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A System Dynamics Model for Evaluating WEEE in Hong Kong

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Abstract

The proportion of waste electrical and electronic equipment (WEEE) within municipal solid waste is increasing globally. Driven by rapid technological advancements and the proliferation of electronic devices, the volume of WEEE is projected to grow significantly in the absence of effective strategies and regulations. To address this challenge, the European Union (EU) implemented the WEEE Directive, aiming to monitor and improve member states' performance in controlling WEEE generation and recycling. Similarly, Hong Kong introduced the Producer Responsibility Scheme (PRS) to regulate WEEE generation, recycling, and landfill disposal. The establishment of WEEE·PARK in the same year further marked Hong Kong's commitment to enhancing its recycling infrastructure. Despite these efforts, the effectiveness of WEEE recycling systems varies across regions. This study evaluates the overall efficiency of WEEE recycling flows in the EU using a system dynamics model, with a detailed focus on Sweden and Denmark as case studies. The analysis explores the strengths and limitations of their recycling systems, offering insights into best practices. Additionally, the study examines Hong Kong's WEEE recycling framework through comparative analysis and system dynamics modeling. Based on the findings, recommendations are proposed to enhance Hong Kong's WEEE recycling system, drawing on lessons from the EU. This research aims to contribute to the global discourse on sustainable WEEE management by providing actionable insights for policymakers and stakeholders.

Keywords
System Dynamics; Waste Management; Waste Electrical and Electronic Equipment; Recycling; Policy.

1. Introduction
In the past few decades, technological advancements have led to the production of an increasing number of electronic devices and equipment. Consequently, waste from electrical and electronic equipment (WEEE) has become one of the fastest-growing waste categories globally. Only 22.3% of the total WEEE generated worldwide was documented as being properly collected and recycled in 2022 (Balde et al., 2024). Due to the rapid growth of WEEE and the low recycling rate, prompt actions must be implemented. One of the most significant reasons for implementing prompt actions and recycling plans is the release of toxic materials and elements, such as arsenic (As), chromium (Cr), selenium (Se), mercury (Hg), and fire-resistant materials, from e-waste. Inappropriate handling of WEEE has also been found to have adverse effects on human physical and mental health. Therefore, electronic waste is a critical issue that must be addressed globally. In Europe, to address the above problems, the WEEE Directive and the Restriction of Hazardous Substances (RoHS) Directive were introduced by the European Union in February 2003. The ultimate goal of these directives is to minimize the hazardous chemicals generated by WEEE. The updated WEEE Directive became effective in February 2014, and the implementation of the first regulation, 2017/699, was adopted in April 2017 (European Commission, 2017). The WEEE Directive and the RoHS Directive have been regularly revised and updated to introduce stricter targets and regulations aimed at enhancing WEEE recycling effectiveness in member states.

In Hong Kong, approximately 70,000 tonnes of WEEE are generated annually (Environmental Protection Department, 2024). To improve WEEE recycling effectiveness, the Hong Kong government launched the Waste Electrical and Electronic Equipment Treatment and Recycling Facility (WEEE·PARK) in Tuen Mun and the Producer Responsibility Scheme on WEEE in 2018. Large electrical equipment, including air conditioners, refrigerators, washing machines, televisions, computers, printers, scanners, and monitors, are regulated under the Producer Responsibility Scheme on WEEE. These regulated WEEE items are sent to WEEE·PARK for treatment and recycling. Suppliers and producers of electrical and electronic equipment are required to register with the Hong Kong Environmental Protection Department. Sellers and distributors endorsed by the department must provide removal services and plans for customers. Other regulations include controls on abandoning regulated electronic equipment under the Producer Responsibility Scheme and disposal licensing Despite the implementation of various WEEE recycling policies and ordinances in different countries, statistics from recent years indicate slow growth in global WEEE collection volumes. For instance, in the EU, only three member states achieved the WEEE collection targets set by the WEEE Directive in 2021, according to the latest statistics (European Commission, 2021). One of the reasons why the WEEE collection targets are difficult to achieve is the methodology used to calculate the WEEE collection rate. Member states must meet the target of 65% under the Electrical and Electronic Equipment Put on the Market (EEE POM) methodology, while the target under the WEEE-generated methodology is 85%, as updated in 2019 (European Commission, 2019). Consequently, countries using the EEE POM methodology for calculating the WEEE collection rate are significantly affected by the volume of EEE POM. When the EEE POM volume increases significantly, even if the collection volume remains the same or even increases, the collection rate calculated using the EEE POM methodology may decrease. This discrepancy may be one of the reasons why some EU member states find it more challenging to meet the WEEE collection targets.

1.1 Objectives

The results and findings of this paper will be presented and further explained based on the outcomes generated by the system dynamics models for each location and scenario. Several key areas that are essential to the findings and will be the focus of this study include: (1) WEEE generation, (2) WEEE collection, (3) WEEE recycling and recovery, and (4) WEEE sent to landfills. These areas play a significant role in determining the effectiveness of WEEE recycling policies and will be thoroughly addressed in this report. Both graphs and statistical tables will be provided as part of the results derived from the system dynamics models.

In addition to the deliverables and focused areas, the objectives of this paper are as follows and will be examined in detail:

1. Investigate the current and forecasted WEEE generation and recycling in the European Union, as analyzed by the system dynamics model.
2. Study and forecast the effectiveness of WEEE collection and recycling systems in Hong Kong, supported by the system dynamics model.
3. Compare and analyze the differences and effectiveness of the system dynamics model results in relation to WEEE recycling systems in Hong Kong.
4. Provide recommendations for improving Hong Kong's WEEE recycling systems.

2. Literature Review

The significant growth of electronic and electrical equipment (EEE) waste presents a challenge to all countries due to the rapid increase in electronic and electrical equipment placed on the market. As a result, various countries have implemented recycling policies and regulations on WEEE to reduce its generation and enhance recycling rates. The European Union (EU) also introduced and enacted the WEEE Directive in 2001 to supervise and manage WEEE recycling progress in EU member states. Research has been conducted on the regulation and competition in the Extended Producer Responsibility(EPR) model of WEEE system among European countries (Favot et al., 2022). The EPR not only requires producers to manage and process waste to reduce the amount sent to landfills but also encourages manufacturers to consider environmental aspects in product design and production processes.

2.1 Extended Producer Responsibility Models for WEEE

There are various types of EPR models for WEEE and two major models for WEEE management in EU countries for implementing WEEE collection and recycling systems: (1) the National Collective Scheme and (2) the Clearing House Model (Dieste et al., 2017). Both models operate using the reverse logistics model, and there are several differences between them. The characteristics and differences of the National Collective Scheme and the Clearing House Model are discussed below. EU member states can choose which collective method to adopt, and in some cases, more than one scheme may be used to operate under the National Collective Scheme. Compared to the Clearing House Model, the National Collective Scheme has less competition in the market. Producers also have the option to manage their own WEEE without participating in a collective scheme. Both manufacturers and collective schemes are responsible for handling the entire process of WEEE collection and recycling, including collection, transportation, and recycling treatment. The National Collective Scheme is typically managed and organized by non-profit organizations. Operations under this scheme are carried out by carriers and recyclers who hold contracts with producers and the National Collective Scheme. Reporting responsibilities lie with producers and collective schemes.

The Clearing House Model, on the other hand, operates within a competitive market. Unlike the National Collective Scheme, the Clearing House Model allows different collective schemes to handle the same WEEE categories, leading to greater competition in the WEEE collection and recycling market. This system is overseen by a national registry that establishes mechanisms and criteria for allocating collection points to collective schemes and manufacturers (European Commission, 2019). Certain responsibilities and criteria must be met by collective schemes, including the following examples:

- Collective schemes and producers are required to fulfill their responsibilities and treat the allocated WEEE.
- The performance of collected and recycled WEEE must be reported annually to the Ministry of the Environment or the European Community

2.2 System Dynamics

System dynamics was first introduced by Jay Forrester through his research on industrial dynamics (Forrester, 1997). The term "industrial dynamics" was later broadened to "system dynamics," a modeling concept that has been utilized in various studies (Sterman, 2015). System dynamics is also closely related to the concepts of soft operations research and systems thinking (Checkland, 1981). By incorporating the principles of soft operations research and systems thinking, system dynamics can address complex problems and systems. System dynamics is capable of identifying and solving issues implicit in social and physical systems characterized by complexity, nonlinearity, and feedback loop structures. Using visual tools, system dynamics can analyze relationships among different variables, such as factors, quantitative data, and information, through computer simulation technology. System dynamics modeling allows individuals to analyze relationships, structures, and behavioral patterns within complex social networks for WEEE policy(Chu et al., 2023).

To construct a system dynamics model, collected data must be input into the model's elements. First, the attributes of each element must be assigned, including names, values, equations, and functions, to enable the model to operate systematically. Subsequently, variables and external inputs relevant to the model and influencing it—such as GDP PPP growth rate, generated WEEE volume, and recycling rate—are added. The model is then modified and adjusted based on evaluations of different scenarios. Feedback loop structures are essential for sustaining the model and will be discussed in subsequent paragraphs. Examples of elements in a system dynamics model include nodes, relationships between nodes, table functions, time variables, and time delays. Each node requires equations or values to complete the model. Once the model is complete, it is run and simulated based on the assigned equations and values, showing how variables change over time. Units and variables, such as time units, start time, stop time, and simulation speed, can be adjusted according to the model's setup. The simulation is conducted based on these fundamental settings and requirements. In addition to the basic elements of a system dynamics model, there are essential concepts for generating different results using the software. These include feedback systems and open systems. A closed-loop concept exists within feedback systems. In a closed-loop system, the results of future actions are influenced and determined by past actions and outcomes. Thus, elements in the system dynamics model, such as variables, inputs, outputs, and stocks in the feedback loop, are interconnected and influence one another to sustain the model (Llerena-Riascos et al., 2021). Conversely, in an open system, outputs and results do not influence inputs. Actions are processed within the open system to generate outputs and results, but these results do not feedback to affect the inputs.

2.3 Research Gap

Despite several past studies conducted using system dynamics to analyze waste electrical and electronic equipment (WEEE), there is limited research on e-waste simulation using system dynamics modeling to compare the effectiveness of WEEE recycling in EU countries and Hong Kong. Most current research on WEEE has successfully addressed issues and effectiveness related to producer responsibility schemes (PRS) through various methods, as well as WEEE topics using system dynamics modeling. Solid contributions and recommendations regarding WEEE have been presented in the mentioned studies. Several studies have also utilized different methods and focused on specific cities. However, there are few papers that compare system dynamics models in EU countries and Hong Kong by simulating future trends and outcomes. Therefore, this research focuses on waste electrical and electronic equipment in EU countries and Hong Kong by examining the effectiveness of e-waste recycling through system dynamics simulation. Recommendations for improving the WEEE recycling system in Hong Kong will be provided based on the current situation and simulation results. Various scenarios and hypotheses will be developed using system dynamics modeling to compare current policies in EU countries as a whole, selected members stated within the EU, and Hong Kong. Consequently, the interrelationship between numerous variables and factors related to e-waste will be analyzed. Stella®, a system dynamic modeling tool, will be used for illustration and simulation of waste electrical and electronic equipment.

3. Methodology

Firstly, statistics and data will be collected online regarding the WEEE situation in EU countries, using databases and datasets from official EU sources and statistical research websites. Similarly, statistics on WEEE in Hong Kong will be gathered to support the evaluation and provide recommendations for WEEE implementation in Hong Kong. To ensure the collection of useful and meaningful data, the fundamental elements and attributes will first be identified and constructed. The current situation and policies related to WEEE in EU countries will be investigated through various research studies. Subsequently, the attributes and elements will be established to collect relevant statistics and information for the system dynamics model. Since system dynamics modeling requires quantitative and numerical data, the information will be sourced from the Internet, including official data releases, news reports, and government reports. Examples of sources include data.europa.eu, the official website of the EU, and Eurostat. For missing or unknown data, average values will be used as replacements. All data and statistics related to the system dynamics elements will be obtained from these sources. The following data points will be included, but are not limited to:

- GDP PPP growth rate:
- Generated WEEE volume per year
- Correlation between GDP PPP and generated WEEE volume
- Large size of WEEE and Small appliances WEEE proportion from the generated WEEE volume
- WEEE collection volume
- WEEE sorting rate from the collection point to the recycling and treatment facility
- Annual WEEE sent to landfill

3.1 System Dynamics for WEEE collective system

System dynamics modeling is the primary technology and methodology used in this paper. In this study, the system dynamics model application, STELLA Professional Online, will be utilized. System dynamics modeling is a computer-aided simulation methodology based on feedback systems theory. It allows us to solve and present complex models and relationships while simulating changes over time. By using the elements of system dynamics modeling and inputting various values and equations into the model, the simulation can be run, and data analysis can be generated. The working principles and theories of system dynamics modeling rely on a computer-based mathematical modeling approach for constructing complex systems. Feedback systems theory and other systems thinking approaches are integral to this computer-aided simulation methodology.

- Step 1: Problem Identification and System Definition. In this step, the problems and systems related to WEEE recycling in the targeted countries will be described and defined. As this paper focuses on WEEE recycling systems in EU countries (Sweden and Denmark) and Hong Kong, the systems will be studied for each of these four regions. Various governmental official documents and academic journals will be reviewed to understand the implementation of WEEE recycling and the relationships between different variables.
- Step 2: Translating WEEE Recycling Systems into System Dynamics Modeling Software: The WEEE recycling systems of different countries will be translated into system dynamics modeling software. Data and information related to WEEE recycling systems will be gathered by researching various papers. Relevant data and figures will be input into the model. In addition to the data, the relationships between different variables and processes will be identified and converted into ratios and equations to ensure these relationships are reflected in the results.
- Step 3: Model Simulation and Validation. After constructing the model and entering the data, the model will be run and simulated. Model validation will be performed after generating the results. If errors are identified, the process will return to Step 2 to revise the model and input the data again.

- Step 4: Analysis, Discussion, and Recommendations. Once Step 3 is completed and the model validation is successful, analysis and discussion will be conducted. Based on the system dynamics modeling results, policy suggestions for Hong Kong will be provided.

3.2 Model Development

For the model development in this paper, the system dynamics model is the primary software and framework used to evaluate WEEE in the targeted countries. The system dynamics model will be constructed based on the WEEE recycling system, incorporating recycling policies, and will simulate the WEEE flows and volumes in the targeted countries. In general, the WEEE flows in different regions are divided into several parts, including WEEE generation, WEEE collection processes, WEEE pre-processing systems, WEEE recovery and recycling systems, and WEEE sent to landfill systems. Thus, the system dynamics model for WEEE flows in the EU countries and other regions will be developed according to this structure. For the model settings, the time unit is set to "year" to simulate results over a 10-year period based on the input data. This time unit is chosen because WEEE recycling effectiveness takes time to change, and the data published by WEEE organizations and governments is typically annual. Therefore, "year" is considered the most suitable unit of time. Furthermore, as this paper is considered an initial study for evaluating the WEEE recycling system, the investigation is focused on the short term. Consequently, a 10-year timeline is chosen for model construction.

For model validation, a new model is built based on the original model to verify its accuracy by comparing the results from the two models. The construction and structure of both models are essentially the same. However, the data entered into the models differ. For the main model, the latest data and information from the corresponding countries are used, while the validation model uses data that is approximately 10 years older than the data used in the main model. Since the model simulates results over a 10-year period, entering data that is 10 years older allows the results generated by the model to be compared with the latest actual data. This approach enables the model to be tested and verified using both estimated and actual data. Figure 1 illustrates the diagram of the WEEE flow in the EU using the system dynamics model. The model is divided into seven interrelated parts. No additional factors or variables are added to the model except for the general WEEE collection growth rate, GDP Purchasing Power Parity (PPP), and Electrical and Electronic Equipment Put on the Market (EEE POM). This is because the purpose of the model is to depict the normal WEEE flows in the EU, and various studies have shown a close relationship between WEEE, EEE POM, and GDP (Baldé et al., 2017; Forti et al., 2020; Huisman et al., 2015). These factors are therefore included in the model to enhance its reliability and accuracy. For the generated WEEE amount in the EU, changes in WEEE generation are primarily influenced by GDP PPP growth. Research has identified a strong positive relationship between GDP PPP growth and changes in WEEE generation volume, showing that 0.5 kg of WEEE is generated for every 1,000 international dollars of GDP growth in a country (Baldé et al., 2017). Consequently, the GDP PPP changes for each year and the GDP PPP growth rate are incorporated into the model to calculate annual changes in WEEE generation in the EU. The initial WEEE generated is also included as a variable, serving as a base or starting point for WEEE generation in the EU. This figure is derived from 2021 statistics (Eurostat, 2021). The accumulated changes in generated WEEE in the EU are considered alongside the initial WEEE generation, representing the compound and cumulative growth of WEEE generation. Thus, the annual WEEE-generated volume can be determined.

The formal collected WEEE rate is another variable that influences the annual formal collected and recycled WEEE. Statistics indicate that the EU's collected WEEE has steadily increased from 2010 to 2021 (Eurostat, 2021). Therefore, the WEEE collection rate relative to annual WEEE generation is added to the model. A study has also examined the relationship between changes in EEE POM and WEEE collection volume (Baldé et al., 2017). A positive relationship was found, with a ratio of 1:0.49 between changes in EEE POM and changes in WEEE collection. The changes in WEEE collection influenced by EEE POM growth are thus incorporated as a growth factor for collected WEEE. As a result, the annual formal collected and recycled WEEE is determined by the annual WEEE-generated amount, the formal collected WEEE rate, and the changes in WEEE due to EEE POM growth. For the recycling and landfilling parts of the WEEE flow in the EU, non-recycled and non-recoverable materials and WEEE are sorted out and sent to landfills. Informal WEEE flows include all WEEE that is not formally collected by member states, such as WEEE sent to waste bins, mixed with metal scraps, or handled illegally. Additionally, some materials among the collected WEEE cannot be treated or recycled. Therefore, the non-recoverable ratio and informal WEEE flows are two variables affecting the total amount of non-recycled WEEE sent to landfills. Model validation is conducted to ensure the model's accuracy. This is achieved by using the same system dynamics model for WEEE flows in the EU but inputting data from 10 years prior (Statistics, 2011). By running the same model with a 10-year simulation, the results can be compared with current statistics from 2021. Using the 2010 data as the starting point (year 0), the final results of the

10-year simulation are expected to align with the data and trends observed in 2021. For annual formal collected and recycled WEEE, the results for year 11 are approximately equal to the actual 2021 values, with only a 1.96% error rate. The annual generated WEEE volume from the model is slightly higher than the actual value, but it remains reasonable and consistent with the increasing trend in WEEE generation volume in the EU. Therefore, the model is deemed appropriate for simulating WEEE flows in the EU.

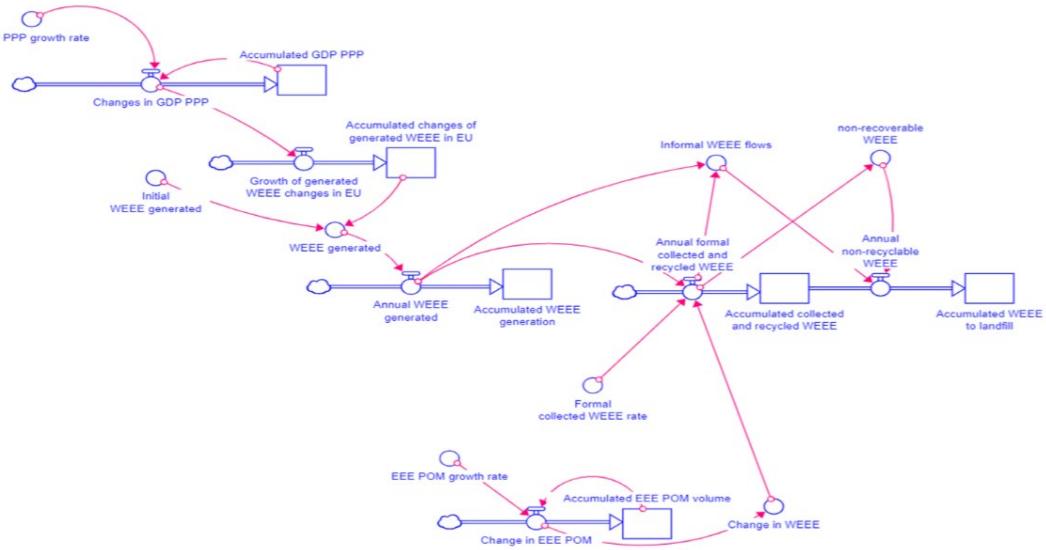

Figure 1. System dynamics model on the WEEE flow in EU

4. Results and Discussion

A system dynamics model for evaluating WEEE flows in the EU has been developed in the previous sections, followed by model validation. In the following sections, an analysis of the WEEE flow in the EU will be conducted. Different member states implement various WEEE policies and regulations to generate the final numbers reported in the WEEE Directive and the previous sections of this paper. Therefore, a more detailed investigation into the EU's WEEE flows and the systems used by different member states will be presented, along with a comprehensive explanation and analysis. To ensure fairness and accuracy in the comparisons between different models and countries, the structure of the system dynamics model for the WEEE recycling systems across different member states will remain similar. GDP PPP will be used as one of the variables for calculating the annual generated WEEE amount in each model, alongside other factors such as WEEE collection volume, WEEE recycling volume, and the amount of WEEE sent to landfills. To produce more detailed results on the annual generated WEEE in different member states for deeper comparison and analysis, the model will also include data on the volume of large WEEE generation and the volume of other WEEE generation categories. The results from the system dynamics model of the WEEE recycling system in the EU, as shown in Figure 2, indicate that the volume of annual WEEE generated, annual formally collected and recycled WEEE, and annual non-recyclable WEEE sent to landfills is steadily increasing. However, there is a significant gap between annual WEEE generated and annual formally collected and recycled WEEE, as illustrated in Figure 2. This demonstrates that the performance and effectiveness of WEEE collection and recycling in the EU is unsatisfactory, and there is room for improvement. Nevertheless, there are limitations to the actions that the WEEE Directive can implement due to the large number of member states in the EU. Each member state has its own WEEE recycling policies, and as a result, the WEEE Directive can only provide targets and supervision for each member state's WEEE recycling outcomes. The data published by the WEEE Directive on behalf of the EU and the results generated from the system dynamics model for EU countries provide an overview of all member states in the EU. However, these limitations make it challenging to study the WEEE recycling system in detail across all EU countries. To address these limitations, this study has been extended to include a comparison between the WEEE recycling system in the EU and Hong Kong. The WEEE recycling system in Hong Kong will be analyzed to evaluate its effectiveness and compare it with EU member states' systems. This approach will provide insights into the strengths and weaknesses of the WEEE recycling systems in these two regions.

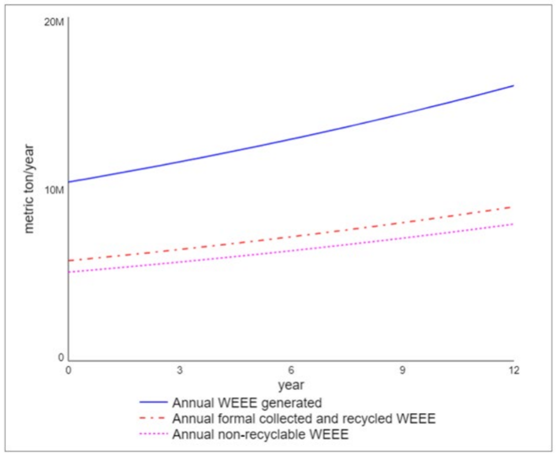

Figure 2. Graphical result on the System dynamics model on the WEEE flow in EU

4.1 System dynamics model on WEEE Flow and recycling system in Hong Kong

In Hong Kong, the government plays a vital role in the WEEE recycling system. The Producer Responsibility Scheme (PRS) was implemented in 2018, alongside the construction of WEEE·PARK, which began providing services in the same year (Environmental Protection Department [EPD], 2018a). ALBA Integrated Waste Solutions (ALBA IWS) Group, a recycling company, formed a joint venture with the government to design, construct, and operate the WEEE recycling facility at WEEE·PARK. This facility processes the collected WEEE into recycled materials (EPD, 2018a). However, under the WEEE recycling system in Hong Kong, WEEE·PARK processes only regulated electrical equipment (REE) and not all types of WEEE. Other types of WEEE are collected at various collection points in Hong Kong and transferred to other recycling companies for further processing (EPD, 2018b). Several major types of electrical equipment are regulated under the PRS in Hong Kong, including air-conditioners, refrigerators, washing machines, televisions, computers, printers, scanners, and monitors (EPD, 2018c). In addition to the requirement for sellers to provide free unwanted REE collection services under the PRS, the public can also dispose of their old REE or other WEEE through other proper recycling channels validated by the EPD. These channels include the GREEN@COMMUNITY recycling stations and the collection hotline operated by WEEE·PARK (EPD, 2018b). The GREEN@COMMUNITY recycling stations and sites are managed by non-profit organizations (EPD, 2018d). WEEE·PARK collects WEEE for further treatment through several regulated methods, including collection from producers, the WEEE·PARK hotline service, GREEN@COMMUNITY, designated collection sites in residential areas, and registered recycling companies (EPD, 2018a; EPD, 2018b). Over time, WEEE·PARK has expanded its collection network to include five regional collection centers in addition to its main facility located in Tuen Mun (EPD, 2018c). With this established logistics network, REE under the PRS is gathered at these regional centers and then transported to WEEE·PARK for further processing (EPD, 2018c). For WEEE outside the scope of regulation under the PRS, there are no specific regulations for its collection or recycling. The public is still allowed to dispose of unregulated WEEE in landfills or send it to non-registered recycling companies. This situation may encourage illegal treatment, disposal, or export of WEEE in Hong Kong. However, GREEN@COMMUNITY and recycling companies in Hong Kong accept non-regulated WEEE from the public on a voluntary basis (EPD, 2018d). The collected non-regulated WEEE from GREEN@COMMUNITY and other recycling companies is sent to licensed local recycling treatment companies or exported overseas for further recycling processes (EPD, 2018d). Once the REE is collected from the aforementioned parties, it is transported to WEEE·PARK for further treatment processes such as refrigerator processing, air-conditioner processing, dismantling and material sorting, and CRT and flat-screen detoxification (EPD, 2018c). The recovered materials from the recycling processes at WEEE·PARK are either exported to other countries, disposed of, or donated to those in need after refurbishment (EPD, 2018a). There are three main flows for collecting WEEE and transporting it to WEEE·PARK and GREEN@COMMUNITY (Figure 3).

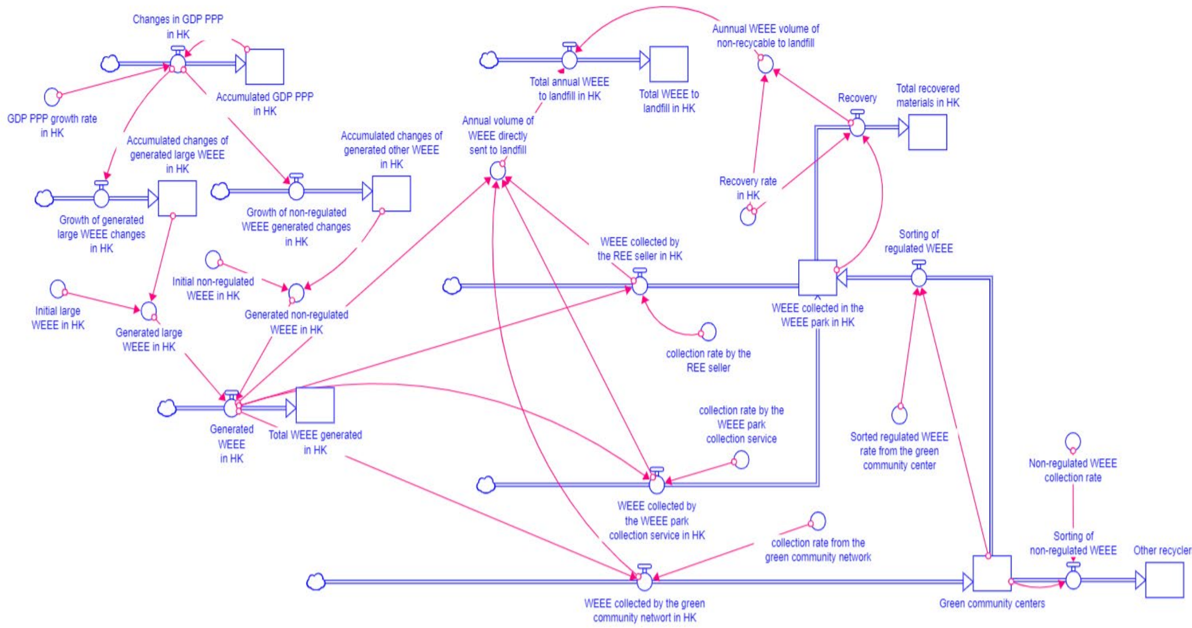

Figure 3. System dynamics model on the WEEE flow in Hong Kong

from the volume of generated WEEE in Hong Kong. Since REE under WEEE regulations is sent directly to WEEE·PARK by REE sellers, and the collection service provided by WEEE·PARK also delivers WEEE directly to the facility, the "WEEE collected by REE sellers in Hong Kong" and the "WEEE collected by the WEEE·PARK collection service in Hong Kong" are the inflows contributing to the accumulated volume of WEEE collected at WEEE·PARK. Only 34.24% of unwanted REE is successfully collected from the public, as indicated by the ratio of REE collected at WEEE·PARK to the total WEEE generated in Hong Kong (Environmental Protection Department, 2021). In addition to the overall WEEE collection rate in Hong Kong, the collection rate of REE sellers and the collection rate of the WEEE·PARK collection service are the variables determining the "WEEE collected by REE sellers in Hong Kong" and the "WEEE collected by the WEEE·PARK collection service in Hong Kong," respectively. For WEEE collected through GREEN@COMMUNITY, the collection rate of GREEN@COMMUNITY relative to the total generated WEEE in Hong Kong is used as a variable to estimate the amount of WEEE collected through the GREEN@COMMUNITY network. The volume of WEEE received by GREEN@COMMUNITY centers is accumulated, with the "sorting of regulated WEEE" being one of its outflows. Since unwanted REE is not the only type of WEEE collected by GREEN@COMMUNITY, the centers sort out WEEE that falls under government WEEE regulations and send it to WEEE·PARK for further treatment and recycling. The REE sorted out by GREEN@COMMUNITY centers becomes one of the inflows to the "WEEE collected at WEEE·PARK in Hong Kong."

4.2 Model validation for the system dynamics model in Hong Kong

Since the entire WEEE PRS and the WEEE · PARK is started and implemented in 2018, there are limited data and resources for the WEEE situation in Hong Kong provided before 2018. Even though there might be some scattered data on the WEEE in Hong Kong before 2018, the data is inaccurate as no regulations are made in that period. Hence, for the model validation on the WEEE recycling systems with the system dynamics model in Hong Kong, the GDP PPP and the major trends on the results estimated from 2010 to 2020 will be discussed for the appropriateness of the model.

For the accumulated GDP PPP in Hong Kong, the GDP PPP that in 2010 is inputted into the model. As shown in **Figure 4**, the actual GDP PPP was 441000954.8k in 2020. By comparing the data in 2020 with the simulation of the model, the final result with the data estimation in 2020 is around 413B, which is 413000000k. The results show that the numbers are similar, and both of the actual trend and estimated trend of the GDP PPP in Hong Kong are increasing with the similar rate. For the generated WEEE in Hong Kong, since there are limited data provided by the government, the generated WEEE in Hong Kong in 2010 is missing. Hence, the estimated results based on the growing trend and growing rate from the system dynamics is inputted to the model and test if the model running appropriately without errors. The estimated result for the generated WEEE in Hong Kong is around 43.4k tonnes in 2010 and 76.9k tonnes in 2020. By comparing with the actual numbers of generated WEEE of 70000 tonnes in Hong Kong in 2020, both of the estimated numbers in 2010 and 2020 are similar and reasonable with the increasing trends. For the WEEE recovery with the estimated results that generated from the system dynamics model on the WEEE recycling systems, the trend of the estimated recovery volume is increasing in a reasonable range. Hence, by summarizing the above data with the estimated and actual statistics, the model is considered to be appropriate. For the results on the volume of WEEE generated in Hong Kong as shown in Figure 4, a rise of the WEEE generation is estimated to be occurred. As the simulation for the model in Hong Kong is started in 2020 with the corresponding data inputted into the model, the final results from the model generated would be simulated as 2030. Hence, for the WEEE generated amount in 2030 shown from the model results, the volume is estimated to 117000 tonnes of WEEE with the increasing percentage of 61.23%. The results from the volume of generated REE and the volume of generated non-REE in Hong Kong are also showing an increasing trend on both categories, with the larger proportion on the non-REE volume. This shows that the generated waste of the non-REE is slightly more than the amount of the waste on REE and so the government should be more aware on the recycling effectiveness on the non-REE in order to enhance the entire recycling rate in Hong Kong.

As shown in **Figure 4**, for the WEEE collection processes in Hong Kong, the overall WEEE collection are rising by the increasing of each of the collection category, including "WEEE collected by green community network in HK", "WEEE collected by the REE seller in HK", and "WEEE collected by the WEEE · PARK collection service in HK". For further evaluation on the "WEEE collected by green community network in HK, the result from this category is not the final result of the WEEE collection by the WEEE · PARK as not all the collected WEEE are regulated by the government and could not be sent to the WEEE · PARK for further treatment. Hence, the estimated numbers of the unwanted REE collected from the GREEN@COMMUNITY should be the "Sorting of regulated REE". While as shown in Figure 4, the amount of the "Sorting of regulated REE" is also rising, meaning there is an estimated increasing amount of REE that are collected from the GREEN@COMMUNITY would be sent to the WEEE · PARK for further treatment. However, by comparing with the REE collected amount from "WEEE collected by the REE seller in HK" and "WEEE collected by the WEEE · PARK collection service in HK", the percentage growth of the "Sorting of regulated REE" are slightly slower than the other two collecting methods. The percentage increase on the "WEEE collected by the REE seller in HK" and "WEEE collected by the WEEE PARK collection service in HK" are 61.42% and 61.27%, whereas the increasing rate of the "Sorting of regulated REE" from 2020 to 2030 is estimated to be 54.44%. This may show that public engagement on recycling WEEE by using the facilities in the GREEN@COMMUNITY programs are less than other WEEE collection methods. For the overall WEEE collected volume in the WEEE PARK, the WEEE collected and sent to the recycling treatment facilities in WEEE · PARK is estimated to increase with a high percentage, at around 78.39% as shown in Figure 4. However, as the "WEEE collected by the REE seller in HK", "WEEE collected by the WEEE · PARK collection service in HK", and the "Sorting of regulated REE" are the variables for the overall WEEE collected volume in the WEEE · PARK and will directly affect the amount of the collected WEEE in the WEEE · PARK. Thus, these results would only be appropriated under the effective collection of WEEE in the society in Hong Kong. In terms of the capacity of the WEEE recycling facilities in the WEEE · PARK, the WEEE PARK will operate more shifts to fulfill the exceeded demand of the treatment when it is over 30,000 tonnes of WEEE. The problem could be solved, and it is assumed that the WEEE · PARK could handle the exceeded amount of the WEEE recycling treatment. Thus, there would not be any limits on the exceeding demands in the model when the results of WEEE collected in the WEEE PARK in Hong Kong are estimated to exceed 300000 tonnes.

	Accumulated GDP PPP in HK	Generated WEEE in HK	Recovery
0	346B	43.4k	12.6k
1	352B	46.5k	14.1k
2	358B	49.6k	15.4k
3	364B	52.8k	16.5k
4	371B	56.1k	17.6k
5	378B	59.4k	18.7k
6	384B	62.8k	19.8k
7	391B	66.2k	21k
8	398B	69.7k	22.1k
9	405B	73.3k	23.3k
Final	413B	76.9k	24.5k

	WEEE collected by the green community networt in HK	Sorting of regulated WEEE	WEEE collected by the REE seller in HK	WEEE collected by the WEEE park collection service in HK
0	831	439	19.7k	3.46k
1	878	447	20.8k	3.66k
2	925	466	22k	3.85k
3	974	490	23.1k	4.06k
4	1.02k	515	24.3k	4.26k
5	1.07k	541	25.5k	4.47k
6	1.12k	567	26.7k	4.69k
7	1.18k	594	27.9k	4.9k
8	1.23k	622	29.2k	5.12k
9	1.28k	650	30.5k	5.35k
Final	1.34k	678	31.8k	5.58k

	Annual volume of WEEE directly sent to landfill	Aunnual WEEE volume of non-recycable to landfill	Total annual WEEE to landfill in HK
0	46k	2.84k	48.8k
1	48.6k	3.18k	51.8k
2	51.2k	3.43k	54.7k
3	53.9k	3.64k	57.6k
4	56.7k	3.84k	60.5k
5	59.5k	4.04k	63.5k
6	62.3k	4.24k	66.5k
7	65.2k	4.44k	69.6k
8	68.1k	4.65k	72.8k
9	71.1k	4.86k	76k
Final	74.2k	5.07k	79.2k

Figure 4. Results on the model validation with the value of ten years ago in Hong Kong

4.3 Discussion

To enhance the effectiveness of WEEE recycling in Hong Kong, the recycling rate could be increased by improving the WEEE collection process. As mentioned in the above sections, the WEEE collection rate is relatively low—only around 34.24% of generated WEEE is collected (Environmental Protection Department, 2021). Therefore, public engagement in WEEE recycling schemes should be strengthened to raise awareness about WEEE recycling. Additionally, increasing the number of collection points could further encourage public participation Although some recyclers provide in-store collection services and others, such as The Loops Hong Kong, offer door-to-door WEEE collection services (The Loops Hong Kong, 2021), public awareness of these services remains low. Few people are aware of these companies, and the charges imposed by non-governmental recyclers for collection services also contribute to low public engagement. Since the collection service under the Producer Responsibility Scheme (PRS) provided by the government is free, while other recyclers charge for their services, the effectiveness of these non-governmental collection services is limited.

In light of this, it is recommended that the government take a more active role in WEEE recycling schemes and enhance public awareness through increased promotions and more collection sites. The more convenient WEEE recycling becomes, the more likely the public will engage in it. Consequently, the gap between the collection rate and the WEEE generation rate would narrow, improving the effectiveness of the entire WEEE recycling system in Hong Kong. Regarding the WEEE recovery process in Hong Kong, WEEE·PARK only accepts and processes regulated electrical equipment (REE). WEEE outside the scope of regulation is not accepted or collected by WEEE·PARK for further recycling. However, according to statistics released by the Environmental Protection Department (EPD) in Hong Kong, there is unused capacity at WEEE·PARK that could accommodate additional WEEE (Environmental Protection Department, 2021). The designed capacity of WEEE·PARK is 30,000 tonnes, while the average capacity utilization from 2019 to 2022 was only 23,000 tonnes. Thus, it is suggested that WEEE·PARK accept more WEEE outside the current government regulations and expand the categories of WEEE covered under the PRS. This would better utilize the recycling facility's resources and capacity, thereby increasing the recovery rate and enabling the recovery of more recyclable materials. Such an approach could also reduce illegal WEEE treatment by ensuring better management at WEEE·PARK compared to other recyclers in Hong Kong. With this recommendation, the total documented recycling volume in Hong Kong would increase, and the overall effectiveness of WEEE recycling in Hong Kong would be enhanced.

5. Conclusion

In conclusion, this study provides a comprehensive evaluation of the performance and effectiveness of Hong Kong's WEEE recycling system through the application of system dynamics models. By developing a deep understanding of Hong Kong's entire recycling system, an accurate and comprehensive model was constructed. The analysis reveals that while Hong Kong has made significant progress in implementing WEEE recycling initiatives, there are substantial gaps in the system's effectiveness when compared to international standards, such as those in the EU. Specifically, Hong Kong's number of WEEE collection points is critically low compared to the EU, where more extensive networks of collection facilities have been established. This disparity results in fewer collection points serving a larger population in Hong Kong, leading to challenges in managing the volume of WEEE and effectively engaging the public. The study identifies the number of collection points and public engagement as critical indicators of WEEE recycling effectiveness. Enhancing these factors could significantly improve Hong Kong's system by increasing accessibility and participation in recycling initiatives, as demonstrated by the EU's success in fostering higher recycling rates through similar measures. The findings underscore the need for targeted policies in Hong Kong to expand the network of collection points and foster greater public awareness and involvement in WEEE recycling. However, this study acknowledges certain limitations, primarily due to the availability of resources and data provided by the Hong Kong government. The system dynamics model was developed based on general assumptions and the current situation, with simulations predicting the effectiveness of the existing system over the next ten years. Future research could enhance the model's accuracy by incorporating more detailed data and statistics from diverse sources, including comparative data from the EU. Additionally, conducting interviews and surveys could provide valuable insights to refine the model and further improve the understanding of Hong Kong's WEEE recycling system.

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References

Balde CP, Kuehr R, Yamamoto T, McDonald R, D'Angelo E, Althaf S et al. The Global E-waste Monitor 2024. Bonn, Geneva: International Telecommunication Union, United Nations Institute for Training and Resources; 2024 (https://ewastemonitor.info/)

Checkland, P.B. *Systems Thinking, Systems Practice*, J. Wiley, Chichester. 1981,

Chu, Tao, Yongguang Zhong, and Weiqiang Jia. "Incorporating self-employed maintainers into WEEE formal recycling system: A system dynamic approach." *Journal of Environmental Management* 345 , 118777. 2023
Dieste, Marcos. "A Comparison of Different Models for Collection of WEEE in Europe." International Journal of Environmental Science and Development, EJournal Publishing, 2017.
Eurpoean Commision, 2017, Waste from Electrical and Electronic Equipment (WEEE) - European Commission, access in 2024
European Commission., *Directive 2012/19/EU on waste electrical and electronic equipment (WEEE).* 2019. Retrieved from https://ec.europa.eu/environment/topics/waste-and-recycling/weee-directive_en
Environment Protection Department, Producer Responsibility Schemes | Environmental Protection Department, 2024. https://www.epd.gov.hk/epd/english/environmentinhk/waste/pro_responsibility/index.html, accessed in 27 Mar 2024
Environmental Protection Department, *Monitoring of solid waste in Hong Kong: Waste statistics for 2021.* Retrieved March 1, 2023, from https://www.wastereduction.gov.hk/sites/default/files/msw2021.pdf
European WEEE Research Network, *WEEE2 – Definition and understanding of the 6 categories (15.08.2018).* 2018. Retrieved October 1, 2019, from https://www.ewrn.org/fileadmin/ewrn/documents/191001_EWRN_Definition_6_categories_fin.pdf
European Commission, Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). 2019. Retrieved March 1, 2023, from https://weee.gov.hk/en/background/regulatory-measures/
European Environment Agency, *Waste electrical and electronic equipment (WEEE) recycling in Europe.* 2021. Retrieved from https://www.eea.europa.eu
Favot, Marinella, et al. "Regulation and competition in the extended producer responsibility models: Results in the WEEE sector in Europe." *Waste Management* 145, 60-71. 2022
Forrester, Jay Wright. "Industrial dynamics." *Journal of the Operational Research Society* 48.10 (1997): 1037-1041.
Huisman, Jaco. "Eco-efficiency evaluation of WEEE take-back systems." *Waste electrical and electronic equipment (WEEE) handbook*. Woodhead Publishing, 2012. 93-119.
Hong Kong Legislative Council., *Producer Responsibility Scheme on Waste Electrical and Electronic Equipment.* 2018. Retrieved from https://www.legco.gov.hk
Sterman, John, "System dynamics perspectives and modeling opportunities for research in operations management." *Journal of Operations Management* 39 , 1-5. 2015
Statisica, 2011, Global e-waste - statistics & facts | Statista
WEEE·PARK, *Overview of WEEE·PARK operations and capacity.* 2022. Retrieved from https://www.weeepark.com.hk
WEEE·PARK, *Overview of WEEE·PARK operations and capacity.* 2022. Retrieved from https://www.weeepark.com.hk

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