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Designing Scenarios for Integrated and Sustainable E-Waste Management: Case of Indonesia

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Abstract: Poorly managed e-waste can lead to public health and environmental problems resulting from the leakage of toxic e-waste substances. Building upon the integrated e-waste management (IEWM) concept, this study aims to propose an integrated and sustainable e-waste management strategy. It also suggests alternative processes for the effective collection, treatment, and disposal of e-waste. In its first stage of system dynamics modeling, the study employed an integrated approach comprising interviews and the Causal Loop Diagram (CLD). Based on the stakeholders' collaboration and resource management, two alternative scenarios have been proposed: 1) integration to community collection; and 2) scavengers as collection agents. Both scenarios have been implemented by means of public–private partnership (PPP) with industries. Interrelating factors such as governance, physical system, and sustainability aspects have also been analyzed. The proposed alternative scenarios can benefit the municipal government in terms of improving the existing e-waste management channels and, therefore, facilitating a better e-waste management system. They can also ensure better collaboration with related stakeholders in recycling, manufacturing, smelter industry processes, etc., together with strengthening the relationship between the community and the informal sector.

Keywords: causal loop diagram, e-waste management, integrated waste management, sustainability, system dynamics.

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INTRODUCTION

There is an urgent demand for secondary raw materials due to the depleting natural resources and Waste of Electrical and Electronic Equipment (WEEE) or e-waste has been proposed to be a prospective source (Tesfaye et al., 2017). E-waste originates from Electrical and Electronic Equipment (EEE) which is no longer being used and still consists of precious metals (i.e., gold, silver) and base metals (e.g., copper, aluminium, iron, nickel) which are valuable (Tesfaye et al., 2017). Some types of the e-waste are coming from computers, mobile phones, printed circuit boards (PCBs), batteries, until washing machines and refrigerators which mostly can be found from households (Zeng & Li, 2016). Being able to harness the valuable metals from these sources can suffice and answer our shortage problems.

Contrary to the potential, the concern circles around the fact that uncontrolled and unmanaged e-waste will result in public health and environmental damages (Ikhlayel, 2018). This is due to intricate constituents of e-waste which consists of metals, polymers, ceramics and other materials that demand special handling and treatment (Tesfaye et al., 2017). Between 2014 and 2019, the global amount of e-waste has increased up to 21 percent from 44.4 to 53.6 Mt. The global e-waste generation average was 7.3 kg per capita in 2019 and projected to double its amount in under 20 years (Forti et al., 2020). However, in 2019, the amount of documented and recycled e-waste only made up to less than 20% of generated e-waste (Forti et al., 2020). Hence, a proper e-waste management system is needed to ensure no environmental damages, as well as maximise resource recovery and gain the optimum benefits from economic, environmental, and social perspectives.

Despite the global attention to e-waste management, developed countries have advantages due to the readily available infrastructure and regulations (Sthiannopkao & Wong, 2013). On the contrary, e-waste problem in developing countries is more challenging due to a combination of several issues, such as insufficient regulations and enforcement, improper e-waste management system, informal sector domination and low awareness from the citizens to dispose of e-waste responsibly (Ikhlayel, 2018; Maheswari et al., 2019). In addition, e-waste is getting attention because of the huge amount of resource absorption and unsustainable handling at End-of-Life (EOL) stage, which includes the lack of infrastructure for proper collection and treatment to ensure minimum health and environmental hazards (Forti et al., 2020). This problem poses a new degree of threat since most of unmanaged e-waste is in developing countries with their high population and subsequent growing Electrical and Electronic Equipment (EEE) consumption rate (Sthiannopkao & Wong, 2013).

Existing studies which focused on e-waste management in developing countries were ranging from e-waste generation estimation (Andarani & Goto, 2014; Dasgupta et al., 2017; Peralta & Fontanos, 2006), collection system (Qu et al., 2013; Shi et al., 2020), barriers, challenges and opportunities (Kumar & Dixit, 2018; Parajuly et al., 2018), until ways to deal and integrate with informal sector (Ardi & Leisten, 2016; Maheswari et al., 2019). However, there is a dearth in literature which covers an integrated e-waste management (IEWM) system as a solution for the challenges, centres upon policy-making and factoring sustainability aspects. Moreover, as a developing and fourth-most populated country in the world, Indonesia possesses both prospects and challenges for e-waste management which are unique to be explored. The urgency heightened as the projected e-waste annual growth is reaching 15% (Santoso et al., 2019). Specifically in Indonesia, to the authors knowledge, a study which also discusses collection and disposal routes from household e-waste generation is still limited.

Therefore, this research aims to contribute to those gaps by exploring the potential improvements of integrated e-waste management (IEWM) which factors sustainability aspects (i.e., economic, environmental, and social) which is called the integrated and sustainable e-waste management, as well as proposing alternative scenarios for collection, treatment and disposal routes using a case from Bandung City. The alternative scenarios are based on stakeholders' collaboration and cover e-waste generated by households, such as televisions (TVs), refrigerators, washing machines, computers and mobile phones (Andarani & Goto, 2014). Since this study focuses within the scope of municipal waste management, the main decision-maker is municipal or regional government. The research questions are formulated as follows:

RQ 1. How can an integrated e-waste management (IEWM) system be improved into an integrated and sustainable e-waste management system based on the case of Bandung City, Indonesia?

RQ 2. Based on the improvements, what are the proposed alternative scenarios for integrated and sustainable e-waste management system based on the case of Bandung City, Indonesia?

This study employs a combination of interviews and modelling using Causal Loop Diagram (CLD) as the first stage of system dynamics modelling, using a systems thinking approach to see this problem holistically for answering those questions. In accordance, this study contributes theoretically by expanding the IEWM concept and considering sustainability aspects as significant factors in dealing with today's waste problems. The presented CLD can be used as a basis for building further system dynamics simulation. In addition, the recommendations can give practical insights and improve policymaking at municipal government level towards designing a more effective e-waste management system.

METHODS

This study employs a mixed methods which combines qualitative data obtained from interviews and CLD as the first stage of system dynamics modelling. Systems thinking approach is used as a basis to provide a holistic view in understanding a problem which can be helpful in improving e-waste management system within the scope of a city (Ding et al., 2018; Ng et al., 2019; Ng & To, 2020). Moreover, the rationale to use a systems thinking approach is based on the complexity of e-waste management system, such as the need of policy- and decision-maker who understand the issue completely; the collaboration between related stakeholders; the interrelated nature of e-waste management system between individuals and institutions; and concern about the impacts to the sustainability aspects (environment, economic and social).

The general approach of this study is as follows. First, we studied the existing research on e-waste management, as well as the government regulations pertaining to e-waste in Indonesia. This helped us to do the second step which is the system analysis. This step was aimed to set the boundary and further understand the context which is Bandung City, Indonesia. The boundary of the study is municipality, with an emphasis on household e-waste (e.g., mobile phones, computers, laptops, washing machines, refrigerators, TVs). We chose Bandung as one of the exemplar cities in Indonesia due to its growing initiatives regarding waste management and sustainability (Khoiruman & Haryanto, 2017). E-waste generation in Bandung itself is predicted to increase by 4.5 kilo tons/year as the improvement of the citizen's wealth (Widyarsana et al., 2021). Several studies have also been conducted in Bandung which can be a great avenue to be further developed (Humaira & Sembiring, 2018; Maheswari et al., 2019; Widyarsana et al., 2021).

Then, the data collection and analysis were aimed to provide alternative scenarios based on the integrated and sustainable e-waste management, as well as stakeholders' collaboration as the development of IEWM concept. Accordingly, we conducted primary data collections through semi-structured interviews with three main stakeholders. Each of them has a differing role, whether in policymaking or provides channels for e-waste collection and handling as shown in Table 1. These stakeholders provided input and vision to shape the improvement and alternative scenarios. Sustainability considerations were also made sure to be incorporated into the proposed improvement and alternative scenarios, as well as depicted in the CLD models. The CLD is beneficial to visualise the interrelation and causal relationships between factors affecting the system (Papachristos, 2019; Zamil & Hassan, 2019); thus, the problem can be understood better, including the interrelated factors between e-waste management components and sustainability aspects (i.e., economic, environmental and social). Finally, the results and analysis were validated by an expert to yield better results and recommendations.

Table 1 Data collection and Interview Contents with the Key Stakeholders

No	Interviewee	Role(s)	Interview Contents
1	Bandung City Environmental and Sanitation Service	Policymaker for municipal waste management in Bandung City, Indonesia.	• Current practice of hazardous waste management in Bandung City. • Problems and challenges of hazardous waste management in Bandung City. • Future targets and plans for hazardous waste management in Bandung City.
2	E-waste community in Indonesia	• Provides drop-box services for e-waste collection in Indonesia, including Bandung City. • Sorts and transfers collected e-waste to treatment plants/ industries.	• Current practice and data of e-waste collection system. • Personnel and operational needs. • Problems and challenges of e-waste collection system. • Funding sources and financial data of e-waste collection system. • Future targets and plans for e-waste collection system.
3	Waste bank service in Bandung City	• Provides waste collection, sorting and processing facilities (general waste types) across Bandung City with incentive mechanism.	• Current practice and data of collected waste. • Personnel and operational needs. • Funding sources and financial aspects of waste collection system.

RESULTS AND DISCUSSION

Existing E-Waste Management Condition in Bandung City, Indonesia

Since the waste overflow incident in 2005, the government of Bandung City has made huge efforts to educate, facilitate, as well as create waste-related programs which target citizens and institutions, to better manage the municipal waste (Zulkhairil, 2020). On the household level, the main practice that is highly enforced and maintained is '3Rs' – reduce, reuse and recycle. Movements based on community or districts and subdistricts are noticeable and encouraged by the government, even some of them are monitored within prioritisation levels (Dinas Lingkungan Hidup dan Kebersihan Kota Bandung, 2019). The focus generally targets solid waste, and the need to separate waste is mainly for organic and inorganic waste, emphasising on highly generated inorganic waste, such as plastics and papers.

Meanwhile, existing regulations in Indonesia, both at national and regional level classify e-waste as a type of hazardous waste. Other countries which have implemented e-waste regulations, such as China, Japan and European countries usually have their own definition and classification of e-waste, as well as the regulations which aimed to control e-waste flow and regulate consumers and producers regarding their roles in handling e-waste (Cao et al., 2016; D'Adamo et al., 2016; Nithya et al., 2021; Yoshida et al., 2016). The latest regulation in Indonesia is the Government Regulation No. 27 of 2020 about specific waste management. As one of the types in specific waste, the regulation requires municipal government to design hazardous waste management, which includes e-waste whether from household, commercial, industrial or other institutions. The management entails the activities of reduce, reuse, recycling and treatment through proper sorting and collection. Furthermore, not only the municipal government, producers or manufacturers also have responsibility to reduce the content of hazardous materials in their products and provide a take-back system (a form of EPR supporting system) as channels to bring back their products to them. The objective of this regulation is to reduce unmanaged hazardous waste which will end up at landfills or pollute unwanted places.

In accordance with the regulation, municipal government of Bandung City is working on the details of the technical instructions for hazardous waste management for all levels. For the existing system, the government still focuses on commercial level, such as for companies or institutions in which they have responsibility to dispose of the hazardous waste properly and the government provides channels to transfer the waste to licensed third-party companies. Moreover, the government is also working on establishing sanitary landfills for hazardous waste. But unfortunately, there is still a lack of e-waste specialization on the household level regarding how it differs from other hazardous or inorganic waste and how to dispose of it to the available channels.

One of the main challenges is the fact that selling e-waste to the informal sector is still the common practice, since this is regarded as the main and profitable channel, as well as the perception that e-waste still has a market value even after no longer being used. This phenomenon is also evident in other developing countries, such as India and China (Ardi & Leisten, 2016; Chi et al., 2011; Shi et al., 2020). Another challenge is the citizen's awareness. For people who already have environmental awareness, disposing of e-waste properly will become a self-interest. However, for others who still lack the awareness, they need encouragement or incentives to shift their behaviour from the status quo. With a limited municipal government fund and multiple sectors to prioritise, there will be financial schemes which need to be developed. Hence, the design of e-waste management system should be cost-efficient and effective to handle e-waste.

In the meantime, there are several facilities which are available to dispose of e-waste. These channels are registered and managed responsibly by formal institutions and communities, thus ensuring the minimum health and environmental risks. The first channel is the waste banks, managed by non-profit organisations or co-managed by the municipal government. The waste banks function as a collection point, where people can drop-off all kinds of tradeable waste (e.g., plastics, metals, papers), get a reward (i.e., waste bank balance) based on the quantity and type of waste and eventually can be exchanged by an incentive. There are several other activities in the waste bank centre as well, including sorting, recycling and waste trading. Meanwhile, the second channel is e-waste drop-box. The drop-box facilitates people to dispose of e-waste, accessible by people in public places. They also can drop-off their e-waste at the drop-box agent, similar to the waste bank, but only for e-waste and there is no reward system, solely relying on people's awareness. Both channels depend on the willingness of people to deposit their e-waste, whether by reward or no reward system. Challenges remain, for the waste banks, most of the waste is still plastics. While for the drop-box, the segment of people who use it is still limited to young adults. Hence, although the channels exist, the utilisation on both channels for e-waste is still minimum. Further improvement of the existing e-waste management system which will not incur high cost and provide sustainable solution is needed.

Proposed Integrated and Sustainable E-Waste Management System

Ikhlayel (2018) provided a concept to integrate e-waste with a solid waste management system called integrated e-waste management (IEWM) (Ikhlayel, 2018). The integration is developed by using an existing collection system and disposal sites, along with available recycling facilities, in which it can substantially ease the financial burden of government. Chi et al. (2011) also proposed IEWM by cooperating with the informal sector, such as employing labour from informal sector for manual dismantling, providing industrial park to manage informal recycling or enhancing the technologies in informal recycling.

Furthermore, the IEWM should also be accompanied by a sustainable waste management. This concept consists of two main systems, which are physical and governance. Physical system entails e-waste management activities, i.e., collection, treatment and disposal and recovery, in which there are considerations for human health, environment and closing the loop of resources, consecutively. Meanwhile, the governance system entails

inclusivity, financial sustainability and proper policies. To achieve integration and sustainability, the combination between the two systems must be adopted and adjusted to the regional characteristics (UN-HABITAT, 2010).

Based on the IEWM and sustainable waste management concepts, along with reflecting them to the condition of Bandung City, some improvements based on three aspects can be identified. First, the regulations are needed to be enforced and elaborated by the government, i.e., municipal government, along with the implementation strategy. The implementation strategy entails technical, financial and sustainability considerations to provide a comprehensive and long-term vision. The regulations can control a range of stakeholders, including consumers and producers. For the consumers or at household level, such program like '3Rs' can be enforced, maintained and monitored based on the districts or subdistricts for better decentralisation. Retribution fee based on 'polluters pay' principle can also be applied (Maheswari et al., 2019), whether as e-waste recycling fees based on the type of EEE or merged with municipal waste retribution (Pandebesie et al., 2019), or even integrated in the form of deposit-refund system (Wang et al., 2020). Meanwhile, for the producers or manufacturers, the regulations should cover the EPR concept with more details, as mentioned in Act No. 18 of 2008, to enforce the product design responsibility and provide a take-back system, or in the form of collaboration and agreements between municipal government and the producers, i.e. Public-Private Partnership (PPP) (Andarani & Goto, 2014). This regulation to encourage stakeholders' collaboration will highly align with the UN's Sustainable Development Goals (SDGs) (Jones et al., 2017).

In addition, based on the low probability that the formal system will take over the domination of the informal sector, the government also has to find alternatives to integrate with the informal sector in the long run (Besiou et al., 2012). This can be done through regulations which are developed to embrace the informal sector, for example establishing a registered second-hand market or employing scavengers as door-to-door collection agents. Several options also found in the literature, such as facilitating informal e-waste businesses through industrial parks or legalising them, upgrade and make their technologies safer for their work safety, health and environment (Chi et al., 2011; Ikhlayel, 2018; Kumar & Dixit, 2018).

Second, the physical elements of e-waste management. For the collection until disposal and treatment system, existing channels such as waste banks and drop-box can be maximised for collection. These are highly encouraged ideas, as mentioned in the literature (Ikhlayel, 2018; Kazancoglu et al., 2020). The main waste bank can be used as the e-waste exchange platform where citizens can exchange their e-waste and get an incentive. Moreover, the e-waste exchange platform also functions as a hub to connect micro collection channels which are the drop-box and waste bank branches to related disposal and treatment stakeholders, such as manufacturers, smelters, recycling companies and treatment facilities. Some connections are already established in the existing system, such as between the drop-box collection system from community and commercial hazardous waste treatment from municipal government. Hence, expansion for collaboration between stakeholders are highly feasible, since there are many types of collaboration that can be initiated, whether as co-managers, financial, collection and treatment support. The utilisation of these facilities will also promote '3Rs' principle, circular economy from the stakeholders' collaboration, even EPR concept with the take-back system for the producers (Andarani & Goto, 2014).

Third, the awareness of citizens. Promotional campaigns are encouraged to educate and remind the citizens of waste sorting from the generation point. In addition to that, the government can design a deposit-refund system, in which there will be retribution for waste management, including for e-waste. This retribution is based on the 'polluters pay' principle which has been implemented in other countries as well (Kumar & Dixit, 2018; Maheswari et al., 2019; Wang et al., 2020). After the retribution, the citizens will also get a chance to have an incentive as refund, if they put their waste at the e-waste exchange platform. The same reward such

as bank balance and electricity tokens can be used as well. This system can leverage the collection points and improve citizens' awareness towards responsible waste disposal. Finally, to conclude the improvement, the links between the government, consumers and producers, as well as the physical system which comprises of e-waste generation, collection, disposal and treatment stages are depicted in Figure 1 as a proposed integrated and sustainable e-waste management system.

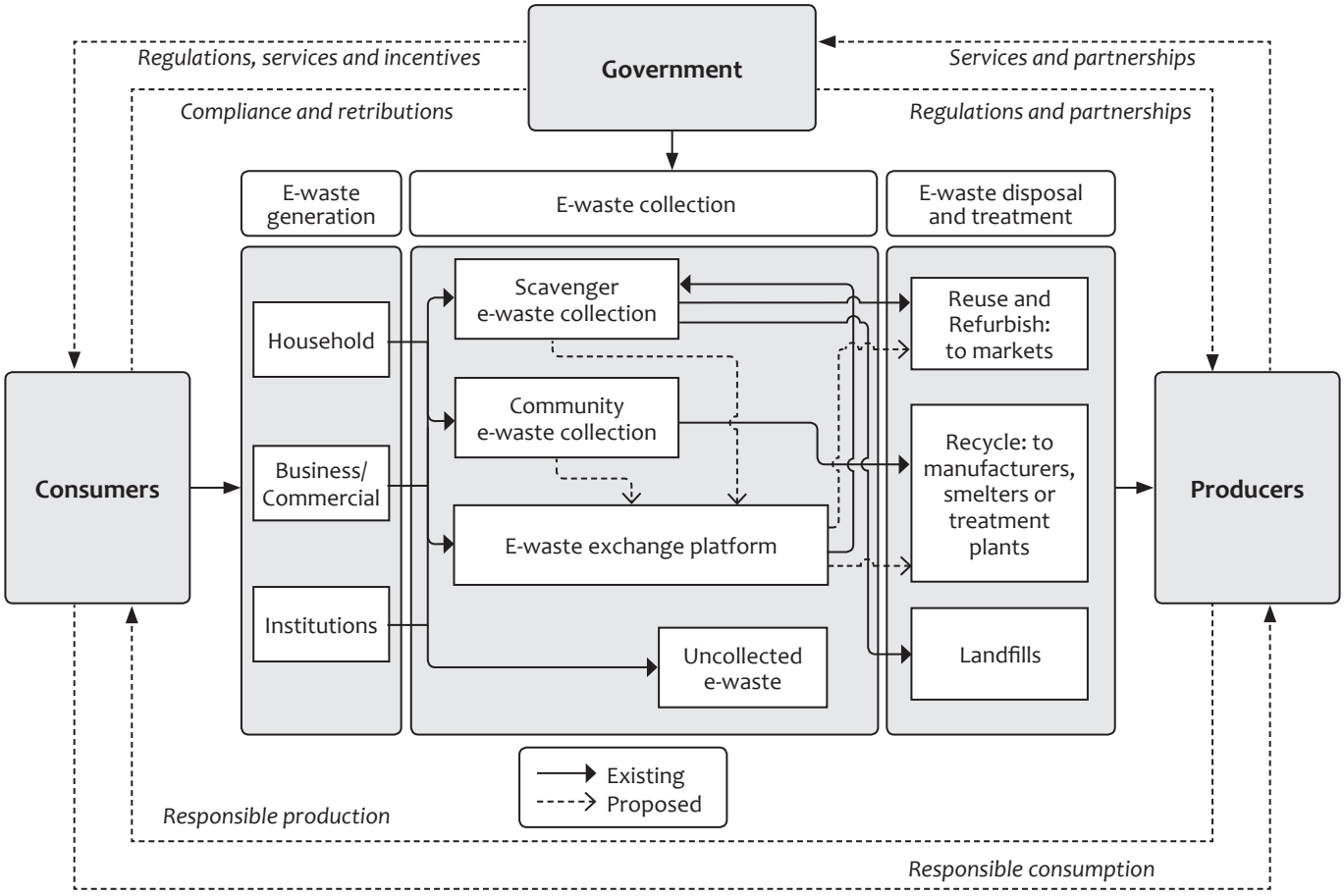

Figure 1 Proposed Integrated and Sustainable E-Waste Management System

Alternative Scenarios for Integrated and Sustainable E-Waste Management System

Based on the proposed improvement of IEWM, two main alternative scenarios are developed to give options for municipal government, targeting the collection, treatment, and disposal routes. These scenarios are also represented as stages, since the improvements are more feasible to be done incrementally, thus giving a growing space for the government to develop and implement an IEWM system. The first scenario is the moderate e-waste collection and PPP which focus on maximising the existing infrastructure for waste collection, which are the e-waste exchange platform (main waste bank), waste bank branches and drop-box. The municipal government can collaborate with the community who already managed the network of drop-box and further strengthen the system by enforcing people to dispose of e-waste to the available channels. For the treatment and recycling, collaborations through PPP are initiated to handle e-waste properly, as well as recover value from e-waste for secondary raw materials. Producers can benefit from the collection services, while the government can get benefits from the responsibly handled e-waste. Moreover, PPP with profit-sharing scheme can provide greater

benefits to producers by reducing raw materials cost and to the government by improving the overall services for waste management with the additional revenue.

The second scenario is the extensive e-waste collection and PPP which expand the coverage of e-waste collection by integrating with informal sector, specifically the scavengers as door-to-door collection agents. They also can be employed in the waste banks to help with the sorting activities. From the employment aspect, they can get a fixed income and being registered as workers which will eventually improve their welfare. The government can ease the burden of competing with the informal sector and find a solution to combine the two systems. However, integrating with the informal sector may take a longer time and more difficult to manage, since the informal sector, along with the actors within that chain already has its own network and system. Further endeavour must be done to approach them strategically and able to persuade or change them with minimum resistance. The main distinction between the proposed alternative scenarios can be seen in Table 2.

Table 2 Main Distinction Between the Proposed Alternative Scenarios

Alternative scenario	Integration with community	Integration with informal sector	Integration with industries
Moderate e-waste collection and PPP	✓		✓
Extensive e-waste collection and PPP	✓	✓	✓

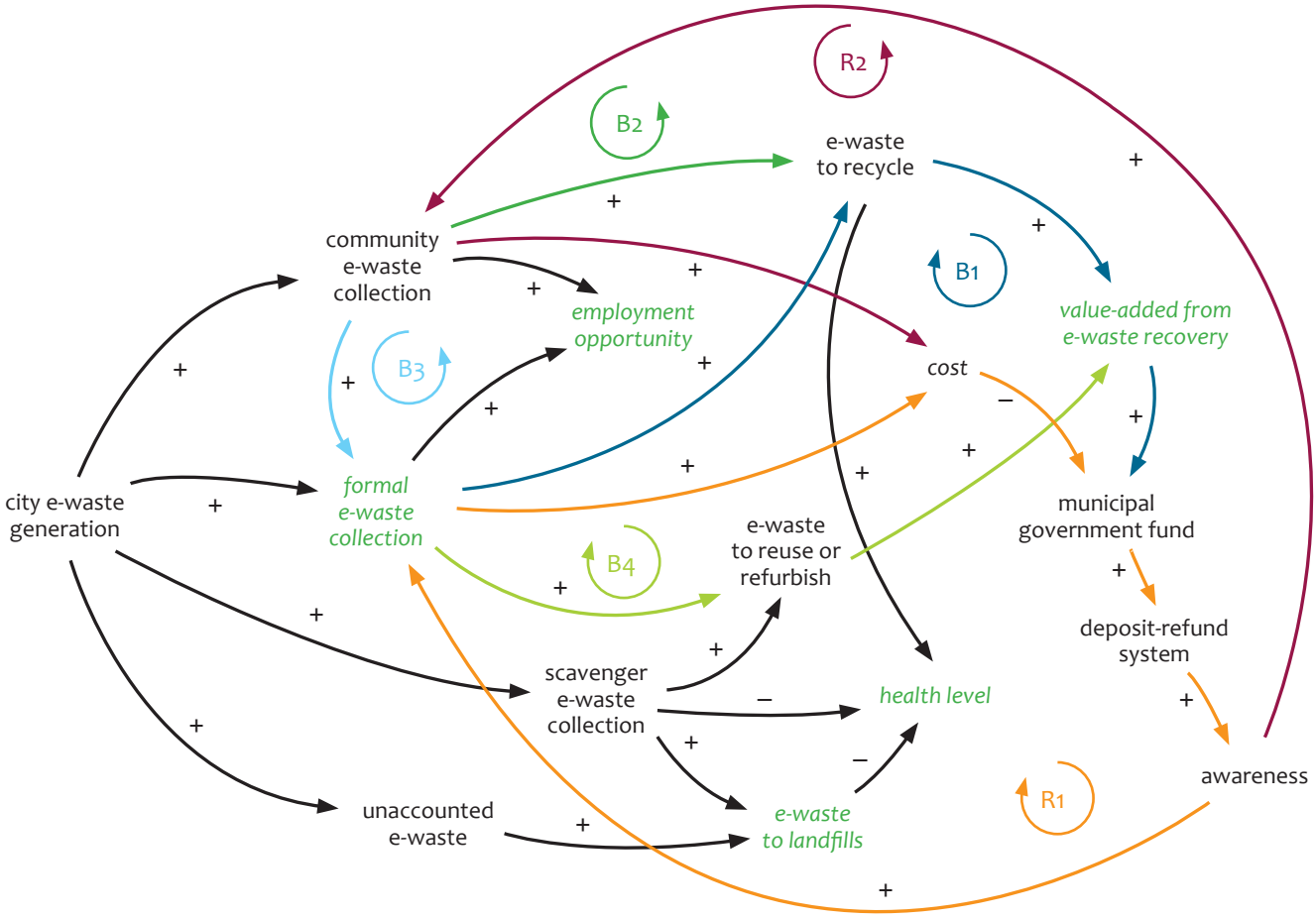

Figure 2 CLD for Scenario 1

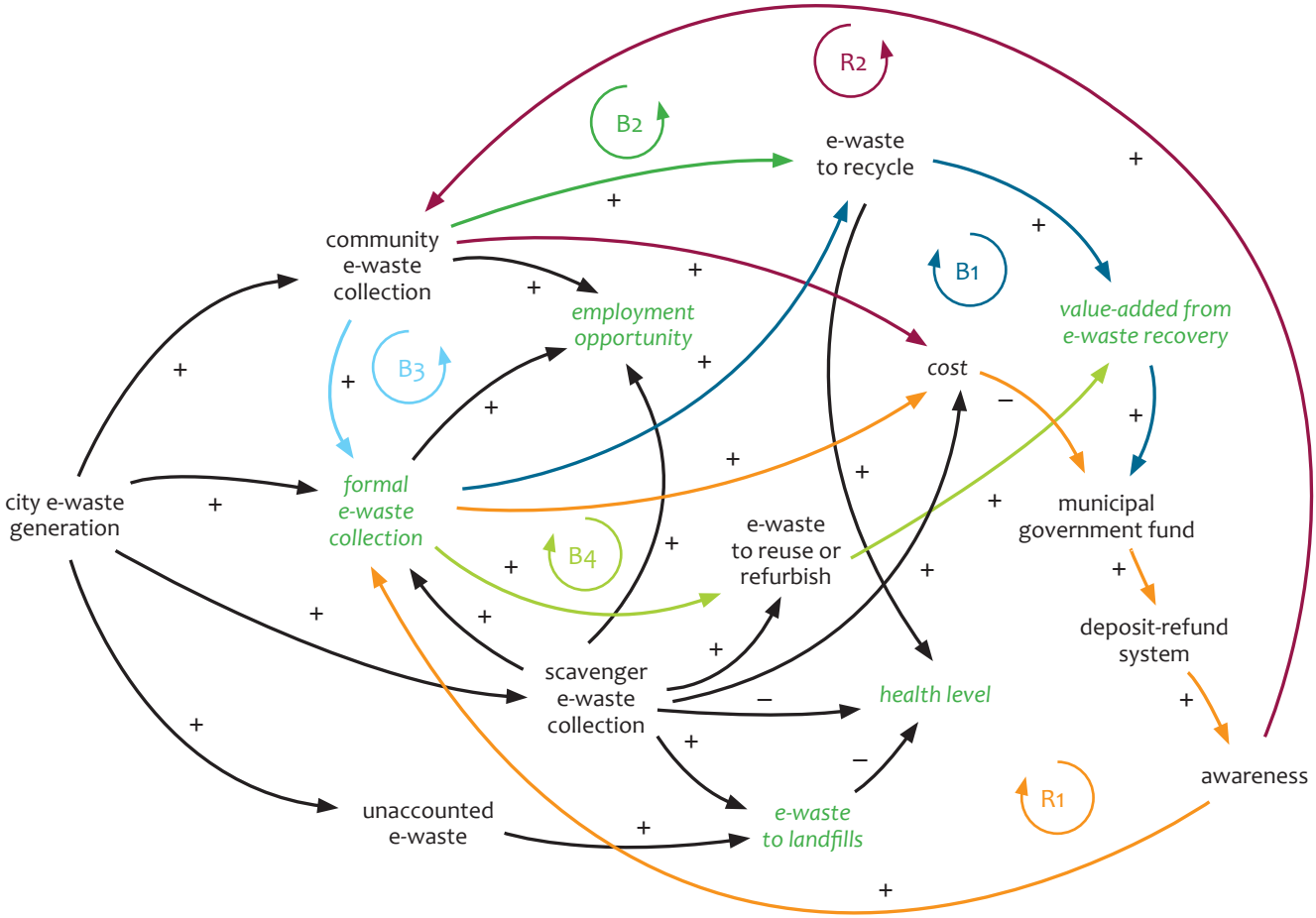

Figure 3 CLD for Scenario 2

Additionally, to have a better understanding of the alternative scenarios and the associated factors, a CLD for each scenario is constructed (Figure 2 and 3), along with the sustainability indicators which can help for further assessments. The CLD can be used as the basis to develop the system dynamics simulation for future studies. Six sustainability indicators (i.e., economic, environmental and social) that suit this study context are chosen, which are *cost* and value-added from e-waste recovery for economic (Kazancoglu et al., 2020; Maheswari et al., 2020); e-waste to landfills and formal e-waste collection for environmental (Forti et al., 2020); and health level and employment opportunity for social aspect (Kazancoglu et al., 2020; Maheswari et al., 2020).

For the first scenario, there are two reinforcing loops (R1, R2) that centre upon *cost* which affects negatively to municipal government fund. R1 loops around the *formal e-waste collection*, while R2 around the *community e-waste collection*. For the balancing loops, B1 and B2 are riveting around *e-waste to recycle* with improves *value-added from e-waste recovery* and eventually will improve *community e-waste collection* (B1) and *formal e-waste collection* (B2). B3 exists because of the collaboration between municipal government and community which will further improve the overall *formal e-waste collection*. B4 circles around *e-waste to reuse or refurbish* which will improve *value-added from e-waste recovery* and eventually *improve formal e-waste collection* as well.

Meanwhile, for the second scenario, the loops are the same as the first one, adding relationships between *formal e-waste collection* and *scavenger e-waste collection*, as well as an improved *employment opportunity* due to the scavengers' employment by the municipal government. This reflects the main distinction with the first

scenario in which there is an integration with scavengers as one of the main actors in informal sector. Further impacts for both alternative scenarios to the sustainability indicators are shown in Table 3.

Table 3 Impacts of Each Alternative Scenario to Sustainability Indicators

Alternative scenario	Economic	Environmental	Social
Moderate e-waste collection and PPP	• Additional cost for infrastructure. • Potential revenue from e-waste reuse, refurbish and recycling.	• Medium control of e-waste collection, treatment and disposal. • Less uncollected e-waste to landfills.	• Citizen can reap benefits from incentives (deposit-refund system at e-waste exchange platform); • Better inclusivity through community employment. • Public health concern is relieved due to controlled e-waste disposal.
Extensive e-waste collection and PPP	• Additional cost for infrastructure and labour. • Potential revenue from e-waste reuse, refurbish and recycling.	• High control of e-waste collection, treatment and disposal. • Less uncollected e-waste.	• Citizen can reap benefits from incentives (deposit-refund system at e-waste exchange platform); • Better inclusivity through community and informal sector employment. • Public health concern is relieved due to controlled e-waste disposal.

CONCLUSION

This study proposes an improvement for integrated e-waste management (IEWM) called the integrated and sustainable e-waste management. The improvement is aimed to enforce regulations, integrate physical elements of e-waste management system and improve citizen's awareness. An e-waste exchange platform is proposed and highlighted to connect the collection to treatment and disposal routes, along with maximising the available infrastructure. The focus of the improvement is to establish strong relationships between the government, especially municipal government, producers or industries in general and consumers of EEE. From the improvement, alternative scenarios for municipal government are developed to enhance the current collection system and transfer e-waste to industries which handle proper treatment and recycling for e-waste. Interrelating factors within each scenario are also portrayed in the CLD as the first stage of system dynamics modelling, embedding sustainability aspects as indicators. The first scenario focuses on collaborating with community e-waste collection and initiating PPP with related industries. Meanwhile, the second scenario further expands the coverage of e-waste collection through employing scavengers as door-to-door collection agents, as well as maintaining and extending PPP. Each scenario has its own degree of change which should be made by the government, as well as considerations in terms of financial stability, social and environmental impacts. In short, the second scenario presents more social challenges and needs more resources, since integrating with informal sector is more complex. However, an effort to reach informal sector integration will have huge impacts on the overall e-waste networks, as well as improve social welfare through new employment opportunities. There are several limitations of this study which lead to the future research agenda. First, since this study focus on city-wide e-waste management system, not all stakeholders are given an in-depth analysis of the needs and roles, such as for producers or industries. New research which expands the horizon into the producers are also needed, such as explore more on EPR concept and its potential integration to the existing collection system. Second, in reality, the policy at municipal government level also highly depends on the national level, which is

not covered in this study. Hence, further study should be aimed to capture government role at national level, integrate the plan nationally, set the framework and vision, as well as making the enforcement become more formal and impactful. Financial research on the deposit-refund system to find the value to be implemented by the government is also necessary for policy design. Lastly, this study provides a general framework in a qualitative manner. In terms of assessing the alternative scenarios, system dynamics simulation is required to develop the CLD model, especially for such case in which the availability of e-waste data is limited.

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