0.13
	B5: Income	-8.75	-0.26	-1.52	5.75	0.13
X_Intention	X1: consciousness	1.00	0.81	-	-	-
	X2: Values	1.00	0.77	19.79	0.05	0.00***
	X3: Common Sense	1.06	0.88	24.03	0.04	0.00***
	X4: Specialty	1.04	0.85	22.60	0.05	0.00***
	X5: Social Responsibility	1.08	0.90	24.95	0.04	0.00***
	X6: Civil Obligation	1.04	0.86	23.02	0.05	0.00***
	X7: Governmental Responsibility	0.36	0.15	3.29	0.11	0.00***
Y_Behaviour	Y1: Personal Recycling	1.00	0.74	-	-	-

	Y2: Circle Promotion	1.02	0.86	20.02	0.05	0.00***
	Y3: Social Publicity and Education	0.83	0.44	9.67	0.09	0.00***
	Y4: Institutional Recycling	1.09	0.79	18.27	0.06	0.00***
	Y5: Market Contracting Recovery	1.07	0.84	19.42	0.06	0.00***
I_Internal Environme	I1: Attention	1.00	0.89	-	-	-
	I2: Trust	0.93	0.81	23.77	0.04	0.00***
	I3: Cooperation	0.69	0.42	9.73	0.07	0.00***
	I4: Expectation	0.61	0.36	8.22	0.07	0.00***
	I5: Excitation	0.86	0.77	21.99	0.04	0.00***
E_External Environme	E1: Bylaw	1.00	0.87	-	-	-
	E2: Cultural Atmosphere	1.04	0.88	27.78	0.04	0.00***
	E3: Infrastructure	1.09	0.94	31.90	0.03	0.00***
	E4: Publicity and Education	1.04	0.86	26.56	0.04	0.00***
	E5: Technical Innovation	1.03	0.89	28.82	0.04	0.00***
D_Disorder Factors	D1: Disorder Factor	1.00	0.21	-	-	-
	D2: Disorder Factor	1.44	0.36	3.98	0.36	0.00***
	D3: Disorder Factor	2.32	0.46	4.19	0.56	0.00***
	D4: Disorder Factor	3.42	0.67	4.41	0.78	0.00***
	D5: Disorder Factor	3.68	0.70	4.42	0.83	0.00***
	D6: Disorder Factor	4.34	0.78	4.46	0.97	0.00***
	D7: Disorder Factor	5.23	0.84	4.48	1.17	0.00***
	D8: Disorder Factor	5.50	0.78	4.46	1.23	0.00***
	D9: Disorder Factor	1.57	0.20	3.14	0.50	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.						

Source: prepared by the author

(3) Model path coefficient analysis: as shown in Table 3.27, the trend of the model path coefficients of Model 5's attitudes toward residents' e-waste recycling behavior is as follows: 1) the general situation of residents has a non-significant impact on residents' e-waste recycling behavior (Standard coefficient=-0.86, P=0.11), which suggests that with the control variables, residents' e-waste recycling behavior development is more negative; 2) Residents' e-waste recycling attitude has a significant positive effect on residents' e-waste recycling behavior (Standard coefficient=0.18, P=0.001***), which indicates that under the regulation of the internal and external environments and the intervention of incentives, the residents' e-waste recycling attitude has a significant positive effect on the recycling behavior; 3) Residents' The solution of obstacles to e-waste recycling will have a significant

positive effect on residents' e-waste recycling behavior (Standard coefficient=0.01, P=0.009***). This suggests that residents' e-waste behavior must be sustainable in in solving the barrier factors; 4) The inner environment of residents' e-waste recycling has a significant positive effect on residents' e-waste recycling attitudes (Standard coefficient=0.74, P=0.00***), which suggests that residents are motivated to change their intrinsic subjective consciousness after solving the barrier problems, to change the intrinsic subjective behavioral intention, which positively affects residents' e-waste recycling attitudes.4) The positive effect of the external environment of residents' e-waste recycling on residents' e-waste recycling attitudes is insignificant (Standard coefficient=0.06, P=0.57), which suggests that incentives are mainly difficult to change the external environment, and have an (5) The influence of residents' e-waste recycling attitudes on obstacles is significant (Standard coefficient=-0.06, P=0.022**), which indicates that residents' e-waste recycling attitudes are more obviously negatively affected by obstacles.

Table 3.27 – The results of model path coefficient analysis in model 5

Factor (Subactive variable)	→	Analysis items (explicit variables)	Non-standard coefficient	Standard coefficient	SEx	Z	P
B_Base Situation	→	Y_Behaviour	-16.14	-0.86	10.00	-1.61	0.11
X_Intention	→	Y_Behaviour	0.19	0.18	0.06	3.40	0.001***
D_Disorder Factors	→	Y_Behaviour	0.00	0.01	0.03	-0.02	0.009***
I_Internal Environme	→	X_Intention	0.65	0.74	0.10	6.20	0.00***
E_External Environme	→	X_Intention	0.06	0.06	0.10	0.56	0.57
X_Intention	→	D_Disorder Factors	-0.04	-0.06	0.04	-1.23	0.022**

Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.

Source: prepared by the author

(4) Analysis of model fitting effect: as shown in Table 3.28, the fitting effect of model 5 is better, and the fitting effect of model path coefficient is significant (χ^2=4304.32, P=0.00***), which indicates that the empirical results of structural equations of model 5 are valid, and the prediction of model path coefficients is more in line with reality.

Table 3.28 – The results of model fitting effect analysis in model 5

χ^2	df	P
-	-	>0.05
4304.32	925.00	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(5) Summary analysis of Model 5: Based on the above analysis, the hypothesis H5 of this study about Model 5 holds, that is, under the premise that the general situation of the residents is basically unchanged, as well as on the basis of theoretical models 1, 2, and 3, the residents will adjust the residents' willingness to recycle e-waste to intervene in the residents' behaviors and to promote the sustainability of recycling of e-waste by solving the problems caused by the factors of barriers to recycling of e-waste. Moreover, under the joint regulation of internal and external environments, issues such as punishment and supervision measures, system construction, infrastructure construction, and cultural facilities affect residents' behavioral intention of e-waste recycling to a certain extent, thus positively intervening in the sustainable development of e-waste recycling behavior.

Integrated practice of behavioral attitudes towards e-waste recycling

(1) Reliability and validity test: the results of the reliability and validity test of the questionnaire of model 6 in this study: 1) Normalized Cronbach's alpha coefficient=0.90, then it shows that the data of this questionnaire meets the

reliability standard of model 6; 2) KMO=0.93, P=0.00***, then it shows that the structural equation analysis of the data of the questionnaire of model 6 is valid.

Table 3.29 – The results of the reliability and validity test in model 6

Cronbach's αcoefficient	Normalized Cronbach's α coefficient	Index	N
0.87	0.90	45	500
KMO			0.93
Bartlett Sphelicity test		Approximate chi square	15364.67
		df	780
		P	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.			

Source: prepared by the author

(2) Analysis of factor loading coefficients: as shown in Table 3.30, based on the factor loading coefficients of Models 1, 2 and 3, the abnormalities of the factor loading coefficients of the residents' attitudes towards e-waste recycling behavior of Model 6 are as follows: 1) In the factor loading coefficients of the residents' general situation, B2:Age and B5:Income are -0.01 and -0.26, respectively, which indicates that the residents' age and income have large differences and negatively affect the control variables of Model 2, which may influence the direction of residents' e-waste recycling behavior; 2) In the factor loading coefficients of residents' e-waste recycling attitudes, each latent variable positively affects residents' e-waste recycling attitudes, and the latent variable (X7:Governmental Responsibility) has a Standard load coefficient=0.15, which contributes the least to residents' e-waste recycling attitudes, indicating that all 500 respondents believe that governmental responsibility has a stable influence on residents' e-waste recycling attitudes; 3) In the factor load coefficients of residents' e-waste recycling behaviors, each latent variable has a positive influence on residents' e-waste recycling behaviors, and the Stability coefficient of the latent variable (Y3: Social Publicity and Education) has a positive influence on residents' e-waste recycling behaviors. Social Publicity and

Education) has a Standard load coefficient=0.44, which contributes the least to residents' e-waste recycling behavior, which indicates that there is still a need to strengthen publicity and education within the society to promote the process of residents' e-waste recycling; 4) In the factor loading coefficients of the internal environment of residents' e-waste recycling, all the latent variables have a positive effect on residents' e-waste recycling behavior. coefficients, each latent variable positively affects the internal environment of residents' e-waste recycling, and the Standard load coefficient of the latent variable (I1: Attention) = 0.89, P>0.05, which does not significantly contribute to residents' e-waste recycling behaviors, which suggests that Attention does not have a significant impact on residents' internal subjective consciousness of e-waste recycling. significant influence; 5) In the factor loading coefficients of the external environment of residents' e-waste recycling, each latent variable positively influences the external environment of residents' e-waste recycling, and the Standard load coefficient of the latent variable (E1:Bylaw) = 0.87, P>0.05, contributes insignificantly to residents' e-waste recycling behavior, which indicates that the construction of laws and regulations does not have a significant impact on the external resources of residential e-waste recycling; 6) In the factor loading coefficients of the incentives for residential e-waste recycling, each latent variable has a positive impact on the incentives for residential e-waste recycling, and the Standard load coefficient of the latent variable (P1:Promote Measure) = 0.24, P>0.05, which contributes insignificantly to the behavior of residential e-waste recycling. 0.24, P>0.05, the intervention effect on residents' e-waste recycling behavior is not significant, which indicates that incentives such as publicity and education do not have a significant intervention effect on residents' e-waste recycling behavior; 7) In the factor loading coefficients of barriers to residents' e-waste recycling, each latent variable has a positive impact on barriers to residential e-waste recycling, and the latent variable (D1: Disorder Factor) has a positive impact on barriers to residential e-waste recycling. Disorder Factor) has Standard load coefficient=0.21, P>0.05, which is not significant for the intervention of barriers to residential e-waste recycling behavior, which indicates that issues such as punishment and supervision do not have a significant effect on the intervention of residential e-waste recycling behavior.

Table 3.30 – The results of factor loading coefficient analysis in model 6

Index	Variables	Non-standard load coefficient	Standard load coefficient	z	S.E.	P
B_Base Situation	B1: Gender	1.00	0.07	-	-	-
	B2: Age	-0.19	-0.01	-0.21	0.90	0.83
	B3: Education	8.80	0.48	1.56	5.64	0.12
	B4: Occupation	88.50	1.00	1.52	58.42	0.13
	B5: Income	-8.75	-0.26	-1.52	5.75	0.13
X_Intention	X1: consciousness	1.00	0.81	-	-	-
	X2: Values	1.00	0.77	19.79	0.05	0.00***
	X3: Common Sense	1.06	0.88	24.03	0.04	0.00***
	X4: Specialty	1.04	0.85	22.60	0.05	0.00***
	X5: Social Responsibility	1.08	0.90	24.95	0.04	0.00***
	X6: Civil Obligation	1.04	0.86	23.02	0.05	0.00***
	X7: Governmental Responsibility	0.36	0.15	3.29	0.11	0.00***
Y_Behaviour	Y1: Personal Recycling	1.00	0.74	-	-	-
	Y2: Circle Promotion	1.02	0.86	20.02	0.05	0.00***
	Y3: Social Publicity and Education	0.83	0.44	9.67	0.09	0.00***
	Y4: Institutional Recycling	1.09	0.79	18.27	0.06	0.00***
	Y5: Market Contracting Recovery	1.07	0.84	19.42	0.06	0.00***
I_Internal Environme	I1: Attention	1.00	0.89	-	-	-
	I2: Trust	0.93	0.81	23.77	0.04	0.00***
	I3: Cooperation	0.69	0.42	9.73	0.07	0.00***
	I4: Expectation	0.61	0.36	8.22	0.07	0.00***
	I5: Excitation	0.86	0.77	21.99	0.04	0.00***
E_External Environme	E1: Bylaw	1.00	0.87	-	-	-
	E2: Cultural Atmosphere	1.04	0.88	27.78	0.04	0.00***
	E3: Infrastructure	1.09	0.94	31.90	0.03	0.00***
	E4: Publicity and Education	1.04	0.86	26.56	0.04	0.00***
	E5: Technical Innovation	1.03	0.89	28.82	0.04	0.00***
P_Promote Factors	P1: Promote Measure	1.00	0.24	-	-	-
	P2: Promote Measure	1.71	0.37	4.53	0.38	0.00***
	P3: Promote Measure	1.84	0.52	4.96	0.37	0.00***
	P4: Promote Measure	2.85	0.65	5.14	0.55	0.00***
	P5: Promote Measure	2.90	0.66	5.15	0.56	0.00***
	P6: Promote Measure	4.19	0.80	5.27	0.80	0.00***

	P7: Promote Measure	4.40	0.83	5.29	0.83	0.00***
	P8: Promote Measure	5.08	0.84	5.29	0.96	0.00***
	P9: Promote Measure	1.57	0.23	3.66	0.43	0.00***
D_Disorder Factors	D1: Disorder Factor	1.00	0.21	-	-	-
	D2: Disorder Factor	1.44	0.36	3.98	0.36	0.00***
	D3: Disorder Factor	2.32	0.46	4.19	0.56	0.00***
	D4: Disorder Factor	3.42	0.67	4.41	0.78	0.00***
	D5: Disorder Factor	3.68	0.70	4.42	0.83	0.00***
	D6: Disorder Factor	4.34	0.78	4.46	0.97	0.00***
	D7: Disorder Factor	5.23	0.84	4.48	1.17	0.00***
	D8: Disorder Factor	5.50	0.78	4.46	1.23	0.00***
	D9: Disorder Factor	1.57	0.20	3.14	0.50	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.						

Source: prepared by the author

(3) Model path coefficient analysis: as shown in Table 3.31, the trend of the model path coefficients of the attitudes of residents' e-waste recycling behaviors for Model 6 is as follows: 1) the general situation of residents has a non-significant impact on residents' e-waste recycling behaviors (Standard coefficient=-0.85, P=0.11), which indicates that, with the control variables, the residents' e-waste recycling behaviors development is more negative; 2) Residents' e-waste recycling attitude has a significant positive effect on residents' e-waste recycling behavior (Standard coefficient=0.18, P=0.001***), which indicates that under the regulation of the internal and external environment and the intervention of incentives, the residents' e-waste recycling attitude has a significant positive effect on recycling behavior; 3) Residents' incentives for e-waste recycling can have a significant positive effect on residents' e-waste recycling behavior (Standard coefficient=0.02, P=0.004***), which indicates that under the comprehensive practice, incentives for residents' e-waste recycling can positively intervene in residents' e-waste recycling behaviors; 4) barriers to residents' e-waste recycling can have a significant positive effect on residential e-waste recycling behavior has a significant negative effect (Standard coefficient=-0.04, P=0.003***), which suggests that residential e-waste behavior must be sustainable in addressing the barrier factors; 5) the intrinsic environment of residential e-waste recycling has a significant positive effect on the

attitudes of residential e-waste recycling (Standard coefficient=0.74, P=0.00***), which suggests that residents are motivated to change their intrinsic subjective behavioral intention and positively influence their e-waste recycling attitudes after solving the obstacle problem.6) The external environment of residents' e-waste recycling does not have a significant positive influence on residents' e-waste recycling attitudes (Standard coefficient=0.07, P=0.005***), which indicates that under the comprehensive practice, the external environmental conditions change to produce a significant positive effect on residents' e-waste recycling attitudes; 7) residents' e-waste recycling attitudes have a significant effect on incentives (Standard coefficient=-0.06, P= 0.014**), which indicates that residents' e-waste recycling attitudes are significantly affected by the intervention of incentives; 8) residents' e-waste recycling attitudes have a significant effect on obstacles (Standard coefficient=-0.07, P=0.002***), which suggests that residents' e-waste recycling attitudes are more significantly affected by the negative impact of obstacles.

Table 3.31 – The results of factor loading coefficient analysis in model 6

Factor (Subactive variable)	→	Analysis items (explicit variables)	Non-standard coefficient	Standard coefficient	SEx	Z	P
B_Base Situation	→	Y_Behaviour	-16.36	-0.85	10.28	-1.59	0.11
X_Intention	→	Y_Behaviour	0.19	0.18	0.06	3.43	0.001***
P_Promote Factors	→	Y_Behaviour	0.03	0.02	0.03	0.84	0.004***
D_Disorder Factors	→	Y_Behaviour	-0.04	-0.03	0.04	-1.04	0.003***
I_Internal Environme	→	X_Intention	0.64	0.74	0.10	6.18	0.00***
E_External Environme	→	X_Intention	0.06	0.07	0.10	0.59	0.005***
X_Intention	→	P_Promote Factors	-0.06	-0.08	0.04	-1.48	0.014**
X_Intention	→	D_Disorder	-0.05	-0.07	0.04	-1.27	0.002***

		Factors					
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.							

Source: prepared by the author

(4) Analysis of model fitting effect: as shown in Table 3.32, the fitting effect of model 6 is better and the fitting effect of model path coefficients is significant (χ^2=4304.17, P=0.00***), which indicates that the empirical results of structural equations of model 6 are valid and the prediction of model path coefficients is more in line with reality.

Table 3.32 – The results of model fitting effect analysis in model 6

χ^2	df	P
-	-	>0.05
4304.17	924.00	0.00***
Note: * * * *, * * and * represent the significance levels of 1%, 5% and 10%, respectively.		

Source: prepared by the author

(5) Summary analysis of Model 6: Based on the above analysis, the hypothesis H6 of this study on Model 6 holds, that is, under the premise that the general situation of residents is basically unchanged, as well as on the basis of theoretical Models 1, 2, and 3, residents will take relevant incentives by solving the problems caused by obstacles to the recycling of e-waste, so as to promote the willingness of residents to recycle e-waste to intervene in the behavior of residents, and to promote the sustainable development of electronic waste recycling. waste recycling sustainable development. Moreover, under the joint regulation of the internal and external environment, the solution of problems such as punishment and supervision measures, system construction, infrastructure construction, cultural facilities, and the joint intervention of incentives such as publicity and education, reward and punishment system, and material rewards, the behavioral intention of residents to recycle e-waste is influenced to a certain extent, thus positively intervening in the sustainable development of e-waste recycling behavior.

Discussion of results

1. Relational mechanisms of behavioral attitudes towards e-waste recycling

Residents' attitudes toward e-waste recycling positively affect residents' e-waste recycling behavior (Standard coefficient=3.03, P=0.037**). Residents' e-waste recycling attitudes mainly refer to the seven aspects of personal awareness, values, common sense, professional knowledge, social responsibility, legal responsibility, and governmental responsibility regarding e-waste recycling, and residents' recycling behaviors towards e-waste mainly include personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial organizations, and market recycling behaviors, and this study mainly discusses here the aspects of residents' e-waste recycling attitudes under the premise of controlling the variable This study mainly discusses the influence paths of the various aspects of residents' e-waste recycling attitudes on residents' e-waste recycling behavior under the premise of controlling variables.

With the development of science and technology, the quantity of e-waste increases year by year, and the residents' e-waste recycling behavior has attracted widespread attention. Residents' e-waste recycling attitudes and behaviors have an important impact on environmental protection. Therefore, this paper focuses on the influencing factors and paths of residents' e-waste recycling attitudes and behaviors.

First, residents' e-waste recycling attitudes mainly refer to individuals' awareness, values, common sense, professional knowledge, social responsibility, and legal responsibility regarding e-waste recycling. These factors have a significant impact on residents' e-waste recycling behavior. For example, if residents lack awareness of e-waste recycling, they may not realize the impact of e-waste on the environment and may not adopt recycling behaviors. If residents lack the values of e-waste recycling, they may not consider recycling e-waste as their responsibility and may not adopt recycling behaviors. If residents lack common sense in e-waste recycling, they may not know how to dispose of e-waste properly and will not adopt recycling behaviors. If residents lack professional knowledge of e-waste recycling, they may not know how to properly dispose of e-waste and will not adopt recycling behaviors. If residents lack social responsibility for e-waste recycling, they may not consider themselves responsible for recycling e-waste and may not adopt recycling behaviors. If residents lack the legal responsibility to recycle e-waste, they may not know that they have a legal obligation to recycle e-waste and will not adopt recycling behaviors.

Secondly, residents' e-waste recycling behaviors mainly contain personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial organizations and market recycling behaviors. These factors have an important influence on residents' e-waste recycling attitudes. For example, if residents adopt personal recycling behavior, they may pay more attention to the importance of e-waste recycling and adopt recycling behavior more actively. If residents adopt family recycling behaviors, they may pay more attention to the environmental awareness of their family members and take more active family environmental protection measures. If residents have adopted publicity and education behaviors, they may attach more importance to the spread of environmental awareness and will also be more active in publicizing environmental protection knowledge. If residents have adopted the recycling channel of commercial organizations, they may attach more importance to the environmental awareness of commercial organizations, and will also participate more actively in the environmental protection activities of commercial organizations. If residents have adopted the recycling behavior of the market, they may attach more importance to the environmental awareness of the market and participate more actively in the environmental activities of the market.

2. Internal control mechanisms for behavioral attitudes towards e-waste recycling

Under the regulation of the internal environment, residents' attitude toward e-waste recycling positively affects residents' e-waste recycling behavior (Standard coefficient=0.16, P=0.00***). Residents' e-waste recycling attitude mainly refers to the seven major aspects of personal awareness, values, common sense, professional knowledge, social responsibility, legal responsibility, and governmental responsibility regarding e-waste recycling, and residents' recycling behaviors of e-waste mainly contain personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial institutions, and market recycling behaviors. The internal environment mainly refers to the subjective consciousness of residents, which contains personal concern, trust, cooperation, expectation, and incentive for e-waste recycling. This study mainly discusses here the path of influence of various aspects of residents' e-waste recycling attitudes on residents' e-waste recycling behaviors under the premise of controlling variables and the moderating effect of intrinsic environment on residents' e-waste recycling attitudes.

With the continuous development of science and technology, the replacement of electronic products has become more and more rapid, and e-waste has also increased. The disposal of e-waste has become a global problem, and the attitude of residents to e-waste recycling is one of the important factors to solve this problem. Residents' attitudes towards e-waste recycling mainly include seven major aspects, including personal awareness, values, common sense, professional knowledge, social responsibility, legal responsibility, and governmental responsibility regarding e-waste recycling (Shevchenko & Danko, 2023; Qu et al., 2023). The influencing factors of these aspects are multifaceted, including the individual's educational background, social environment, policies, and regulations. Among these aspects, personal consciousness and values are one of the most important factors. Individual awareness and values refer to an individual's perception and attitude towards e-waste recycling. If individuals are aware of the hazards of e-waste to the environment and health, and believe that recycling e-waste is a social responsibility and obligation, then they will participate more actively in e-waste recycling actions. On the contrary, if individuals do not realize the hazards of e-waste or believe that recycling e-waste is unnecessary, then they will have a negative attitude towards e-waste recycling. In addition to personal awareness and values, individuals' professional knowledge and social responsibility will also affect their attitudes towards e-waste recycling. If individuals have the relevant professional knowledge to recognize and handle e-waste properly, then they will participate more actively in e-waste recycling actions. If individuals do not have the relevant professional knowledge or lack a sense of social responsibility, they will have a negative attitude towards e-waste recycling.

In terms of residents' e-waste recycling behaviors, they mainly include personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial organizations, and market recycling behaviors. The influencing factors of these behaviors are also multifaceted, including individual economic status, social environment, policies, and regulations. Individual economic status is one of the important factors affecting individual e-waste recycling behavior. If individuals are in a better economic situation and can afford the cost of recycling e-waste, then they will participate more actively in e-waste recycling actions. On the contrary, if individuals are in a poorer economic situation and cannot afford the cost of recycling e-waste, then they will have a negative attitude towards e-waste recycling. The social environment and policies and regulations also affect individuals' e-waste recycling behavior. If the social environment and policies and regulations can provide convenient recycling channels and corresponding incentives, then individuals will participate in e-waste recycling actions more actively. On the contrary, if the social environment and policies and regulations are not supportive, then individuals will have a negative attitude towards e-waste recycling.

In terms of the internal environment, it mainly refers to the individual's subjective consciousness, including the individual's concern, trust, cooperation, expectation, and motivation towards e-waste recycling. These factors can have an important moderating effect on individuals' attitudes toward e-waste recycling. Individuals' concern for e-waste recycling affects their e-waste recycling behavior. If individuals are highly concerned about e-waste recycling, they will be more active in e-waste recycling actions. On the contrary, if individuals are not concerned about e-waste recycling, then they will have a negative attitude towards e-waste recycling. Individuals' trust in e-waste recycling also affects their e-waste recycling behavior.

If individuals hold trust in recycling channels and disposal methods, then they will participate more actively in e-waste recycling actions. On the contrary, if individuals lack trust in recycling channels and disposal methods, then they will have a negative attitude towards e-waste recycling. The extent to which individuals cooperate with e-waste recycling also affects their e-waste recycling behavior. If individuals can cooperate with others in e-waste recycling actions, then they will participate more actively in e-waste recycling actions. On the contrary, if individuals lack cooperation, then they will have a negative attitude towards e-waste recycling. The extent to which individuals expect e-waste recycling will also affect their e-waste recycling behavior. If individuals expect that recycling e-waste will bring some revenue or social recognition, then they will participate more actively in e-waste recycling actions. On the contrary, if individuals have no expectation of recycling e-waste, then they will have a negative attitude towards e-waste recycling. The extent to which e-waste recycling motivates individuals also affects their e-waste recycling behavior. If individuals are provided with appropriate incentives, such as rewards or honors, then they will be more motivated to participate in e-waste recycling actions. On the contrary, if individuals are not incentivized, they will have a negative attitude towards e-waste recycling.

In summary, residents' e-waste recycling attitude has an important influence on residents' e-waste recycling behavior. Under the premise of controlling variables and the moderating effect of the inner environment on residents' e-waste recycling attitudes, the paths of influence of the various aspects of residents' e-waste recycling attitudes on residents' e-waste recycling behaviors are multifaceted, and the joint efforts of the government, enterprises, and individuals are needed to realize the effective recycling and disposal of e-waste.

3. External environment of behavioral attitudes towards e-waste recycling

Under the regulation of the external environment, residents' attitudes toward e-waste recycling have a positive effect on residents' e-waste recycling behavior (Standard coefficient=0.33, P=0.00***). Residents' e-waste recycling attitude mainly refers to the seven aspects of personal awareness, values, common sense, professional knowledge, social responsibility, legal responsibility, and governmental responsibility regarding e-waste recycling, and residents' e-waste recycling behaviors mainly include personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial institutions, and market recycling behaviors. The external environment mainly refers to external opportunities and resources, including external regulations, cultural atmosphere, infrastructure, publicity and education, and technological innovation for e-waste recycling. This study mainly discusses here the influence paths of various aspects of residents' e-waste recycling attitudes on residents' e-waste recycling behaviors under the premise of controlling variables and the moderating effect of external environment on residents' e-waste recycling attitudes.

First, the government's regulations on e-waste recycling have a positive impact on residents' attitudes towards e-waste recycling. A series of regulations formulated by the government, such as laws, regulations, and policy measures, can effectively regulate residents' e-waste recycling behaviors and raise their awareness of recycling, thus promoting the formation of residents' e-waste recycling attitudes.

Second, the cultural atmosphere also has an impact on residents' attitudes towards e-waste recycling. The cultural atmosphere of a city can influence residents' values and ideologies, thus affecting their attitudes towards e-waste recycling. For example, a city's cultural atmosphere that emphasizes environmental protection can prompt residents to pay more attention to e-waste recycling, thus forming good recycling habits.

Thirdly, infrastructure is also an important factor influencing residents' attitudes towards e-waste recycling. A well-developed e-waste recycling infrastructure can provide residents with convenient recycling channels, thus promoting the formation of residents' e-waste recycling attitudes. For example, the establishment of recycling stations and the provision of convenient recycling tools can increase residents' motivation to recycle.

Fourthly, publicity and education are also important factors affecting residents' attitude towards e-waste recycling. Through publicity and education, the

Government can raise residents' awareness of recycling and make them understand the hazards of e-waste and the importance of recycling, thus forming good recycling habits.

Fifth, technological innovation is also an important factor influencing residents' attitude towards e-waste recycling. With the development of science and technology, more and more new technologies are applied to e-waste recycling, such as intelligent recycling system, robot recycling, etc. These new technologies can improve the recycling efficiency of residents, thus promoting the formation of residents' attitude towards e-waste recycling. To summarize, the influence of external environment on residents' attitude towards e-waste recycling is significant. The government should strengthen the construction of regulations, cultural atmosphere, infrastructure, publicity and education, and technological innovation to promote the formation of residents' e-waste recycling attitude.

4. Incentives for behavioral attitudes towards e-waste recycling

Under the regulation of internal and external environment and the intervention of incentives on residents' e-waste recycling behavior, residents' attitude towards e-waste recycling has a positive effect on residents' e-waste recycling behavior (Standard coefficient=0.05, P=0.037**). Residents' e-waste recycling attitude mainly refers to the seven major aspects of personal awareness, values, common sense, professional knowledge, social responsibility, legal responsibility, and governmental responsibility regarding e-waste recycling, and residents' recycling behaviors towards e-waste mainly contain personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial institutions, and market recycling behaviors. The internal environment mainly refers to the subjective consciousness of the residents, including personal concern, trust, cooperation, expectation, and incentive for e-waste recycling. The external environment mainly refers to external opportunities and resources, including external regulations, cultural atmosphere, infrastructure, publicity and education, and technological innovation for e-waste recycling. The incentives mainly refer to the positive actions taken by the residents towards e-waste recycling behavior, which contains publicity and education, promotion activities, infrastructure, cultural atmosphere, and personnel supervision. This study mainly discusses here the path of influence of various aspects of residents' e-waste recycling attitudes on residents' e-waste recycling behavior under the premise of controlling variables and the moderating effect of internal and external environment on residents' e-waste recycling attitudes.

First, personal recycling behavior is the most basic part of residents' e-waste recycling attitude. If residents are not aware of the hazards of e-waste or the impact of their recycling behavior on the environment, then they will not take active recycling actions. Therefore, publicity and education are very important. The government and social organizations can popularize the knowledge of e-waste among residents through various means to raise their environmental awareness, thus promoting changes in personal recycling behavior.

Second, family recycling behavior is also a non-negligible part of residents' e-waste recycling attitude. Family is the most basic social unit of everyone, and the mutual influence and interaction among family members play an important role in the formation and change of individual recycling behavior. Therefore, family members should encourage and support each other to participate in e-waste recycling actions, to form a favorable atmosphere for family recycling.

Third, publicity and education behavior are an important part of residents' attitude towards e-waste recycling. The government and social organizations can popularize the knowledge of e-waste among residents through various means and raise their environmental awareness, thus promoting changes in personal recycling behavior. For example, e-waste recycling bins can be set up in public places such as communities, schools and shopping malls, and the importance of e-waste recycling can be publicized to residents through publicity and education.

Fourth, the recycling channels of commercial organizations and market recycling behaviors are also important links in residents' attitude towards e-waste recycling. Commercial organizations can improve their sense of social responsibility and image by recycling e-waste, and at the same time provide convenient recycling channels for residents. Market recycling behavior, on the other hand, can improve the utilization rate of resources by recycling e-waste, thus reducing the pollution of the environment. In the intrinsic environment of residents' attitude towards e-waste recycling, factors such as individuals' concern for e-waste recycling, trust, cooperation, expectations, and incentives are very important in influencing individuals' recycling behavior. If residents do not pay much attention to e-waste recycling, or do not have enough trust in recycling channels, then they will not take active recycling actions. Therefore, the government and social organizations can increase residents' concern and trust in e-waste recycling through various means, thus promoting changes in individual recycling behavior. In the external environment of residents' e-waste recycling attitudes, external regulations on e-waste recycling, cultural atmosphere, infrastructure, publicity and education, technological innovation and other factors are also very important in influencing individual recycling behavior. If the government has formulated sound regulations for e-waste recycling or if the social atmosphere is more supportive of e-waste recycling, then residents are more likely to take positive recycling actions. At the same time, the improvement of infrastructure and the promotion of technological innovation can also provide residents with more convenient and efficient recycling channels, thus promoting changes in personal recycling behavior.

In conclusion, the change of residents' attitude towards e-waste recycling requires the joint efforts of the government, social organizations, commercial institutions, and residents. The government and social organizations can improve residents' environmental awareness and recycling enthusiasm through publicity and education, formulation of rules and regulations, etc.; commercial organizations can improve their social responsibility and image by recycling e-waste, and at the same time provide residents with convenient recycling channels; and residents need to actively participate in e-waste recycling actions, so as to jointly promote the effective treatment of e-waste and the rational use of resources. The residents need to actively participate in e-waste recycling actions, to jointly promote the effective treatment of e-waste and rational utilization of resources.

5. Mechanisms of barriers to behavioral attitudes towards e-waste recycling

Under the regulation of internal and external environment and the intervention of barrier problem solving on residents' e-waste recycling behavior, residents' attitude towards e-waste recycling has a positive effect on residents' e-waste recycling behavior (Standard coefficient=0.01, P=0.009***). Residents' e-waste recycling attitude mainly refers to the seven major aspects of personal awareness, values, common sense, professional knowledge, social responsibility, legal responsibility, and governmental responsibility regarding e-waste recycling, and residents' recycling behaviors towards e-waste mainly contain personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial institutions, and market recycling behaviors. The internal environment mainly refers to the subjective consciousness of the residents, including personal concern, trust, cooperation, expectation, and incentive for e-waste recycling. The external environment mainly refers to external opportunities and resources, including external regulations, cultural atmosphere, infrastructure, publicity and education, and technological innovation for e-waste recycling. Barrier factors mainly refer to the problems encountered in the process of residents' e-waste recycling, including insufficient publicity and education, inadequate infrastructure, insufficient cultural atmosphere, lack of formal supervision, lack of material incentives, and low level of recycling awareness. In this study, under the premise of solving the various obstacles of residents' e-waste recycling problems, the moderating effect of internal and external environments on residents' attitudes toward e-waste recycling, and the path of influence of the various aspects of residents' attitudes toward e-waste recycling on residents' e-waste recycling behaviors are the focus of this paper. Through the analysis of residents' e-waste recycling attitudes, internal and external environments, we can better understand the influencing factors of residents' e-waste recycling behaviors, to provide theoretical support and practical guidance for the government and enterprises to formulate better policies.

First, in solving the problem of insufficient publicity and education, the government and enterprises should step up publicity and education efforts to raise residents' awareness of and attention to e-waste recycling. Publicity and education can be carried out through various channels such as the media, communities, and schools, so that residents can understand the harm of e-waste to the environment and the importance of recycling. At the same time, various activities and competitions can also be organized to stimulate residents to participate in e-waste recycling.

Secondly, in solving the problem of imperfect infrastructure construction, the government and enterprises should increase their investment in e-waste recycling infrastructure construction and improve the construction and management of infrastructure. Infrastructure construction can be strengthened, such as establishing more recycling stations and setting up more recycling trucks. At the same time, the management and maintenance of the infrastructure can also be strengthened to ensure the normal operation of the infrastructure.

Once again, in solving the problem of insufficient cultural atmosphere, the government and enterprises should strengthen the construction and management of the culture related to e-waste recycling. Various cultural activities and competitions can be organized to enable residents to understand the cultural connotation and value significance of e-waste recycling. At the same time, publicity and education on the culture related to e-waste recycling can also be strengthened to enhance residents' sense of identity and belonging to e-waste recycling.

Finally, in solving the problem of lack of formal supervision, governments and enterprises should strengthen the supervision of e-waste recycling. Strict supervision and management of e-waste recycling can be carried out through the establishment of specialized supervisory bodies and systems. At the same time, the supervision of individuals and enterprises involved in e-waste recycling can also be strengthened to ensure that e-waste is reasonably handled and safely utilized.

In conclusion, solving the various obstacles to residents' e-waste recycling is of great significance in promoting residents' e-waste recycling behavior. Through measures such as strengthening publicity and education, improving infrastructure, building a cultural atmosphere, and strengthening supervision, the level of residents' e-waste recycling awareness and behavior can be effectively raised, contributing to the construction of a green and environmentally friendly society.

6. Practical paths for behavioral attitudes towards e-waste recycling

Under the regulation of internal and external environment, the joint intervention of incentives and obstacles to residents' e-waste recycling behavior, residents' attitude towards e-waste recycling has a positive impact on residents' e-waste recycling behavior (Standard coefficient=0.18, P=0.001***). Residents' e-waste recycling attitude mainly refers to the seven major aspects of personal awareness, values, common sense, professional knowledge, social responsibility, legal responsibility, and governmental responsibility regarding e-waste recycling, and residents' recycling behaviors towards e-waste mainly contain personal recycling behaviors, family recycling behaviors, publicity and education behaviors, recycling channels of commercial institutions, and market recycling behaviors. The internal environment mainly refers to the subjective consciousness of the residents, including personal concern, trust, cooperation, expectation, and incentive for e-waste recycling. The external environment mainly refers to external opportunities and resources, including external regulations, cultural atmosphere, infrastructure, publicity and education, and technological innovation for e-waste recycling. Incentives mainly refer to the positive actions taken by residents towards e-waste recycling behavior, including publicity and education, promotional activities, infrastructure, cultural atmosphere, personnel supervision, and other aspects. Obstacles mainly refer to the problems encountered in the process of residents' e-waste recycling, including insufficient publicity and education, inadequate infrastructure, insufficient cultural atmosphere, lack of formal supervision, lack of material incentives, and low degree of recycling awareness. This study mainly discusses here the path of influence of various aspects of residents' e-waste recycling attitudes on residents' e-waste recycling behavior under the premise of solving various barrier problems and incentives to intervene in residents' e-waste recycling behavior, and the moderating effect of internal and external environments on residents' attitudes toward e-waste recycling.

Residents have a high level of concern and expectation for e-waste recycling, and they will be more inclined to engage in recycling behavior. Also, if residents trust the e-waste recycling system, they may be more likely to participate in recycling activities. Residents are more likely to actively engage in recycling behavior if they believe that their recycling behavior will lead to positive outcomes, such as receiving material rewards or social recognition.

A good external environment can help residents to recycle e-waste better. For example, if there is a well-established system of laws and regulations, residents will know what they need to comply with when recycling e-waste. If there is a good cultural atmosphere, residents may be more inclined to participate in recycling behavior because it is socially acceptable. If there is a well-developed infrastructure, residents may find it more convenient to engage in recycling behavior. If there is an extensive publicity and education campaign, residents will understand the importance of e-waste recycling. If there is an environment of technological innovation, residents will be able to utilize new technological means to improve recycling efficiency.

An effective incentive can encourage residents to recycle e-waste. For example, if there is an outreach and education campaign to inform residents of the benefits of recycling e-waste, they are more likely to engage in recycling behavior. If there is a promotional campaign that informs residents of ways to recycle e-waste, they are more likely to engage in recycling activities. If there is a well-developed infrastructure, residents are more likely to engage in recycling behavior. If there is a good cultural atmosphere, residents may be more inclined to participate in recycling behavior because it is socially acceptable. Residents may be more likely to comply with recycling regulations if there is someone to monitor their recycling behavior.

An effective incentive to address these barriers could encourage residents to recycle e-waste. For example, if there is an outreach and education campaign that informs residents about the benefits of recycling e-waste, they are more likely to engage in recycling behaviors. If there is an outreach campaign that informs residents about ways to recycle e-waste, they are more likely to engage in recycling activities. If there is a well-developed infrastructure, residents are more likely to engage in recycling behavior. If there is a good cultural atmosphere, residents may be more inclined to participate in recycling behavior because it is socially acceptable. Residents may be more likely to comply with recycling regulations if there is someone to monitor their recycling behavior.

3.3 Practical recommendations for the development of urban electronic waste management system in China

China produces a large amount of e-waste every year, but the recycling rate is minimal. To avoid causing severe environmental pollution and affecting human health, the Chinese government has focused on recycling e-wastes. E-waste contains precious metals and critical minerals, which are misplaced resources and have recycling value. We combined the incentive system with the smart e-waste collecting system and constructed a set of incentive measures suitable for China’s smart e-waste collection system, which is conducive to enhancing the e-waste recovery rate and is applicable. The existing smart e-waste collection system adopts a single economic incentive method. It faces fierce competition from unauthorized informal recyclers, resulting in a small number of users and a failure to fully utilize its advantages. In the reverse logistics of e-waste recycling, consumers are the starting point of product recycling. By analyzing the characteristics and determinants of Chinese users’ recycling behavior, this study selected appropriate incentives for a smart e-waste collection system to satisfy Chinese consumers’ perceptions of end-of-life electrical and electronic equipment. The incentive system is based on economic incentives, including currency, reward points, and tax incentives, and combines negative incentives, mainly fines. Rewards and punishments are employed simultaneously to achieve long-term and sustainable incentive effects. The incentive system is based on the convenient infrastructure of the smart e-waste collection system, and its financial model must be shared by multiple stakeholders from the government, smart e-waste systems, and manufacturers.

The legal and informal sectors of China’s e-waste recycling management system comprise two independent yet interrelated portions. Due to a lack of monitoring and related norms and regulations, informal e-waste recycling has become a business in some parts of China, such as Guiyu Town in Guangdong Province and Taizhou City in Zhejiang Province, posing substantial environmental and public health risks. According to reports, the average concentration of lead in the blood of local children in Guiyu Town is 15.3 lg/dl, and children whose lead content exceeds 10 lg/dl are advised to seek treatment. Approximately 60% of China’s recyclable e-waste went into the informal recycling process, resulting in a supply shortage in the legal recycling sector. The management of e-waste recycling in China is remarkably impeded. According to Yang et al. (2008), existing informal collectors and recyclers must be transformed or integrated into the formal recycling sector, and the informal sector must be regularized through regulations and standards to increase the collection rate and to completely utilize the resources in e-waste.

Residents in developed countries, such as Germany, Spain, and other countries in the European Union, are required to deliver e-waste to collection stations, and producers are responsible for the cost of recycling. Consumers in Japan pay for the recycling of e-waste because the selling price of new electronic devices includes recycling charges. In most locations in the United States, the expense of e-waste recycling is shared by producers, citizens, and the government. Since the environmental awareness and economic levels of developing countries are relatively low compared with those of developed countries, incentive programs to persuade residents to recycle their e-waste must be implemented. In China, e-waste is regarded as a valuable commodity that may be refurbished and remanufactured before being sold in the secondary market. Wang et al. (2011) considered collection price as one of the determinants of Beijing residents’ willingness and behavior to recycle e-waste. Chi et al. (2014) found that collection price is one of the critical factors for Chinese residents to choose recyclers, accounting for 23.8%. The introduction of economic incentives into formal recycling systems is conducive to increasing recovery rates.

To cope with the increasing amount of WEEE and its potential environmental impact, the Chinese government has promulgated a series of regulations to promote the development of the e-waste recycling industry. In 2002, China banned the importation of dangerous waste from electrical and electronic products. In 2006, China promulgated the Ordinance on Management of Prevention and Control of Pollution from Electronic and Information Products, which was regarded as the China Restriction of Hazardous Substances Directive. In 2009, China launched a pilot project on old-for-new replacements for household appliances. In 2011, the regulation on the Management of Recycling and Disposal of Waste Electrical and Electronic Products, known as the China WEEE Directive, went into effect. The regulation pushed for EPR, which states that EEE manufacturers are responsible for the entire life cycle of electronic items and must recycle EoL EEE. Large EEE producers are willing to recycle their EoL EEE because the product design is recyclable rather than linear. They have created standard processing facilities for e-wastes, such as Haier and Huaxing, which aim to remanufacture and transform e-wastes to utilize EoL EEE effectively. However, they are currently unable to gather enough e-waste to sustain their typical manufacturing capacity, resulting in the production line's closure or only infrequent operation.

Consumers are unaware of the impact of informal WEEE recycling on the environment and human health due to a lack of environmental knowledge and social responsibility. EoL EEE holders prefer informal collection channels due to their comparatively high currency income, and they are unwilling to bear the cost of e-waste recovery. Due to the features of e-waste flow, China's economic development level, cheap labor, and current recycling models, China must construct a personal collection system consistent with the current conditions, rather than copying the WEEE collection models of other countries.

In 2015, China's National Development and Reform Commission issued a CE promotion plan. This plan aims to provide policy support for the development of new recycling methods, such as intelligent recycling and automatic recycling, and to actively promote an Internet-based e-waste collection strategy. The Internet-based e-waste collection platform, which combines online transactions and offline logistics via websites and mobile phone applications, is rapidly expanding. Manufacturers, Internet corporations, and recycling enterprises have expressed interest in intelligent e-waste recycling. China released the "Internet +" Green Ecological Action Implementation Plan in 2016 to promote dynamic environmental monitoring, develop innovative environmental protection technologies, and improve recycling and online resource trade. Innovative e-waste collection and recycling technology help increase recycling rates; however, the ultimate effect is determined by e-waste owners and encouraging customers to actively participate in a formal e-waste collecting platform based on intelligent technologies.

The Internet-based e-waste collection platform allows participants to make online appointments for on-site e-waste collection. The network platform can track the information, material, and capital flow for consumers, e-commerce platforms, registered recycling plants, third-party logistics firms, cooperative collection companies, and secondhand product buyers. Internet-based e-waste collection makes online transactions increasingly convenient for consumers and provides them with quick access to the official e-waste management system by utilizing information technologies, such as the Internet, IoT, and smartphone apps. By contrast, the Internet-based e-waste collecting system is still in its infancy, and its implementation is plagued with obstacles. The government, the platform, and the users are the platform's three stakeholders. Determining how to entice consumers to use the smart e-waste collection platform is crucial. E-waste is plentiful in China, but only a minute percentage of it is recycled using an environmentally friendly method. According to studies, e-waste recycling in China has been significantly hampered by user participation.

Smart e-waste collection, as an innovative solution, may be able to successfully address the issues of e-waste collection and dismantling. Online tracking, processing, and tracing of recycled products are all possible with this new technology. System functions include data statistics, order collection, warehouse storage, and dismantle quality. Residents' inclination to recycle may be influenced by the economic rewards of smart recycling. Collectors' bids maximize the income of consumers who participate in e-waste recycling. This article explores ways to encourage consumers to participate in smart e-waste recycling through incentives.

Materials and Methods

Several scholars have studied the influencing variables of waste recycling behavior, and the theory of planned behavior is widely acknowledged and implemented as a psychological theory. Azjen (1985) proposed the concept of planned behavior, which states that human behavior is a type of planned behavior. Furthermore, behavioral intention is the most crucial aspect in defining recycling behavior. Individuals' behavioral intentions are determined by their attitudes, subjective norms, and perceived behavioral control and are influenced by these three elements, as shown in Figure 3.9. People's behaviors are influenced by intention and perceived behavioral control. According to this theory, the perceived behavioral control that occurs in e-waste recycling represents the individual's ease or difficulty in completing this activity. According to Boldero (1995), recycling convenience, storage space, and the simplicity of use of recycling facilities are all factors that influence consumers' recycling behavior. Consumer behavior is one of the most essential factors in e-waste management. Consumers play two critical roles in the life cycle of e-waste: users and owners. The e-waste management system is ineffective if users do not actively participate.

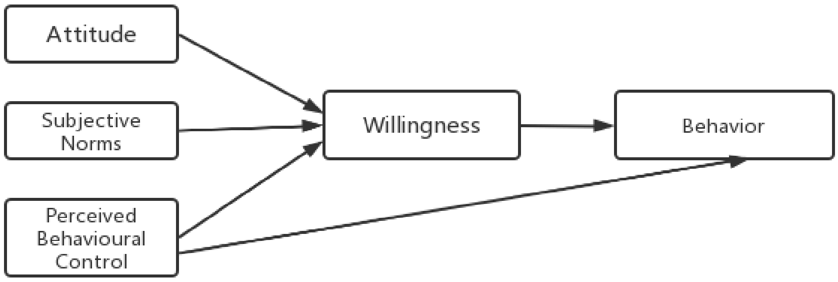

Figure 3.9 - Theory of Planned Behavior, TPB

Source: prepared by the author based on Wang et al. (2019)

Expectation theory, also known as valence-means-expectation theory, was proposed by Victor Froome. He believes that incentives depend on the value evaluation (valency) of the action result and its corresponding expectation, and the formula expressed is as $M = V \times E$. Therefore, the expectations of individuals must be considered to obtain optimal incentives; that is, individuals can achieve certain benefits through their efforts, and beneficial results should be rewarded. Furthermore, this reward must be determined in accordance with the demands of the individual. We analyzed how to formulate incentive mechanisms for consumers to increase the recycling rate of waste electrical appliances based on the characteristics of the benefits generated by recycling waste electrical appliances using the incentive mechanism of expectation theory.

To solve the problem of e-waste collection and recycling, we must first resolve obstacles, such as service inconvenience, and introduce changes in services or infrastructure. Innovative recycling platforms based on the Internet and IoT technologies make recycling highly convenient for consumers. Under the premise of ensuring that the infrastructure is established, incentives enable consumers to engage in rational behavior. Incentives are considered as means to maximize the efficiency of waste management infrastructure. If no infrastructure is available to facilitate recycling, even if consumers have a high awareness of recycling, this will lead to frustration in recycling behavior. By contrast, even with a complete recycling delivery system, but the willingness and motivation of consumers to recycle is low—indicating that consumer participation is low – the recycling system cannot be promoted well, as shown in Figure 3.10.

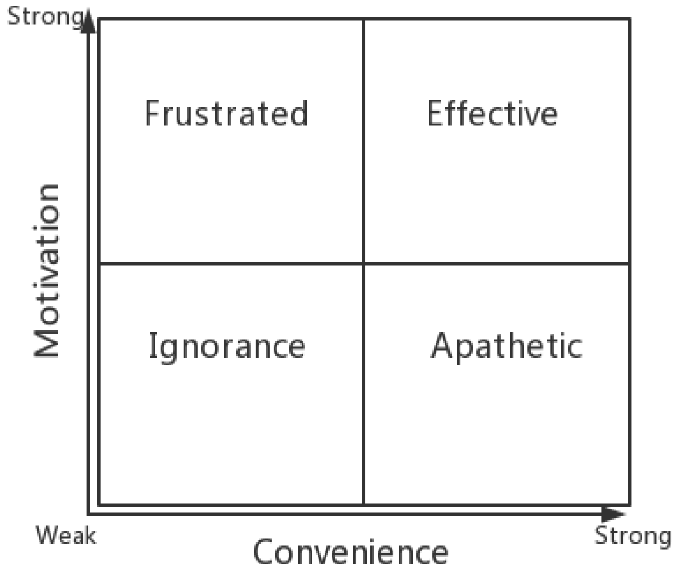

Figure 3.10 – Interaction between motivation and convenience

Source: prepared by the author based on AEAT Evaluation of the Household Waste Incentives Pilot Scheme

Consumers' willingness to recycle e-waste is affected by several factors, including policies, regulations, socio-economic factors, convenience, environmental awareness, attitudes, motivations, and traditional habits. Colesca et al. (2014) considered that the characteristics of different countries affect the collection and recycling behavior of e-waste. Different countries have different methods to collect and dispose of e-waste. Understanding the efficiency of existing collection channels and residents' recycling preferences is a prerequisite for the successful design of the e-waste collection system in China.

The recycling rate of e-waste in European countries is at the top level globally, and the level of awareness and knowledge of e-waste recycling are vital factors that affect the behavior of European consumers. However, American consumers are highly concerned about the convenience of e-waste recycling. In developing countries, such as India, and in Africa with relatively backward economic development, e-waste recycling depends on the informal sector to varying degrees.

Although the formal sector has been expanding with the support of pilot projects and recycling projects initiated by the Chinese government, especially in highly developed regions of China, the informal sector still dominates the e-waste management industry. In China's e-waste management system, consumers have no specific responsibilities, and the role of consumers is limited to passive interactions with the e-waste department. E-waste is a tradable commodity with a high reuse rate in China. Despite the poor technical and environmental performance of the informal e-waste disposal department, it is still accepted by Chinese consumers. The development of smart e-waste recycling technology has reduced the time and economic costs of consumers for e-waste collection and recycling. However, establishing e-waste recycling habits still takes several years. Under the premise of China's current social economy and people's environmental awareness, some measures must be considered to change the dominant position of informal recycling methods and increase the recycling rate.

Through an analysis of papers related to China's e-waste recycling in recent years, the main determinants of China's consumer e-waste recycling behavior are sorted out, as shown in Table 3.33. According to Chi et al. (2014), economic benefits, convenient recycling, and environmental awareness are vital determinants for residents in selecting disposal channels. The lack of economic incentives is why a large amount of e-waste does not enter the formal recycling sector. Li et al. (2012) emphasized that monetary incentives and raising environmental awareness are effective ways to improve the effective recycling of mobile phones by researching consumer mobile phone recycling behavior. Yin et al. (2014) studied mobile phone recycling behavior and willingness to pay for e-waste recycling (WTP) among Chinese consumers. Considering traditional Chinese consumers and low WTP, manufacturers and the government should jointly undertake the cost of recycling used mobile phones. Consumers are encouraged to participate in the recycling of used mobile phones through financial incentives and regulatory requirements and to integrate informal sellers and recycling workshops into the formal recycling system. Orlins et al. (2016) found that consumers and public institutions are more willing to sell e-waste to informal collectors because of higher economic benefits. Because traditional customs are aware of the residual worth of e-waste, over 90% of Chinese individuals are unwilling to pay for recycling.

Table 3.33 Determinants of Chinese consumers’ recycling behavior

Consumer’s Recycling Behavior Determinants in China	Economic incentives	Convenience	Habits	Attitude, Mentality	Environmental awareness	Income	Education level	Privacy security
Chi et al. 2014	√	√			√			
Orlins and Guan 2016	√	√		√	√			
Li et al. 2012	√				√			
Yin et al. 2014	√					√	√	
Liu et al. 2006	√	√						
Wang et al. 2011	√	√	√			√		
Wang et al. 2019	√	√		√	√			
Wang et al. 2019				√	√			
Qu et al. 2019	√	√						√
Ignatuschtschenko 2017	√		√	√	√			

Source: prepared by the author

Scholars conducted case studies based on the e-waste recycling situation in different regions of China to analyze the behavior of home e-waste recycling in China. Due to Beijing’s limited living space, residents are eager to recycle e-waste rather than store it at home or discard it as municipal solid waste. Veenstra et al. (2010) utilized the findings of Xi’an as an example to study the flow of e-waste in China. By contrast, Streicher-Porte and Geering (2010) reviewed specific types of e-wastes in Taizhou, and they all deemed that most consumers choose informal hawkers. China’s e-waste management faces a huge problem—but also an opportunity—in regulating and controlling the informal e-waste collecting and recycling sector and integrating it into the formal recycling system. From the analysis of the determinants of China’s consumer electronic waste recycling behavior, economic incentives are one of the primary motivations for Chinese consumers to recycle e-waste. Therefore, the introduction of financial incentives will encourage e-wastes to enter the formal recycling system.

Figure 3.11 shows the recycling weight and number of e-wastes from 2014 to 2019 in China. The overall amount of e-waste recycled and dismantled in 2019 remained steady, with only a minor increase. The amount of waste recycled via businesses' recycling channels is minimal, and novel recycling means, such as Internet+ and reverse logistics recycling, should be encouraged further. Given the poor collection and delayed distribution of subsidy payments in 2020, e-waste dismantling and processing businesses' capacities were underutilized, resulting in a reduced volume of business.

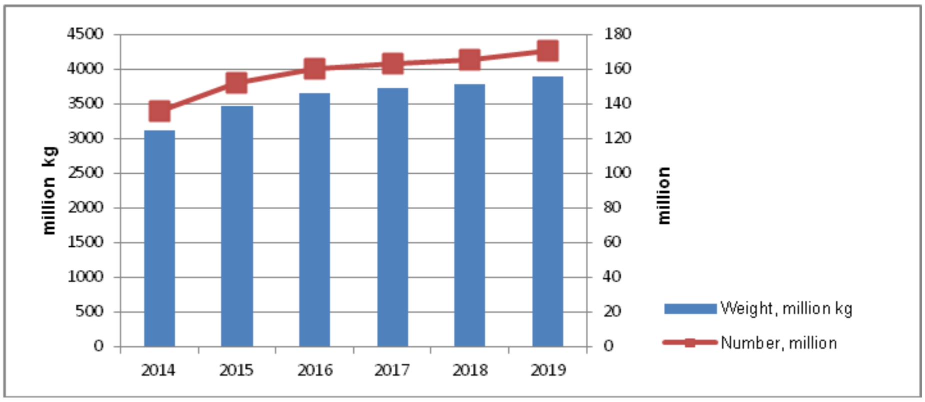

Figure 3.11 – Formal e-waste recycling in China 2014 to 2019

Source: prepared by the author based on the Ministry of Commerce's Report on the Development of China's Renewable Resources Recycling Industry

In China, six primary types of recycling channels are as follows: sold to peddlers, given as donations, sold to the secondhand market, directly discarded, exchanged at retailers or manufacturers, and stored. The proportion of each recycling method in Taizhou City, China, in 2007 is shown in Figure 3.12. Only 12.1% of household appliance waste is recycled in the formal sector (Chi et al., 2014). Among the current disposal methods of household e-wastes in China, storage at home, selling to hawkers, and directly discarding household wastes are the three methods with the most considerable proportion, posing a significant obstacle to official e-waste recycling.

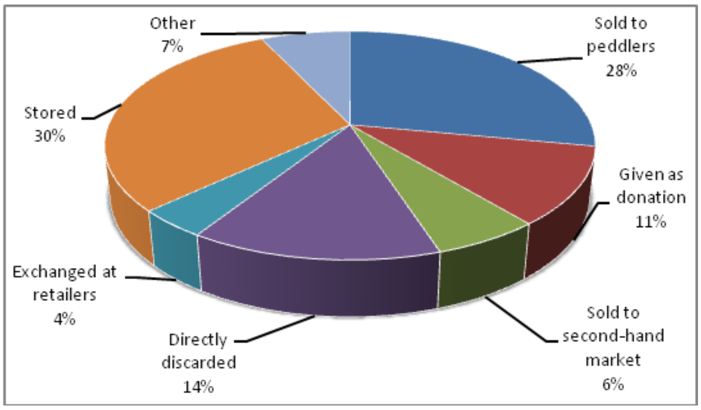

Figure 3.12 – Rates of different e-waste disposal channels in Taizhou in 2007

Source: prepared by the author based on Streicher-Porte and Geering (2010)

Consumers are more likely to keep EoL EEE at home rather than properly dispose of it. According to Yin et al. (2014), up to 47.1% of EoL mobile phones are kept at home in China. Three reasons contribute to this action: first, most consumers (45.9%) are unsure where to recycle their cellphones; second, they are concerned about personal information disclosure (17.7%); and third, they repurpose obsolete cellphones as data storage devices (8.1%). According to the report, consumers are willing to trade their mobile phones with manufacturers or standard retailers for old-for-new activities or bonuses. Given the toxic compounds and precious materials in e-wastes, direct disposal of household waste (14%) will result in substantial environmental damage and resource waste (Yin et al., 2014). The percentage of people who use these three unreasonable disposal methods can be significantly reduced, and the official recovery rate can be enhanced owing to incentives.

Many academics have focused on economic motivation and employed incentives to promote adequate waste management to motivate customers to participate in sustainable waste management. Monetary and non-monetary incentives are two types of incentives. Dixit and Vaish (2015) classified incentives into three categories: financial incentives, environmental incentives, and social incentives. Defra (2021) used a “carrot or stick” technique to distribute currency and volunteer incentives. The four forms of financial carrots are as follows: prize draw, currency reward incentives, currency rewards, and currency discounts. Individuals or communities that participate in the recycling program will be rewarded financially. Fee-based plans and required participation, which refer to the penalty or taxation of not participating in the recycling program, are examples of financial penalties. Community rewards, charitable donations, school rewards, and personal non-monetary rewards are the four forms of voluntary carrots. They appeal to people's generosity and willingness to help the community and the environment. Ylä-Mella et al. (2015) suggested that a currency deposit refund system must be implemented to promote the return of e-wastes in Finland because 70% of respondents stated that a deposit of 20 euros would encourage them to return their old mobile phones. The Thai government proposed charging fees for the sale of certain electronic items and using the collected money to buy back WEEE from homes to reduce the negative impact of the informal recycling industry on the community and the environment. Fullerton and Wolverton (2015) considered this strategy a deposit-refund system (DRS) update that incorporates the front-end product cost and the back-end repurchase method. The back-end repurchase is different because it is motivated by financial incentives. The wide-scale use of DRS to EEE recycling is a difficult task. The residual value after use varies due to the uniqueness of EEE, different types and models, and service life, making it impossible to calculate how much deposit to collect in advance. More than 60% of respondents in Beijing, China, sold their outdated household appliances to hawkers, and acceptance of using DRS to dispose of e-waste is low.

China has established a special subsidy fund for electronic device manufacturers and importers, which gives proportional subsidies to e-waste dismantling and treatment enterprises, depending on the actual amount of e-waste deconstructed. Monetary incentives must be given to recycling businesses through the deployment of fund subsidies. The list of e-waste disposal fund-subsidized enterprises must be dynamically changed, the subsidy mechanism must be optimized, and the policy orientation of eliminating the backward enterprises must be developed. However, significant flaws exist, primarily in fund auditing and environmental oversight, as well as insufficient subsidy collection and delays.

The incentive mechanism and discussion

We investigated the incentive mechanism of a smart e-waste recycling system and suggested a comprehensive reward system that primarily consists of three components. The first component is monetary compensation. The electronic payment will be made to the account of the e-waste generator based on the e-waste recycling price. Second, the smart recycling platform must work with major e-commerce platforms and hypermarkets that sell electrical appliances. If consumers need to buy new appliances, outmoded appliances can be recycled for cash through a smart recycling system, similar to the old-for-new program. Humanely, the types of electrical appliances purchased and recycled can differ. Furthermore, the smart recycling system's reverse logistics can be flexible and diversified. For example, small household appliances can be delivered, with the delivery fee covered by the Internet recycling site. A smart recycling system may form a cooperative agreement with the courier firm to reduce delivery costs. For large and heavy household appliances, the smart recycling platform's employees will schedule a pick-up appointment with the e-waste holder. These above-mentioned options are monetary incentives. The third component combines non-monetary rewards. Consumers who participate in recycling on the smart e-waste recycling system can earn reward points in exchange for social benefits in their local areas. Points can be redeemed for tickets to local attractions, public activities, and small appliances (Han & Shevchenko, 2021).

China has three primary sources of e-waste: households, institutional sources, and equipment manufacturers. How to persuade consumers to deal with EoL EEE through appropriate channels, rather than selling them to household workshops, must be determined. Relevant laws and regulations can be developed, and the implementation process can be tracked to control the two latter forms of e-waste. In this process, the incentive mechanism is also crucial. Enterprises that return e-wastes to a formal recycler may be eligible for tax concessions, exemptions, or preferential treatment from the government. By contrast, enterprises that give e-wastes to unlicensed recyclers should be severely penalized. Specific fine standards can be formulated. Companies that violate relevant legislation will lose a lot of money. Due to governmental restrictions, few businesses will risk selling generated e-wastes to illegal collectors and recyclers.

Figure 3.13 shows the incentive mechanism of a smart e-waste system. Consumers participating in the smart e-waste recycling system receive monetary incentives and accumulated reward points. Furthermore, administrative laws govern e-waste institutional sources, such as colleges and businesses, and tax reductions are employed as incentives. In addition, fines are given as negative incentives. This incentive scheme has obvious advantages compared with the current single-currency incentive with low recycling prices in the smart e-waste collection system.

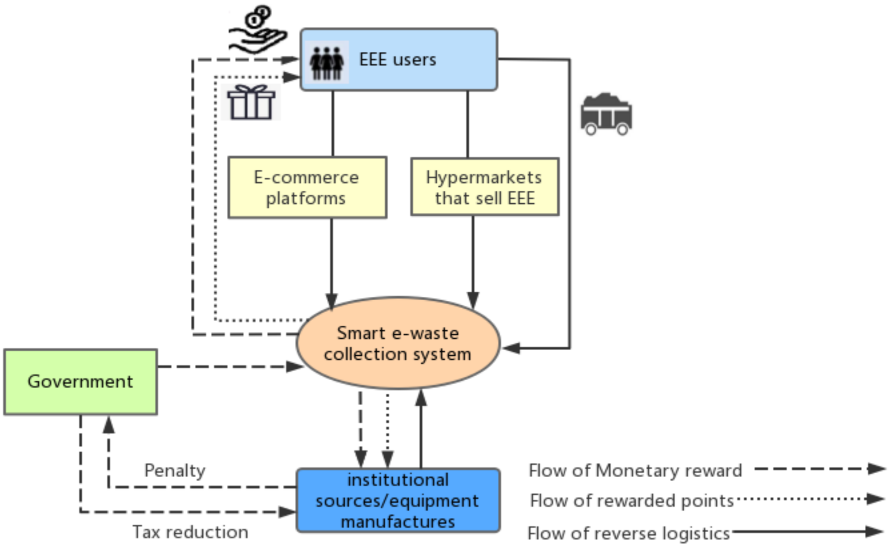

Figure 3.13 – Incentive mechanism of a smart e-waste system

Source: prepared by the author

Currency incentives have been integrated into China’s smart e-waste recycling system. Smart recycling systems based on the Internet, such as Taolv and Aihuishou, estimate the quotation of waste based on the user’s basic information and photos of obsolete household equipment and then analyze it professionally. Finally, the user’s account will receive cash. Informal collectors compete with smart recycling platforms, and the only way to acquire a competitive advantage is to increase recycling prices. As a result, smart recycling platforms require government financial incentives to raise recycling prices and attract price-sensitive users (Han & Shevchenko, 2021).

To tackle the problem of the insufficient supply of e-waste by formal recycling firms, the smart recycling system collaborates with e-commerce platforms that offer discount links to the smart e-waste recycling system. In this manner, the smart recycling system can be pushed, and consumers who buy new home appliances can be directed to it so that they can appreciate the ease of the new recycling process and increase the amount of e-waste recycled. This new trade-in incentive will remind consumers who are used to storing them at home to discard their EoL EEE responsibly. Similarly, smart recycling solutions can work with hypermarkets that sell electrical products. Log in to the smart recycling system via a mobile phone or computer terminal application while purchasing new home appliances in the store to recycle old home appliances. The selling price of new appliances can directly reduce the corresponding recycling price of recycled old appliances. Every time a user engages in a recycling behavior through the smart recycling system, the behavior is logged and awarded points. Different points are given depending on how difficult the type of household appliance is to recycle. Old appliances that easily flow into informal recycling, store at home, and throw as ordinary garbage can be assigned a high-point value, and we can accumulate the points. When points reach a certain value, they can be traded for various rewards.

The Chinese government's introduction of the old-for-new policy in 2009 demonstrated that monetary incentives could overcome e-waste collection barriers in China. Twenty-six million obsolete appliances were collected during the initiative's 18-month implementation (Cao et al., 2016). However, the plan's implementation will necessitate significant government funding. The incentive mechanism suggested in this study does not require any extra infrastructure and uses the current intelligent recycling system's staff and warehouses. The incentive fund is shared by the government, the smart e-waste recycling system, and the manufacturers. The Chinese government provides subsidies to a special fund based on the number of recyclers dismantled. Special funds are collected from manufacturers or importers through the EPR system. Economic incentives can enhance the reverse recovery rate of e-waste by promoting collaboration and active participation among stakeholders.

Fiscal expenditures as incentives in the early stages are necessary to use; however, as social, and economic development, environmental awareness, and the establishment of proper e-waste disposal habits progress, the degree of economic motivation is reduced, eventually evolving into consumers' free voluntary recycling behavior. By contrast, after informal individual collectors are incorporated into the formal recycling organization, environmentally friendly disposal and dismantling methods are used. Individual collectors will not recycle at unreasonably high prices, and no profitable space will be available for informal recycling. The smart way of recycling will become the first choice for people. The smart recycling system not only makes recycling easier, but also ensures that abandoned electronic products are correctly recycled and that personal information is kept private. Therefore, it has a unique advantage compared with the recycling of individual hawkers. However, for smart recycling platforms to gain traction, an incentive mechanism is required.

Given that e-waste is profitable in China, individuals usually sell these wastes, and the WTP is very low. Due to the influence of time and capital expenses, even though some people have developed an environmental consciousness and a willingness to recycle e-waste, they have not considered e-waste recycling actions. As a new technology, the smart recycling solution has evident advantages over traditional recycling systems. The smart collection and recycling system assures not only the ease of collection and recycling but also the protection of personal privacy, as well as open and transparent transaction pricing. Incorporating an incentive mechanism into the smart recycling system aims to increase awareness and promote the smart e-waste collection and recycling system, increase the recovery rate of discarded electronic goods through monetary and non-monetary incentives, solve the problem of an insufficient supply of formal recycling enterprises, and encourage the effective implementation of the CE. Municipalities, smart recycling platforms, and manufacturers should share the currency source of financial incentives. In developing countries, providing financial incentives to recycling enterprises during the early stages of e-waste recycling is a widespread and necessary practice. The smart waste recycling system requires financial assistance, and the incentive mechanism's purpose is to raise the average price above that of informal individual hawkers' recycling prices.

Many fields employ coupons, rebates, gifts, and prizes as economic incentives to boost the recycling rate of recyclable materials. The smart recycling collection system collaborates with online e-commerce platforms and offline electrical appliance stores to recycle old appliances from the sale of new appliances and to expand the smart recycling system's user base. This incentive program benefits not only distributors but also the entire smart recycling system. This program is feasible and a win–win situation. Reward points have been incorporated into the smart e-waste collection system. To generate excellent incentive effects, communities, businesses, and other social groups must cooperate to ensure that numerous benefits can be obtained by accumulating points in consumers' accounts (Han, 2023).

Negative incentives are also crucial for improving the incentive mechanism. Developing countries have a widespread lack of legislation and regulations for the recycling and disposal of e-wastes. Relevant laws and regulations are created to supervise and penalize forbidden recycling methods and ecologically detrimental dismantling methods to ensure that rewards and penalties are coordinated. Schools, institutions, and businesses, as independent legal entities, are frequently faced with batch processing of e-wastes. Their e-waste typically has identifiable signs that are easy to track and trace. They are required by legal policies to participate in official recycling. If the entity performs an excellent job of implementing the regulations, the government may give favorable taxation; otherwise, administrative fines may be applied.

Individual hawker recycling dominates the traditional recycling method; the recycling market is chaotic, and the recycling channels are hidden, making supervision challenging. Statistics on the amount of e-waste recycled, the type of recycling, and the resources available for disassembly are difficult to obtain. E-waste is lured into the smart recycling system through an incentive mechanism. The data flow is clear, and you may collect a lot of important information on e-waste recycling. Smart technologies, such as big data analysis, can help stakeholders keep abreast of e-waste recycling. Manufacturers should also be forced to consider disassembly and environmental factors during recycling, as well as incorporate CE principles into new product design.

Conclusions to section 3

In section 3 "Case Study of Urban E-waste Management Programs", the construction of a municipal e-waste recycling management system is selected as a representative e-waste management system for the case study. This study analyzes city Xinxiang's plan to promote e-waste management using advanced digital technology innovation and the construction of an intelligent logistics recycling system for used home appliances. At the same time, this study investigates the e-waste recycling behavioral willingness of citizens in city Xinxiang based on cognitive-behavioral theory. To realize an advanced e-waste management system in the city based on digital IT, this study designed an incentive mechanism for an intelligent e-waste management system in China. The main conclusions drawn from this study are as follows.

1. E-waste recycling has problems such as difficult supervision and low efficiency, so how to build an efficient and intelligent collection system for used home appliances to provide fresh ideas for efficient recycling. This paper presents a case study of urban e-waste management with China's city Xinxiang as a representative. IoT technology constitutes the key technology of the intelligent recycling system of waste home appliances, and the IoT intelligent recycling bins, as the information collection terminal of waste electronic products, can provide residents with the delivery service and information supply of waste electronic products. RFID tags, bar coding of warehouse management, logistics tracking

technology, data sharing and data backtracking, and other key DTs, provide an intelligent platform of municipal e-waste management.

2. Based on the problems of e-waste management in the city, such as the low recycling rate of e-waste, the lack of planning and relevant organizations for e-waste recycling, the lack of data statistics and tracking of the recycling process, and the lack of intelligent supervision and management of e-waste recycling, this study proposes corresponding countermeasures. An advanced intelligent logistics e-waste recycling system is proposed for city Xinxiang. The intelligent logistics recycling system for waste home appliances consists of four parts: the coverage of waste home appliance logistics and recycling network, the tracking of the used home appliance logistics and recycling process, the intelligent recommendation of waste home appliance logistics and recycling routes, and the inventory management of waste home appliance. The three-tier logistics and recycling system is built with "point, station and center" as the core, obtaining data through the urban IoT sensing network, using logistics tracking technology to realize the tracking of the process and the sharing of heterogeneous data. A visualized logistics operation platform is established to optimize the transportation routes of vehicles, and then the inventory of e-waste is intelligently and comprehensively managed.

3. Based on the Theory of Planned Behavior and its extensions, a questionnaire on the current situation of e-waste recycling among residents of Xinxiang city was compiled using a 5-point Likert scale. The questionnaire survey was conducted on 1,000 respondents of Xinxiang city residents, and 678 questionnaires were recovered, among which 500 questionnaires were valid. Six research hypotheses were verified by constructing relevant theoretical models. The research results of Model 1 show that residents' willingness to recycle e-waste will have a direct impact on residents' e-waste recycling behavior, and that personal consciousness and values, social responsibility, and government obligations determine residents' attitudes toward e-waste recycling, which will have a direct impact on e-waste recycling behavior. The findings of Model 2 show that residents' willingness to recycle e-waste is affected by changes in the internal environment,

which adjusts residents' e-waste recycling behavior. Moreover, changes in the internal environment mainly change residents' personal consciousness, values, common sense, and enhance the sense of social responsibility, thus indirectly affecting e-waste recycling behavior. The findings of Model 3 show that residents' willingness to recycle e-waste is affected by changes in the external environment, thus adjusting residents' e-waste recycling behavior. Moreover, changes in the external environment mainly change the technological basis, cultural atmosphere, and infrastructure construction of residents' e-waste recycling, thus indirectly affecting e-waste recycling behavior. The findings of Model 4 indicate that incentives for residents' e-waste recycling will intervene in residents' behavior by adjusting their e-waste recycling intention and promote the sustainable development of e-waste recycling. Moreover, under the joint regulation of internal and external environments, incentives such as publicity and education, reward and punishment systems, and material rewards affect residents' behavioral intention to recycle e-waste to a certain extent, thus positively intervening in the sustainable development of e-waste recycling behavior. The research results of Model 5 show that addressing the barriers to e-waste recycling will adjust the residents' e-waste recycling intentions to intervene in the residents' behavior and promote the sustainable development of e-waste recycling. Moreover, under the joint regulation of internal and external environments, issues such as punishment and supervision measures, institutional development, infrastructure development, and cultural facilities affect residents' behavioral intention to recycle e-waste to a certain extent, thus positively intervening in the sustainable development of e-waste recycling behavior. The research results of Model 6 show that residents will take relevant incentives and solving the problems caused by the obstacle factors of e-waste recycling, to promote the willingness of residents to recycle e-waste to intervene the behavior of residents and promote the sustainable development of e-waste recycling. Moreover, under the joint regulation of the internal and external environment, the solution of problems such as punishment and supervision measures, system construction, infrastructure construction, cultural facilities, and the joint intervention of incentives such as publicity and education, reward and punishment system, and material rewards, the behavioral intention of residents to recycle e-waste is influenced to a certain extent, thus positively intervening in the sustainable development of e-waste recycling behavior.

4. This study argues that the application of advanced digital IT to municipal e-waste management is relevant to solving the e-waste problem. This study proposes an incentive mechanism for e-waste management system based on digital IT to increase consumer participation in a smart e-waste recycling platform. The incentive mechanism is based on monetary incentives, with consumers receiving currency rewards on the smart e-waste recycling platform. Through the cooperation between the smart recycling platform and online and offline home appliance sales, financial incentives are provided to attract more and more consumers to recycle old home appliances stored in their homes or intended to be discarded as household waste. To strengthen the efficiency of the incentive mechanism, consumers on the smart recycling platform are awarded incentive points for each recycling activity, allowing them to fully utilize social resources. Finally, using negative incentives, the entire e-waste recycling process in companies and organizations is monitored. Regulations are improved, and rewards and penalties are implemented simultaneously. In the incentives mechanism, the government, smart recycling systems, manufacturers, retailers, collectors, recyclers, consumers, enterprises, and institutions are all participants, and the financial costs are shared by the government, smart recycling systems, and manufacturers.

CONCLUSIONS

This study systematically elaborates the importance of e-waste management, using the concept of CE to realize the reuse from e-waste to resources. Through a systematic literature review, the systematic approaches and innovations in e-waste management are summarized. The role of digital IT in CE in municipal e-waste management system is analyzed, which can promote CE business model innovation. Based on the theory of CE and evaluation principles, the evaluation index system of urban CE development was designed. It is empirically analyzed that digital technology innovation can reduce environmental pollution and promote the development of urban CE in the long term. A practical study of Xinxiang city was conducted as a case of using advanced digital technology innovation to promote the construction of urban e-waste management system and the citizens' willingness to recycle e-waste was investigated.

1. China's e-waste management system is still in its infancy, and the traditional e-waste collection model, which is based on informal recycling, has seriously hindered the development of e-waste management. With the rapid development of intelligent information technologies, smart e-waste management is a systematic approach and innovation to solve China's e-waste problem. Many scholars have conducted research on this and achieved rich theoretical results, leading to innovative practice of smart recycling. The emergence of e-waste recycling platforms based on the Internet and the IoT has become a key factor in changing the traditional recycling methods in China.

2. This study analyzes the e-waste management legislation and the recycling system constructed in European countries, Japan, and the U.S. These developed countries' e-waste management system and practical experience provide learning and reference for China's e-waste management. To realize the high recycling rate of e-waste, an integrated strategy can be adopted, which is divided into three types: vertically integrated recycling mode centered on producers, vertically integrated

mode centered on third-party recycling and processing, and horizontally integrated mode centered on joint recycling and processing. This study also examines how to increase the availability of WEEE and reduce refurbishment/remanufacturing costs, and analyzes the characteristics of the refurbished/remanufactured electrical and electronic products market.

3. This study proposes a conceptual framework for DTs in CE from the perspective of product lifecycle, where DTs plays an important role in each stage of the product lifecycle: design, use, and end of life. DTs enables a radical improvement of the CE model by achieving the three performance objectives of the CE: improving resource efficiency, extending product life, and closing the loop. From the beginning of the product lifecycle, the design stage of the product, we consider slowing down the resource flow of the product and closing the loop. We utilize the new technologies and innovations provided by Industry 4.0 to design various circular products. In the use stage of the product, a new PSS business model has emerged to meet customer demand for personalized, experiential, and other professional services. The dissertation analyzes the consumer-service-product interaction process in the PSS business model that provides professional services to consumers through the Internet, IoT, cloud platforms, and digital twin technologies. When the product reaches end of life, DTs are beneficial for improving reverse supply chain management, achieving closed-loop through reuse, remanufacturing, and recycling. DTs can support both CE and PSS to realize a circular business model that supports our theoretical framework. The bike-sharing system, an AB-PSS based on a smartphone application, is an example of DTs promoting the transition to CE.

4. This study establishes an evaluation method for CE development based on city level by analyzing existing evaluation methods for CE development. In the design of the urban CE evaluation index system, the principles of systematicity, scientific, comparability and dynamism are followed. The whole urban CE system is divided into three subsystems of economy, environment and resources, and the hierarchical structure of the evaluation index system is determined: the target layer,

criterion layer, element layer and the indicator layer, constituting the multi-objective and multi-level structure of the evaluation model. The evaluation indicators are selected through literature analysis, and the AHP method is used to calculate the weights, and finally the comprehensive index is calculated, which is used to carry out a comprehensive evaluation of the development of urban CE.

5. Based on the panel data of prefecture-level cities from 2003 to 2018, this study empirically examines the impact of smart city policy implementation on the environment and urban CE using the difference method. The empirical results of this study show that smart city construction has a significant relationship with environmental pollution reduction and urban CE development. The implementation of smart city policies reduces environmental pollution and realizes environmental protection on the one hand, and promotes the development of urban CE on the other. This study explores the mediating mechanism of smart city policies to promote the development of CE, and the results show that the implementation of smart city policies can increase the contribution to the development of urban CE through technological innovation. This study conducts a comparative study through the counterfactual test method, and the results show that smart cities can promote urban CE development in the long term, driven by technological innovation. This study further validates the robustness of the findings through a series of robustness tests such as parallel trend detection and changing sample size.

6. The dissertation presents a case study of urban e-waste management, with China's city Xinxiang as a representative. The key technology of the smart e-waste recycling system consists of IoT technology, and the IoT intelligent recycling box, as an information collection terminal for waste electronic products, can provide residents with the delivery service and information supply of waste electronic products. The RFID tags, the barcode of the warehouse management, the logistic tracking technology, data sharing and data backtracking, and other key DTs, provide a smart management platform for the city's e-waste management.

7. This study proposes corresponding countermeasures for the management of e-waste in City. It proposes the establishment of an advanced intelligent logistics

system for e-waste recycling, which consists of four parts: the coverage of the logistics and recycling network for waste household appliances, the tracking of the logistics and recycling process for waste household appliances, the intelligent recommendation of logistics and recycling routes for waste household appliances, and the management of logistics and recycling inventories for waste household appliances. The three-tier logistics recycling system is built with "point, station and center" as the core, obtaining data through the urban IoT sensing network, using logistics tracking technology to realize the tracking of the process and the sharing of heterogeneous data. A visualized logistics operation platform is established to optimize the transportation routes of vehicles, and then intelligently manage the inventory of e-waste in all aspects.

8. This study conducted a questionnaire survey on the current situation of e-waste recycling among residents in Xinxiang city. Based on the Theory of Planned Behavior and its extension as the theoretical foundation, six research hypotheses were verified by constructing relevant theoretical models. The willingness of residents to recycle e-waste will have a direct impact on residents' e-waste recycling behavior. The willingness of residents to recycle e-waste will be affected by changes in the internal environment, thus adjusting residents' e-waste recycling behavior. Residents' willingness to recycle e-waste will be affected by changes in the external environment, thus adjusting residents' e-waste recycling behavior. Incentives for residents to recycle e-waste will intervene in residents' behavior by adjusting residents' willingness to recycle e-waste and promote the sustainable development of e-waste recycling. Addressing barriers to e-waste recycling will adjust residents' willingness to recycle e-waste, intervene in residents' behavior, and promote the sustainable development of e-waste recycling. Adopting relevant incentives to solve the problems caused by e-waste recycling barriers will increase residents' willingness to recycle e-waste, thereby intervening in residents' behavior and promoting the sustainable development of e-waste recycling.

8. A questionnaire survey was conducted among the citizens of Xinxiang city, and statistical analysis methods were used to determine the relationship between the

variables. It was found that residents' willingness to recycle e-waste will directly affect residents' e-waste recycling behavior. Residents' willingness to recycle e-waste is influenced by the internal environment, thereby adjusting residents' e-waste recycling behavior. Residents' willingness to recycle e-waste is affected by the external environment, thereby regulating residents' e-waste recycling behavior. The incentives for residents to recycle e-waste will adjust residents' willingness to promote the sustainable development of e-waste recycling. Addressing barriers to e-waste recycling will adjust residents' willingness to recycle e-waste, intervene in residents' behavior, and promote the sustainable development of e-waste recycling. Adopting relevant incentives to solve the problems caused by e-waste recycling barriers will increase residents' willingness to recycle e-waste, thereby intervening in residents' behavior and promoting the sustainable development of e-waste recycling.

9. This study proposes an incentive mechanism for the e-waste management system based on smart digital IT to increase consumer participation. The incentive system is based on economic incentives, including currency, reward points, and tax incentives, and combines negative incentives, mainly fines. Rewards and punishments are employed simultaneously to achieve long-term and sustainable incentive effects. The incentive system is based on the convenient infrastructure of the smart e-waste collection system. Through the cooperation between the smart recycling platform and online and offline home appliance sales, financial incentives are provided to attract consumers to recycle waste home appliances stored at home or intended to be discarded as solid waste. Finally, negative incentives are used to monitor the entire e-waste recycling process of companies and organizations and improve regulations.

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APPENDICES

Questionnaire of E-Waste Collection and Recovery Status in Xinxiang city

We would be delighted if you could join us in this scientific investigation!

The purpose of our research is to identify the factors that influence the willingness of citizens to recycle e-waste.

It should be emphasized that the survey is anonymous, all data received is strictly confidential and your answers will not be passed on to third parties.

The survey is conducted online and will takes approximately 5 minutes. The survey data is used for academic research only, and there are no standard answers to the questions, just fill them in according to what you think.

Your opinion is important to us and your support is greatly appreciated.

Part 1. Please choose the most appropriate option depending on your situation.

1. Your gender: A. Male B. Female

2. Your age: A. < 18 years old B. 18–25 years old C. 26–30 years old

D. 31– 40 years old E. 41– 50 years old F. 51– 60 years old G.≥ 60 years old

3. Your highest educational background: A. middle school or below

B. High school or polytechnic school C. College degree D. Bachelor degree

E. Postgraduate or above 4. Your current occupation: A. Marketing or sales B. Official C. Self-employed

D. Finance E. Technologist F. University students G. worker H. Service people

I. Teacher J. Medical staff K. Lawyer

Part 2. Please choose the most appropriate option according to your practical actions and thoughts in your daily life.

1. Do you agree that conducting formal e-waste recycling is a meaningful behavior of environmental protection?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

2. Do you agree that the unreasonable disposal of e-waste will have a negative impact on your life and health?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

3. Do you agree that formal e-waste recycling in city is important to leave a better living environment for future generations?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

4. Do you agree that formal e-waste recycling in city is significantly meaningful for solving resource scarcity and environmental problems?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

5. Do you agree that individuals participating in formal e-waste recycling are contributing to society?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

6. Do you agree that every citizen has a responsibility to participate in formal e-waste recycling?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

7. Do you agree that e-waste recycling is the responsibility of the government and has little to do with individuals?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

8. Would you like to participate in formal e-waste recycling, albeit with minimal monetary compensation?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

9. Would you like to tell your family and friends about formal recycling and disposal of e-waste so that more people know about it?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

10. Have you participated in any publicity and education activities related to e-waste recycling?

A. Always

B. Often

C. Sometimes

D. Rarely

E. Never

11. In the future, I am willing to take the initiative to contact a professional recycling organization when dealing with e-waste.

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

12. I tend to buy electronics that promise formal recycling in the future.

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

13. E-waste recycling promotion activities will make you pay attention to legitimate electronic waste recycling behavior.

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

14. Do you trust that legitimate disposal companies can handle electronic waste reasonably?

A. Totally believe in

B. Generally believe in

C. Half-and-half

D. Generally believe in

E. Totally disbelieving in

15. Do you agree that selling e-waste to peddlers is also a form of recycling.

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

16. Do you think peddlers can handle e-waste properly?

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

17. If legitimate e-waste recycling can receive substantial material rewards or cash subsidies, you would participate in formal e-waste recycling.

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

18. If Chinese laws or city regulations explicitly require residents to take responsibility for e-waste recycling, you will participate in formal e-waste recycling.

A. Totally consistent

B. Generally consistent

C. Half-and-half

D. Generally inconsistent

E. Totally inconsistent

19. If your family or friends participate in formal electronic waste recycling, you will participate in formal e-waste recycling as well.

A. Totally consistent

B. Generally consistent

C. Half-and-half

D. Generally inconsistent

E. Totally inconsistent

20. If there is a formal e-waste recycling site or facility near your community, you will carry out formal recycling of electronic waste.

A. Totally consistent

B. Generally consistent

C. Half-and-half

D. Generally inconsistent

E. Totally inconsistent

21. The publicity and promotion activities on the formal e-waste recycling methods will make you more enthusiastic to participate in formal e-waste recycling activities.

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

22. Smart recycling methods based on the Internet and IoT have facilitated e-waste recycling, and you will use this new method for formal e-waste recycling.

A. Totally agree

B. Generally agree

C. Neutral

D. Generally disagree

E. Totally disagree

23. Please rank the following factors that may drive formal e-waste recycling in order of importance.

A. Implementing publicity and education activities on the theme of formal e-waste recycling

B. Setting up banners of formal e-waste recycling in the community

C. Setting up formal recycling sites and infrastructure for e-waste in the community

D. Arrange volunteers to remind e-waste recycling at community sites

E. Establishing laws and regulations for the management of e-waste recycling

F. Setting clear incentives and penalties for e-waste recycling

G. Initiating a cultural atmosphere for formal e-waste recycling in the community

H. Adding specialized staff to supervise e-waste recycling practices in the community

I. Others (please specify)

24. Please rank the importance of the following barriers to your participation in formal e-waste recycling.

A. Insufficient public education on formal recycling for e-waste

B. Lack of sites and infrastructure for formal recycling of e-waste near communities

C. It can take up a lot of an individual's time to participate in formal e-waste recycling

D. No rules and regulations for mandatory electronic waste recycling

E. Insufficient material incentives for participants in formal recycling of e-waste

F. Lack of penalties and supervision for informal e-waste recycling

G. Insufficient cultural and atmosphere for formal e-waste recycling

H. Lack of awareness among residents of the importance of formal e-waste recycling

I. Others (please specify)

Application Certification

On the implementation of the results scientific work on the topic "Development of integrated e-waste management system based on resource-saving in China" by Candidate of Management, Ph.D. Student of the Faculty of Economics and Management of Sumy National Agrarian University Han Yafeng in the work of the School of Computer Science and Technology of Henan Institute of Science and Technology

The results of the scientific work "Development of integrated e-waste management system based on resource-saving in China", performed by Han Yafeng, Ph.D. Student of the Faculty of Economics and Management of Sumy National Agrarian University, were used in the work of the School of Computer Science and Technology of Henan Institute of Science and Technology in the management system of the e-waste process. Public waste electric and electrical equipment of the School enters formal recycling enterprises through collection methods based on the Internet and IoT technology.

School of Computer Science and Technology
of Henan Institute of Science and Technology

June 10, 2023

Application Certification

On the use in the e-waste management system of the results of the research "Development of integrated e-waste management system based on resource-saving in China" by the Ph.D. Student of the Faculty of Economics and Management of Sumy National Agrarian University Han Yafeng

The results of the scientific research within the framework of the work "Development of integrated e-waste management system based on resource-saving in China", prepared by Han Yafeng, Ph.D. Student of the Faculty of Economics and Management of Sumy National Agrarian University, are used for e-waste management in the campus of Henan Institute of Science and Technology.

School of Information and Engineering
of Henan Institute of Science and Technology

河南科技学院 信息工程学院

June 10, 2023