E-waste Assessment in Malaysia

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Abstract

The exponential growth of e-waste contributes to a rapid increase in the amount of e-waste contaminants in landfills. In this study, the waste produced from the recycling of mobile phones will be quantified, highlighting the driving factors that affect the amount of waste reaching landfills. A system dynamics approach was adopted to understand the flow of mobile phone e-waste in an e-waste recycling facility in Malaysia. The analysis found that the efficiency of mobile phone PCBs' precious metals recovery is 13.62%. The analysis also demonstrated that public awareness has the greatest impact in reducing contaminants.

Keywords:

E-waste recycling; end-of-life mobile phones; landfill; system dynamics

1 INTRODUCTION

Waste is a growing problem in many countries [1]. One of the contributors of increasing waste generation is the fast-growing electrical and electronic waste [2]. Global technology enhancement has led to the rapid growth of electronic and electrical equipment (EEE). This is demonstrated by the rapid rate of technological development in electronic devices, especially mobile devices, personal computers and laptops. There is a high market demand driving the economic growth and sales of EEE due to the world's rapid population expansion [3]. Furthermore, the increasing demand of electronic equipment is directly related to the rising importance of technology to the global economy [4].

A study by the Economics Intelligence Unit (EIU) on the manufacturing of electronics in Asia [3], found that developed nations have gradually shifted the manufacturing of electronic technology to East and Southeast Asia due to the lower cost of labour in those countries, thus greatly transforming Asia into an important electronic manufacturing location. Currently, Asia is the largest supplier of the world's electronic products providing 67% of total global production. In the year 2000, the market demand for domestic electrical appliances in Asia was US $18.6bn, or nearly 10% of the world's demand, as shown in Figure 1. The exponential growth of market demand has led to a forecast by the EIU that the demand in Asia for electronic products will be US $159bn, or 22% of world demand, by the year 2014.

The increasing demand of EEE will result in the escalating amount of electronic devices or waste of electronic and electrical equipment (WEEE). E-waste is defined here as electronic and electrical equipment which is no longer useful to the holder or reaches its end-of-life and is disposed of [5]. Nevertheless, there is no standard definition for e-waste. EEE can be both a good business prospect and also an emerging global crisis to the environment if not disposed of properly. Monitors, televisions and mobile phones are some of the common electronic devices that contribute to e-waste generation.

The amount of e-waste generated in Malaysia in 2008 was around 688,000 metric tonnes, which was forecasted to be 1.11 million metric tonnes in 2020 [6]. These figures do not include the hidden trade of e-waste such as illegal imports from developed countries. The exponential growth of e-waste has led to increasing concern about its environmental impacts. Inappropriate e-waste disposal is detrimental to the environment and the population's health. Furthermore, the low level of public awareness has contributed the overflow of e-waste produced in Malaysia. Hence, studies on e-waste system's behaviour in Malaysia are important to identify the driving factors of the e-waste issues, such as government legislation [7] and the efficiency of e-waste recycling processes [6].

This paper aimed to trace the materials flow in an e-waste recycling plant and to find the driving factors to minimise e-waste that ends up in landfill. A system dynamics approach will be used to explore the systemic structure of e-waste recycling in a firm in Malaysia. The modelling of mobile phone's path will be the focus in this paper. Based on those models, tracking of input and output materials flow, key variables, leverage points, and the limiting factors that influence waste flow will be proposed to provide possible solutions for the current e-waste problem in Malaysia.

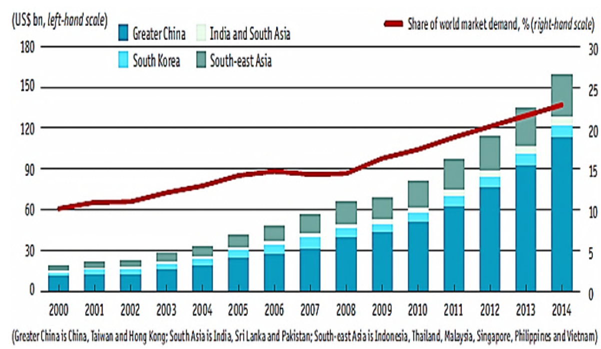

Figure 1: Market demand for domestic electrical appliances in Asia (exclude-Japan) [3].

2 E-WASTE IN MALAYSIA

Malaysia is one of the key countries that receives and dispatches e-waste [6]. According to the guidelines for classification of used EEE in Malaysia, e-waste is defined as waste from electrical or electronic appliances that consist of components such as: accumulators; mercury-switches; glass from cathode-ray tubes and other activated glass or polychlorinated biphenyl-capacitors; and components contaminated with cadmium, mercury, lead, nickel, chromium, copper, lithium, silver, manganese or polychlorinated biphenyl [8]. The quantity of e-waste generated each year is increasing exponentially as shown in Figure 2.

2.1 E-waste Management in Malaysia

E-waste recycling in Malaysia is managed by two divisions: the formal and informal sectors. The formal sector consists of licensed recycling firms, who either fully or partially recover e-waste. Firms in the formal sector appropriately manage e-waste according to the

Department of Environment (DOE) guidelines and regulations [15]. The informal e-waste recycling sector often uses lower efficiency techniques in processing and extracting valuable components [11]. Moreover, their main goal is to retrieve only valuable materials. Most of the informal recycling activities are carried out at "backyard" facilities who apply the most primitive processes [12].

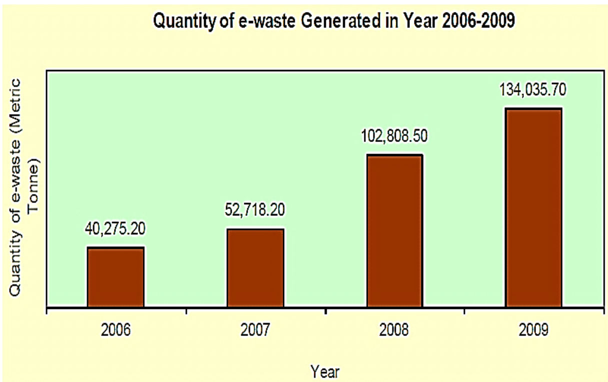

Figure 2: Quantity of E-waste Generated in Malaysia in Year 2006-2009 [10].

Most e-waste ends up in the informal sector because of its monetary incentives, regulation gaps, economic interdependence and their social reality [13]. It is a challenge for the government to control informal e-waste recycling activities, whose environmental impact is greater due to improper processing procedures [12]. Moreover, the downstream of e-waste recycling in the informal sector is difficult to be traced and involves transnational movements of illegal e-waste to and from other countries [14]. Another issue that arises from the flow of e-waste to the informal sector is the competition between the formal and informal recycling sectors for access to e-waste [12], which largely determines the final disposal of e-waste in the country.

Conversely, formal licensed e-waste recycling companies appropriately manage e-waste. Presently, there are 20 full recovery facilities and 132 partial recovery facilities in Malaysia [15]. All of the recovery facilities are owned by private companies. The main techniques or technologies used to recover precious metals from e-waste in Malaysia are wet chemical processes and electrolysis [16].

2.2 Obsolete Mobile Phones

Mobile phones are one of the fastest growing waste streams because of their short average life span, quick technology evolution, and affordability among consumers [17]. The mobile phone penetration rate in Malaysia is around 106% due to multiple subscriptions [18]. This indicates the ability to own more than one mobile phone per user and high demand in the mobile phone market. Furthermore, the mobile phone average life span is about three years [19]. The high demand among consumers and the short average life span imply that more obsolete mobile phones will be generated in future. However, initiatives to recycle part of the components of mobile phones such as mobile phone batteries have been carried out by the DOE and some manufacturers, including Nokia and Sony Ericsson, since 2002 [20]. The Penang E-waste Project studied mobile phone material flows. The results of the study are shown in Figure 3.

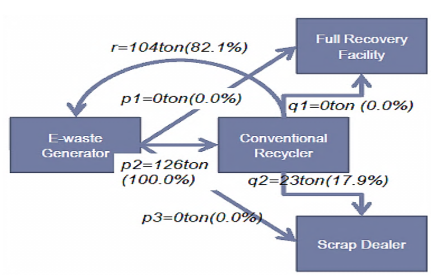

Figure 3: Simplified Mobile Phones Flow in Penang in 2011 [16].

3 METHOD

This study explored the e-waste recycling system through a case study on mobile phones at a formal recycling plant in Malaysia. Information was gathered through two phases: a survey questionnaire via email to understand the overall operation, and an on-site visit to gather information through tours of the facilities and interview sessions.

3.1 E-waste Modelling Process

A system dynamics approach was adopted to explore the systemic structure of the Malaysian firm's e-waste processes. This technique was used because of the dynamic and transforming complexity of the e-waste system in Malaysia. System dynamics assists in developing conceptual and virtual models by identifying the variables in the system and their relationships. Initially, a more generic approach was taken, only modelling the general e-waste path to clearly understand the overall e-waste flow in Malaysia. The focus of the problem was the waste produced by the recycling process, which defined the boundary of the system being explored. The materials flow of mobile phone waste was identified and captured in stock and flow diagrams. An example of a stock and flow diagram can be seen in Figure 4.

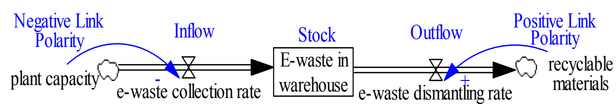

Figure 4: E-waste Stocks and Flows with Influence Diagram[1].

The initial diagram was expanded to further classify the specific processes that created the various stocks and flows of materials that undergo the different chemical processes. The detailed tracking of materials helped identify the data that was needed.

The next step was to formulate a dynamic hypothesis which was based on the behaviour of the documented e-waste system. Modelling tools were used to simulate the e-waste system according to the outlined problem and its boundary. A model boundary chart was developed to determine which factors were to be included and also helped to minimise the complexity of the model. Maps of the causal structure were then developed based on the preliminary hypotheses and key variables. A negative link polarity indicates that when the cause increases, the effect decreases whereas a positive link polarity shows that when the cause increases, the effect increases as shown in Figure 4. The generated influence diagrams were then reviewed by industry personnel and altered and changed where necessary.

The data obtained was used to evaluate the e-waste model and was used to assess how well the conceptual model reflected the virtual model. The conceptual and virtual model of mobile phones' waste path was examined closely and the modelling process was revised

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[1] When the plant achieved the maximum capacity, the e-waste collection rate will be reduced because the plant no longer able to receive more e-waste to be recycled (negative link polarity). When more recyclable materials are used to manufacture electronic products, more e-waste can be dismantled, thus increasing the dismantling rate (positive link polarity).

based on the feedback obtained. A positive loop identifier (the sign in the middle of a loop) indicates the reinforcing loop whereas a negative loop identifier indicates the balancing loop of the variables which circulate in the same direction of the loop. The key variables that drive the e-waste system and leverage points were identified using a feedback loop analysis on the stocks and flows of mobile phone.

4 E-WASTE FLOW ASSESSMENT IN A MODEL RECYCLING PLANT IN MALAYSIA

The following section uses data captured during 2011 from the Malaysian recycling firm. The generic e-waste stock and flow diagram is shown in Figure 5. E-waste is collected and sorted for further dismantling. After dismantling, the e-waste undergoes chemical processes to retrieve valuable materials. The waste is then sent to a different firm for treatment. The defined e-waste problem boundary is shown in Figure 5. This e-waste flow is generic for all types of e-waste in the formal recycling facility.

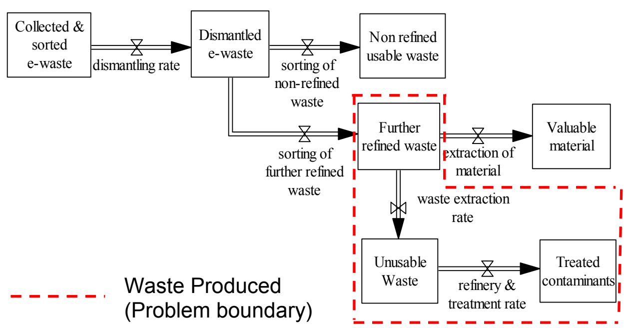

Figure 5: Generic e-waste flow with defined problem boundary.

The e-waste collected by the Malaysian firm passes through four main stations: the warehouse, mechanical plant, chemical plant, and waste treatment plant. Each respective station plays a specific role in the recovery of materials from e-waste. The warehouse stores, sorts, and dismantles the e-waste. A large space is needed to store the e-waste collected, especially WEEE that comes in large volume and a variety of sizes such as server base station (large size), printers and computers (medium size) or mobile phones and cables (small size). These components are disassembled and recyclable materials are collected. Next, the collected Printed Circuit Boards (PCBs) are categorised and transferred to the mechanical plant or chemical plant depending on the characteristics of the PCB: whether the recoverable materials are 'apparent' (easy to get to) or 'hidden' (not easy to get to). The PCBs then go through the precious metal processes in the chemical plant and the leftover waste from the chemical processes is treated at an external waste treatment plant. The high level e-waste process flow is shown in Figure 6. Because it has been sorted, the e-waste can be processed quickly and efficiently upon arrival. While this project focuses on mobile phones, and in particular their PCBs, a similar flow applies to other e-waste products.

4.1 Mobile Phone Flow Analysis and Overall Recovery

The stocks and flows of mobile phone materials generated reference the amount of mobile phone obtained in the year of 2011, which had a total of 12 collections. The general stock and flow diagram of mobile phones and their PCBs from collection is shown in Figure 7.

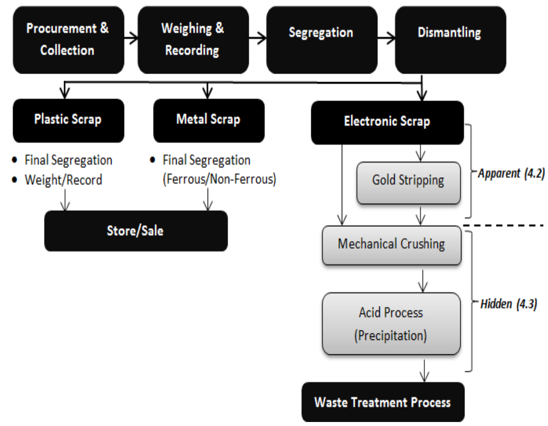

Figure 6: High Level E-waste Process Flow at the Malaysian Firm.

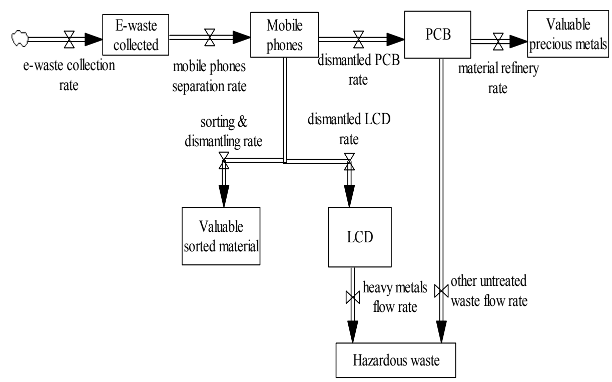

Figure 7: Stock and Flow Diagram of Mobile Phone Materials at the Malaysian Firm.

After the warehouse, the dismantled pile of PCBs goes through the apparent and hidden PCB processes to recover apparent and hidden valuable materials. The percentages of valuable precious metals and waste of mobile phone PCBs from both groups of processes are shown in Table 1: 54.5% of the outputs of the recovery process are valuable materials and 45.5% of outputs are waste.

Valuable Precious Metals		Waste	
Gold	0.022%	Fibre Waste	41.500%
Palladium	0.005%	Tin & trace metal	4.000%
Copper	52.500%	-	
Iron	2.000%	-	

Table 1: The overall mobile phone PCB material composition.

4.2 Stocks and Flows of Apparent PCB Process

The apparent PCB process is a chemical stripping process used to remove gold from the surface of PCBs. The dissolution, which includes the gold, is then purified. The stock and flow diagram of the apparent PCB process is shown in Figure 8.

There were 22.74 kg of dismantled PCBs that underwent the apparent process. The amount of alkaline (waste) solution produced from the stripping process was 3.452 kg. The purification process produced a further 3.448 kg of waste solution and 4.252 g of gold (99.9% purity).

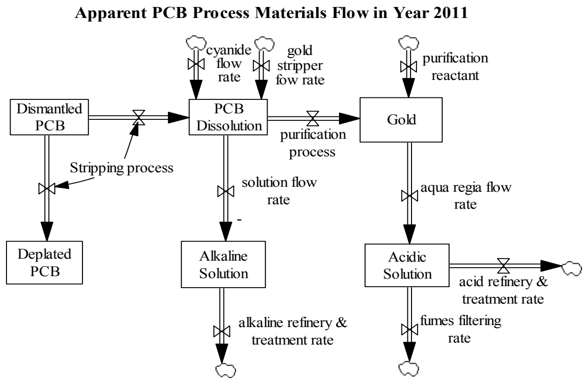

Figure 8: The Apparent PCB Process Materials Flow in the Malaysian Firm.

4.3 Stocks and Flows of Hidden PCB Process

The hidden PCB process is an acid chemical process used to recover precious metals contained in de-plated PCBs such as copper, palladium, and hidden gold. The stock and flow diagram of hidden PCB process is shown in Figure 9. 22.736 kg of de-plated PCBs were crushed and ground in the mechanical plant, before undergoing the two different types of dissolution in chemical processes shown. The estimated amount of powdered PCBs after the separation of ferrous metals using magnetic separator was 22.281 kg. The powdered PCBs are then mixed with nitric acid solution and copper/palladium precipitation agents who sum up to 62 kg to form powdered PCB Dissolution I. After the precipitation process, about 11.94 kg of precious metals retrieved, 50.06 kg of waste produced and 10.34 kg of solid filtered material proceeded to the next dissolution process, Dissolution II. In Dissolution II, 5.25 g of aqua regia solution and the gold precipitation agent are added according to the proportion of gold in the powdered PCBs. The total amount of Dissolution II which was about 10.35 kg produced two outflows: precipitated gold (0.75 g) and waste flow (10.35 kg).

4.4 Efficiency of Recycling Facility

The amount of dismantled mobile phone PCBs was 22.74 kg with an estimated 65.48 kg of processing chemicals added (such as precipitation agents for copper, palladium and gold; aqua regia solution; and alkaline cyanide solution) for the hidden and apparent process. After the mobile phone PCBs underwent the hidden and apparent processes for respective precious metals recovery, 11.95 kg of precious metals was retrieved (stripped gold, precipitated copper, palladium and gold) and 75.82 kg of waste was generated. The overall efficiency of precious metals recovery for mobile phone PCBs was 13.62%. The efficiency of apparent and hidden chemical processes was 0.74% and 16.15% respectively. From these figures, the efficiency of chemical processes for precious metal recovery from PCBs seems low and indicates a high waste being produced in the recovery processes. The total amount of mobile phone related materials was 857.68 kg. From this amount, 821.92 kg of usable materials are disassembled. The efficiency of disassembled valuable materials was 95.8%, which is relatively high. Based on the whole mobile phone recycling processes, the firm has a recycling plant efficiency of 97.2%

$$\eta_{\text{recycling efficiency}} = \frac{\text{precious materials (kg)}}{\text{total inputs (kg)}}$$

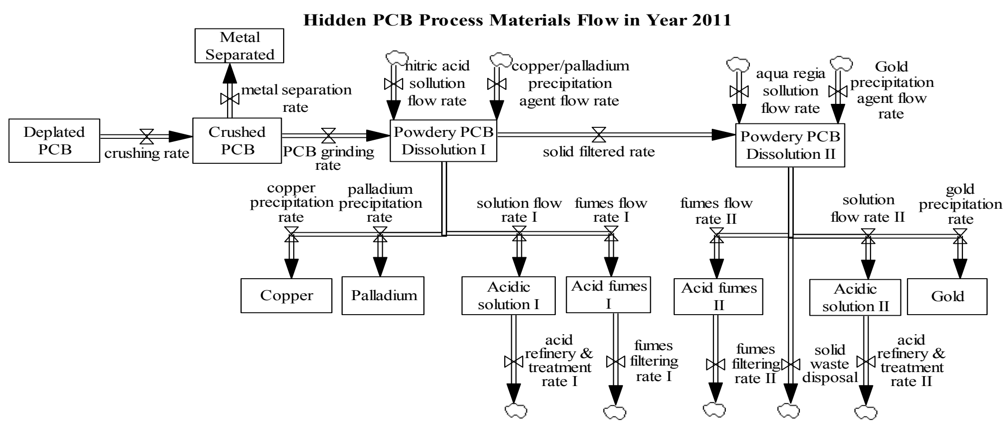

Figure 9: Hidden PCB Process Materials Flow in the Malaysian Firm.

Process	Useful Material Recovered (mass)	Efficiency
Precious metal recovery	11.95	13.62%
Hidden process recovery	25.51	0.74%
Hidden process recovery	11.94	16.15%
Disassembled materials	821.92	95.8%
Recycling plant efficiency	821.92 + 11.95	97.2%

Table 2: Plant Efficiencies.

4.5 Heavy Metals and Other Waste Products

The Malaysian waste treatment plant does not have the facilities to treat and refine hazardous waste such as solidified cyanide, heavy metal sludge, and fibre waste. Instead, the hazardous waste collected is sent to another waste management company for further treatment before disposal in landfill. In this paper, the material flows captured were based on the waste produced from the recycling processes in the Malaysian firm. The amount of produced waste flow after undergoing further waste treatment in another company is not traced. Among the items sent to the secondary facility are dismantled Liquid Crystal Displays, which contain toxic materials such as mercury in the liquid crystalline substances. The displays undergo a process called solidication or cementation. The waste is first mixed with solidified product at a bunker. It is then moved to a tipper lorry and mixed with additional solidified product. The mixture (cementation product) is then transported to a secure, authorised landfill where it is poured into the landfill and left to set as a solid concrete slab. The main objective of this cementation process is to fix the heavy metals into concrete to prevent them leaching into the ground water and the environment. Images of this process can be seen in Figure 10.

(a) Mixture of heavy metal materials and solidified products at tipper lorry. (b) Final disposal of cementation product at reserve area in secure landfill.

Figure 10: LCD Waste Treatment [21].

5 INFLUENCES OF MOBILE PHONE PCB RECYCLING

The recycling plant is effective in the recovery of usable materials; however, waste is still a problem. Therefore, the external system of mobile phone recycling is analysed to identify the driving factors of this problem. The recycling of mobile phones in the Malaysian firm comprises of two main inflows which are the PCBs that come from dismantling and the processing chemicals that are used during the apparent and hidden chemical processes. Conversely, precious metal recovery and waste products are the major outflows. The precious metals recovered are the firm's main source of revenue which offsets the high level of expenditure on chemical waste treatment. The simplified stock and flow diagram of mobile phone PCB recycling can be seen in Figure 11.

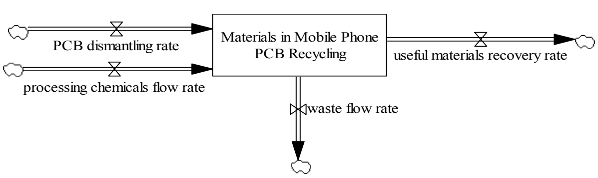

Figure 11: Useful Materials Recovery of Mobile Phone PCB in 2011.

5.1 Mobile Phone Collection

The mobile phones collected in the recycling plant have a tremendous impact on the PCB dismantling rate. The higher the number of mobile phones collected, the greater amount of PCB material can be recycled and the more efficient the plant will be (economies of scale).

The collection of mobile phones is influenced by four main variables: incentives, product turnover, manufacturer end-of-life (EOL) product take back, and public awareness. Incentives are always a driving factor to encourage more people to recycle their used mobile phones. These can be monetary incentives or as a trade-in during the purchase of a new mobile phone. Moreover, high product turnover increases mobile phone collection rates. The product turnover changes according to the average life usage of mobile phones, consumers' market demand and the second-hand market creating a material delay in mobile phone collection for recycling. Public awareness on e-waste collection among Malaysians is still low. Therefore, more mobile phones could be collected if public awareness on e-waste was increased through education, campaigns, or setting up more e-waste collection centres in convenient areas.

The two balancing loops of the recycling cost and incentives loops are shown in Figure 12. The cost variable indicates the upfront recycling cost that must be borne by the manufacturers. It will be used by the manufacturers for future take back schemes, such as the cost of mobile phone collection directly from consumers' home. The availability of such take back services will increase public awareness and encourage the return of used mobile phones to their manufacturers. Another alternative method to increase the mobile phone collection would be through monetary incentives. Nevertheless, the incentives offered will increase the upfront recycling cost. When the recycling cost increases, the manufacturers will decrease incentives offered to reduce future recycling costs.

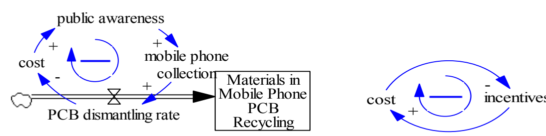

Figure 12: Balancing loops of mobile phone collection.

5.2 Waste Generated

There are a few variables influencing the waste flow rate as represented in Figure 13.

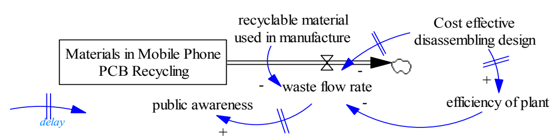

Figure 13: Influences on the waste generated from mobile phone recycling in Malaysia.

The influential factors of the waste flow rate are the recyclable materials used in manufacture, cost effective disassembly design, and the efficiency of the plant. When more recyclable materials are used in manufacture, the more usable materials can be retrieved during the recycling of mobile phones and thus less waste generated. A higher efficiency of recycling plant further reduces the waste flow stream by maximising the recovery of usable materials. Moreover, cost effective disassembly design will produce less waste flow since more materials are recycled with cost effective recycling processes, increasing the recycling plant efficiency. Nevertheless, its influence on the waste flow rate and efficiency of a facilty will take some time because of the inherent delay of mobile phones in the market. The increasing amount of waste ending up in landfill disposal will have an influence on the public awareness when it creates implications to public health. However, an information delay occurs as the waste flow rate has no direct impact on the public awareness unless it reaches a critical level.

5.3 Environmental Law Enforcement

The allowable chemical concentration variable is influenced or influencing other variables as described in Figure 14.

Environmental law enforcement can be measured through the concentration of chemical released to the environment. The allowable chemical concentration that can be released is greatly influenced by public awareness. As public awareness increases, the government will be pressured to take legal action to control the e-waste flow generated. Such action could include a reduction in the allowable chemical concentration that can be released to the environment.

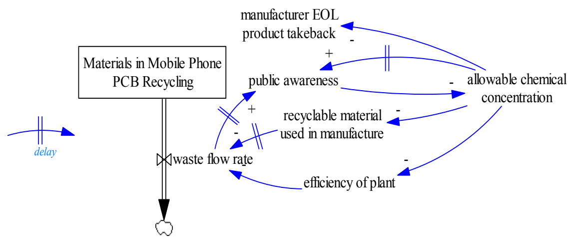

Figure 14: Influences of allowable chemical concentration that can be released in Malaysia.

Mandated Extended Producer Responsibility (EPR) can also help reduce chemicals that leech into the environment from landfill by ensuring more mobiles are collected. EPR among manufacturers, such as product take back schemes, increase EOL product take back, ensuring more mobiles are recycled and less potentially toxic material enters landfills. Nevertheless, the influence of EPR on the waste stream will take several years because of the inherent delay of mobile phones in the market. EPR is a voluntary initiative by manufacturers who are not mandated by current environmental policy in Malaysia [7]. Furthermore, law enforcement on e-waste legislation will increase the efficiency of a plant. Scrap dealers or informal recycling facilities which are commonly found in Malaysia [22] will be pressured to increase their plant efficiency to the same level as full recycling facilities in order to continue their business. The law enforcement balancing loops with public awareness act as pushing factors to further increase the efficiency of a plant and recyclable material used in manufacture (see Figure 14).

6 DRIVING FACTORS TO MINIMISE WASTE PRODUCTION

6.1 Phase 1: Incentive Reinforcing Loop

In the first phase, the key variables and leverage points to intervene in the e-waste system appear to be the incentives and manufacturer EOL product take back variables. These variables drive mobile phone collection rates while reinforcing the public awareness on e-waste. Nevertheless, the recycling plant capacity is the limiting factor because the plant could only handle a fixed amount of capacity despite more mobile phones being collected, as shown in Figure 15.

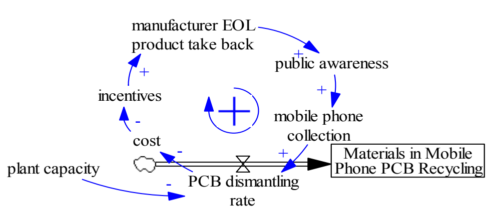

Figure 15: Incentive - Reinforcing Loop.

6.2 Phase 2: Law Enforcement and Public Awareness Loop

In the second phase, both the public awareness and environmental law enforcement have a significant impact in driving the system. Nevertheless, law enforcement, such as new policies and legislation, creates significant delays in reducing the waste in landfill as shown in Figure 16. Conversely, by increasing public awareness levels, the mobile phone collection increases through voluntary incentives or manufacturer take back which has an immediate sustainable impact and drives the environmental law enforcement as well as shown in Figure 17. Therefore, it appears that the central variable that will drive the whole system efficiently is public awareness.

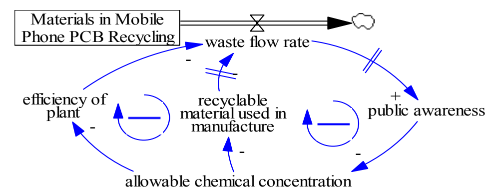

Figure 16: Law Enforcement - Reinforcing Loop.

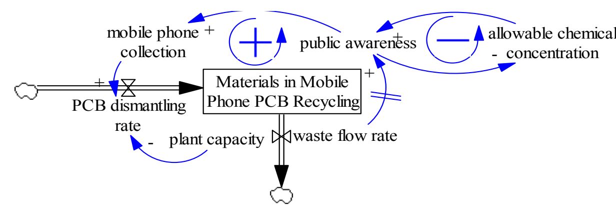

Figure 17: Public Awareness - Reinforcing and Balancing Loop.

7 CONCLUSION

The efficiency of mobile phone PCBs' precious metals recovery appears low, at only 13.62% from an environmental perspective. This is especially the case with the apparent chemical process since even more waste is produced. Nevertheless from an economic perspective, the firm is proficient in recovering precious metals with high purity from mobile phone PCBs, about 99.9% which generates profitable revenue and offset the cost of partial waste treatment.

The e-waste contaminant flows that end up in landfills are influenced by the amount of e-waste flow into the full recovery facilities, informal recyclers, public awareness, and government legislation related to e-waste. Therefore, the driving factors to minimise waste production are:

Incentives - The incentives given will increase the mobile phone collection into full recycling facilities in the initial phase.

Law Enforcement - Law enforcement related to e-waste reduces the toxic concentration that can be released to the environment.

Public Awareness - The public awareness will reduce the amount of e-waste ends up in landfills and reduce the toxicity of waste.

The variable that influences the system to reduce long term waste production in Malaysia is public awareness. Increased public awareness is a key variable for reducing environmental damage caused by chemicals from mobile phones and their recycling processes.

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