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Proposal for used electronic products management in Mexicali

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A R T I C L E I N F O

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A B S T R A C T

Mexicali, a Mexican city located near the US-Mexico border, has faced several challenges related to adopting an integrated e-waste management system. Thus, the main objective of this work is to propose a new system to be implemented in phases. The current system is evaluated using several methodological approaches including field studies, surveys, interviews, and quantitative modeling via material flow analysis. We suggest the need to properly integrate both the formal and informal sectors to achieve the optimal system that mitigates environmental impacts while preserving the positive social and economic traits of the current system. Thus, without supplanting the current reuse, refurbishment, repair and maintenance practices, a hybrid system is proposed, based on a centralized facility that primarily handles those parts or materials that create environmental impacts and health hazards if mishandled. Furthermore, a decentralized transition phase toward the new system is recommended.

Introduction

Information technology plays a key role in modern personal and business activities, facilitated by electrical and electronic equipment (EEE). The growing possession of EEE has several benefits for society, such as enabling virtual work during the pandemic, supporting Sustainable Development Goals #4, 8 and 9 (UN General Assembly, 2015), and enabling digital currency (de Vries and Stoll, 2021). There are also negative aspects such as the (inter-) personal aspects studied by Turkle (2017) and the environmental dimensions (Eerkens et al., 2009; Hischier et al., 2020; Jonkers et al., 2016; Osibanjo and Nnorom, 2007; Williams et al., 2008; Zhang et al., 2020).

Some products reach their end of use (EoU) with one owner and can be returned to service through the reuse, repair and maintenance sectors. Other products at EoU have also reached their end of life (EoL) and require proper dismantling and/or recycling. In particular, management of EEE at the EoL — known as used electronic products (UEP),[1] e-waste, or waste EEE (WEEE) — has raised important concerns in communities, non-governmental organizations (NGOs), academia, and governmental agencies around the world. Some of these concerns relate to inefficient and unsafe recovery and recycling practices seen in some countries of the Global South causing environmental and human health impacts (Heacock et al., 2015; W. Li and Achal, 2020; Rautela et al., 2021). These practices include the open burning or thermal treatment of e-waste parts (T.-Y. Li et al., 2019; Tue et al., 2016), the use of toxic substances to recover precious metals from printed circuit boards (Terazono et al., 2017), and the release of refrigerants (Duan et al., 2018). Over the years, some environmental NGOs and researchers have held the international trade of e-waste from the Global North to the Global South responsible for such recycling practices (e.g., BAN 2002, 2005). However, based on the increasing adoption of EEE in the Global South and associated domestic generation of UEP (Gusukuma et al., 2022; Yu et al., 2010), this argument becomes weaker with time. Also, Kahhat and Williams (2009) and McMahon et al. (2021) state that the trade of used electronics is also intended for reuse purposes. Other scholars focus on the economic and technological obstacles associated with EoL management (e.g., Ghodrat et al., 2016).

Several aspects of the UEP management situation have been assessed

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[1] We use this term, UEP, here to remove the connotation of waste.

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by different scholars; we will reference them throughout this work. Technological approaches to mitigate the environmental impacts of resource recovery and increase efficiency have been proposed (Awasthi et al., 2019; Jadhav and Hocheng, 2015; Wang and Xu, 2015). Conditions have been assessed to enable a more decentralized implementation of e-waste recycling plants, such as in the case of wasted printed circuit boards or WPCB (D'Adamo et al., 2019). The importance of the informal sector in e-waste systems around the world has motivated researchers to study its situation and relationship with the formal sector, to propose improved connections with Extended Producer Responsibility (EPR) systems (Davis, 2021; Davis and Garb, 2015), or to promote the informal/formal linkage that stimulate economic benefits and mitigate environmental impacts (Williams et al., 2013).

Awasthi et al. (2021) recommend attention to consumer behavior and stakeholder interaction in order to enhance the circular economy in the life cycle of EEE, while Parajuly et al. (2020), discuss the importance of the connection between behavioral change and UEP management when understanding the array of possibilities of UEP linked to the circular economy. Ofori & Opoku Mensah (2021) studied how consumers can improve their willingness to take action to achieve more sustainable e-waste management. Appoloni et al. (2021) proposed a way to holistically assess risks in the UEP management sector.

In the last decade, there has been a significant increase of countries (78 countries) that address e-waste in their legislation, policy or regulation (Forti et al., 2020), with some regions or countries taking the lead in e-waste management (Balde et al., 2017). Some of these strategies target the EoL stage, de-emphasizing the importance of the reuse, repair, and maintenance sectors; however, some aspects are slowly changing in favor of the latter (Lepawsky, 2020; Lepawsky et al., 2021; McMahon et al., 2019; Makov & Fitzpatrick, 2021). Japan has a long history of managing UEP, including TVs, refrigerators, washing machines, air conditioners, computers (Ignatuschtschenko, 2018; Kahhat et al., 2008). Laws have been enacted there specific to a set of devices and to differentiate responsibilities (e.g., collection, transportation cost) between consumers and producers (Aoki-Suzuki et al., 2012) and a considerable share of the generated e-waste is collected and handled domestically (Ignatuschtschenko, 2018).

Since 2002, the European Union (EU) has been developing an e-waste management system based on the principle of EPR (E. U. Directive, 2002; Shittu et al., 2021). A decade later, the WEEE Recast directive was adopted to encourage the reuse of UEP (Directive 2012/19/EU, 2012). In some of its member countries, the EU e-waste management strategy has achieved important goals, such as improved collection rates compared to inflows to the market (e.g., 58% in Austria or 82% in Estonia) (Forti et al., 2020; Ylä-Mella and Román, 2019). However, according to Mazahir and colleagues, certain desired benefits (e.g., promoting reuse or reducing environmental impacts) remain unmet. They argue that product-specific perspectives and targets could bring environmental benefits and avoid unintended consequences (Mazahir et al., 2019).

While other countries (e.g., South Korea, Switzerland), exhibit good examples of UEP management, many jurisdictions still lack an e-waste management strategy or any sort of political action toward achievement of that goal (Forti et al., 2018; Shittu et al., 2021). Dismissing the importance of e-waste management could lead not only to environmental and human health issues but to squandering of resources. For example, Gusukuma and Kahhat (2018) pointed out that opportunities for resource recovery in Peru could be lost due to the lack of a management plan related to the analog TV blackout. A similar scenario was seen in Mexico, where the promotion of digital TV was not accompanied by a UEP management plan (Diaz, 2015).

Given the lack of policies in the Global South, solutions applied to the Global North are being applied in the Global South.[2] These merely replicate the successful experiences, often without considering the specific social, cultural or political context of the location where they will be applied. We consider that while the intention is positive, these efforts may lead to unsuccessful attempts or will negatively affect the most vulnerable stakeholders and practices, if the context is not considered. Thus, in this research work we explore a UEP management solution for a location in the Global South[3] that incorporates the local context.

Case study objective, scope and background

Based on the necessity of UEP management systems in the Global South, the objective of this case study is to propose a UEP management system in the city of Mexicali, Mexico that responds to the social, cultural, and political traits of the area. The city of Mexicali (see Fig. 1) is part of the municipality with the same name, which additionally includes rural areas. It is the capital of the state of Baja California (BC) which borders the US states of California and Arizona. Mexicali is located at the northern border of BC, at 32°39′48″N, 115°28′04″W, and in 2020 had a population of about 854,000 (INEGI, 2020).

Mexicali faces several challenges related to adopting an integrated UEP management system. As the city is located near the US-Mexico border, it is associated with high volumes of transborder movement of new and used goods, including EEE and WEEE. The former secretary of the BC Environmental Protection Department, Thelma Castañeda Custodia, was quoted as saying: "Electronics, tires, clothes, a ton of things pass through as goods that are still usable, but very quickly they become waste, rubbish. That's what has us, especially on the border, stuck with a problem now of accumulating tires and other types of waste — electronics and other types of waste that people simply don't know where they can dispose of it." (James, 2018).

In Mexico, municipalities are responsible for providing urban services. One such service is the management of urban solid waste (USW), which includes street sweeping, and the collection and transportation of waste to the transfer zones. After transfer zones, waste subsequently goes to the final disposal site, which is an above-ground, unlined landfill. Two decades ago, environmental engineers assessed the main landfill used by Mexicali, *Hipolito Renteria*, located 25 km southeast of the city, adjacent to agricultural fields (Silva-Kurumiya & Fuentes-Valdez, 2000). They identified multiple public health, community nuisance, and environmental concerns pertaining to the soil, water, and air. According to interviews with 'gleaners' who retrieved recyclable materials from the landfill, the majority were satisfied to work without a boss, however, 2/3 would accept a permanent job if offered.

According to Mexico's legislation, UEP requires special handling, and in the case of the business sector, companies need to take responsibility of it, not the municipality. However, there is a flow of UEP of household origin present in the current USW which requires special handling, and this is where the municipality should focus its efforts and incorporate it into its management. According to a study of UEP generation in Mexicali, 3.68% (by mass) of the USW is UEP (Cruz-Sotelo et al. 2014), and the biggest problem is that there are no other mechanisms for adequate disposal. Therefore, it is necessary to search for strategies to create and implement mechanisms for UEP management.

Researchers have explored other aspects of USW in Mexicali. Used tire management in BC poses a similar set of management challenges, including large volumes of cross-border trade, along with environmental and public health hazards (Spitz, 2018). A characterization of household solid waste in Mexicali estimated the recovery potential of organic and

[2] One defining characteristic of an e-waste system in the Global South, as opposed to the Global North, is the prevalence of the informal sector.

[3] While Mexico is a country of the Global South, it is also an OECD member. As a result, in the case of the transboundary flow of e-waste and the Basel Convention, Mexico operates as an OECD country.

Fig. 1. Geographic location of the study area. Note the landfill, Ejido Hipolito Renteria. Citation: Imagery © TerraMetrics, Map data © 2021 INEGI.

inorganic wastes (Ojeda-Benitez et al., 2003). An assessment of USW in Mexicali highlighted poor implementation of regulations (Calva-Alejo and Rojas-Caldelas, 2014).

Materials and methods

The first stage of the research involved collecting data to learn from UEP management practices in other regions, and then acquiring an in-depth understanding of the situation in Mexicali. The next stage involved analyzing the quantitative and qualitative data collected. In the last stage, an integrated UEP management system was proposed, informed by the findings. The main methodological tools used in each stage are described below and summarized in Figure S.1 and section 2 of the Supporting Information (SI). While the proposed management system is applicable for all UEP, the devices analyzed were desktop and laptop computers, mobile phones, televisions, printers, refrigerators, and clothes washers and dryers.[4] The period of empirical assessment was 2015–2016, with projections made until the year 2035.

The proposed system has four main objectives. First, mitigation of environmental and human health impacts related to UEP collection, dismantling and recycling activities. Second, integration of the main actors (e.g., formal recyclers, waste pickers) without threatening the first objective. Third, the increase of collected and recycled UEP, without discouraging maintenance and repair (M&R), and reuse practices. Fourth, a system capable of being financially sustainable.

[4] One main reason was that the set of devices is very similar to those included in periodic governmental surveys by INEGI: desktop computer, laptop computer, tablet, mobile phone, open digital TV decoder, videogame console, radio, analog TV, digital TV.

Understanding the current situation

Review of existing e-waste management systems

We sought academic and gray literature containing descriptive examples of e-waste management systems and regulatory initiatives pertaining to regional UEP management systems in Latin America (e.g. ONUDI-FMAM, 2021), and the world. The insights gleaned from some of these studies are presented in the results section. This search included documents in Spanish and English as well as the authors' participation in various international e-waste workshops and conferences coordinated by international agencies (e.g., UNIDO or IEMN). We then analyzed the systems to identify commonalities or differences with Mexicali, which allowed us to identify best practices or alternative configurations that the proposed Mexicali system might adapt.

We identified the UEP flows through each management system reviewed. Quantitative estimates of the flows were captured when available. Note that the scope of some of the systems reviewed was a country, while for others it was a city; this is a function of the assessments undertaken and available for review. In some cases, UEP management systems at the country scale influence the systems at the city scale.

Mexicali field studies

Several field studies were performed during the years 2015 and 2016. The goal was to better understand the origin of the UEP and different patterns of use, reuse, disposal and end of life for EEE. They took place at the main landfill *Hipolito Renteria*, a waste transfer zone, with collectors, and in electronic shopping areas and the streets of Mexicali. It is important to note that some of these sites are frequently visited by part of the research team for related research projects, and thus there is an updated understanding of the waste management system in Mexicali.

The methods used during the field studies included site observations and structured interviews with identified main actors involved in the waste management system. The main actors included so-called waste pickers, vendors of UEP, M&R shops, scrap dealers, and recyclable waste collectors (*acopiadoras*). More than 190 waste pickers in the transfer zone, landfill, and streets were interviewed, along with operators of 165 s-hand and M&R electronic stores. The questionnaires for waste pickers included questions related to the types of items that were normally collected, average work hours, use of safety equipment, and process flows when dealing with collected UEP. In the case of second-hand electronic stores, questions were related to the origin and trade of second-hand equipment, and EoL management of them. In the M&R case, questions targeted the types of EEE that were repaired, prices related to the equipment bought and sold, and the inventory of used EEE. The questionnaires, in Spanish, are available upon request.

City and national EEE user surveys

City-level residential surveys. In 2015, a residential UEP survey was conducted in the city of Mexicali. With a sample of 400 homes representing around 266,000 households, there was a 10% margin of error. The survey questionnaire was applied in the five zones of the city and included four sections: (1) Household profile (i.e., gender, number of members, level of education attained and profession of the "owner"), (2) Consumer habits, (3) Disposal practices and awareness about UEP management programs, and (4) Willingness to participate in future UEP programs.

City-level industrial, and institutional surveys. The industrial and institutional sectors were also investigated using surveys in 2015. A total of 12 surveys were deployed, with 10 in the industrial sector as well as the main university and college. The survey questionnaire included questions related to the acquisition and EoU practices of EEE, such as typical lifespan, replacement and storage times, collection services.

Modeling past and future flows of UEP

A material flow analysis (MFA) was performed to estimate the past and future flows of the set of EEE investigated. This was done by combining data gathered across the various surveys in combination with demographic estimates. UEP generators were aggregated into two groups: the residential and non-residential sectors (i.e., business and commercial), as proposed by Kahhat and Williams (2012). Flows of electronics at the EoU were calculated by a scale-up of the survey to the city-level based on the method proposed by Kahhat & Williams (2012). EoL scenarios used in this study were developed and validated by Kahhat and Williams (2012) and Miller et al. (2016). Moreover, the Sales Obsolescence Method, illustrated in Miller et al. (2016) was selected as an alternative approach, based on the sales and lifespan of electronic products.

A limitation of this MFA model for estimating recent and future flows is that the surveys were conducted in prior years. Technology and preferences for EEE evolve rather quickly; while uncertainty is inherent in projections, we assume conditions evolve using 2013 assumptions, which adds uncertainty. A more detailed explanation of the projection approach is shown in the SI (Section 4).

Proposing an integrated UEP management system

Based on the results of the qualitative and quantitative analyses, we developed a proposed UEP management system design that includes two phases to allow a proper transition of the system and its actors: decentralized and centralized phases.

Results and discussion

Main findings of the current e-waste system

Actors and flows of materials

Different actors (e.g., informal waste pickers, collectors, scrap dealers, and formal recyclers) play important roles in the activities related to the reverse supply chain of electronics in Mexicali as depicted in Fig. 2. As observed, the selection and collection of recyclables (including UEP) are done by waste pickers walking in the streets (WP_W) and on site (WP_S) at the transfer zone and landfill. Municipal trash truck workers double as opportunistic waste pickers (WP_T) of valuable items while collecting municipal solid waste along the collection route, and thus are also part of the system.

Market value of UEPs

Depending on the condition of the UEP collected by the waste picker, it is channeled in different ways. This could include a dismantling step followed by sale as a recycled commodity, or preparation for reuse via the local second-hand market. Market value or demand and consciousness of this economic potential plays a major role in these decisions, similar to what Estrada-Ayub and Kahhat (2014) identified in other areas of Mexico. Fig. 3 provides the range of payments received per UEP item by walking waste pickers. Functioning items generally received higher payments than non-functioning, with fridges, video game systems, stereos, digital TVs, and computers receiving the highest payments.

Acopiadoras

If the market value of recyclables is identified, the *acopiadoras* or collectors will gather them. This is demonstrated in Fig. 4, which shows that waste pickers collect a variety of recyclable materials to sell to the *acopiadoras*, with most collecting metal and plastic which have a clear market value in the reverse supply chain. The characteristics of the *acopiadoras* differ among establishments, including size, on-site

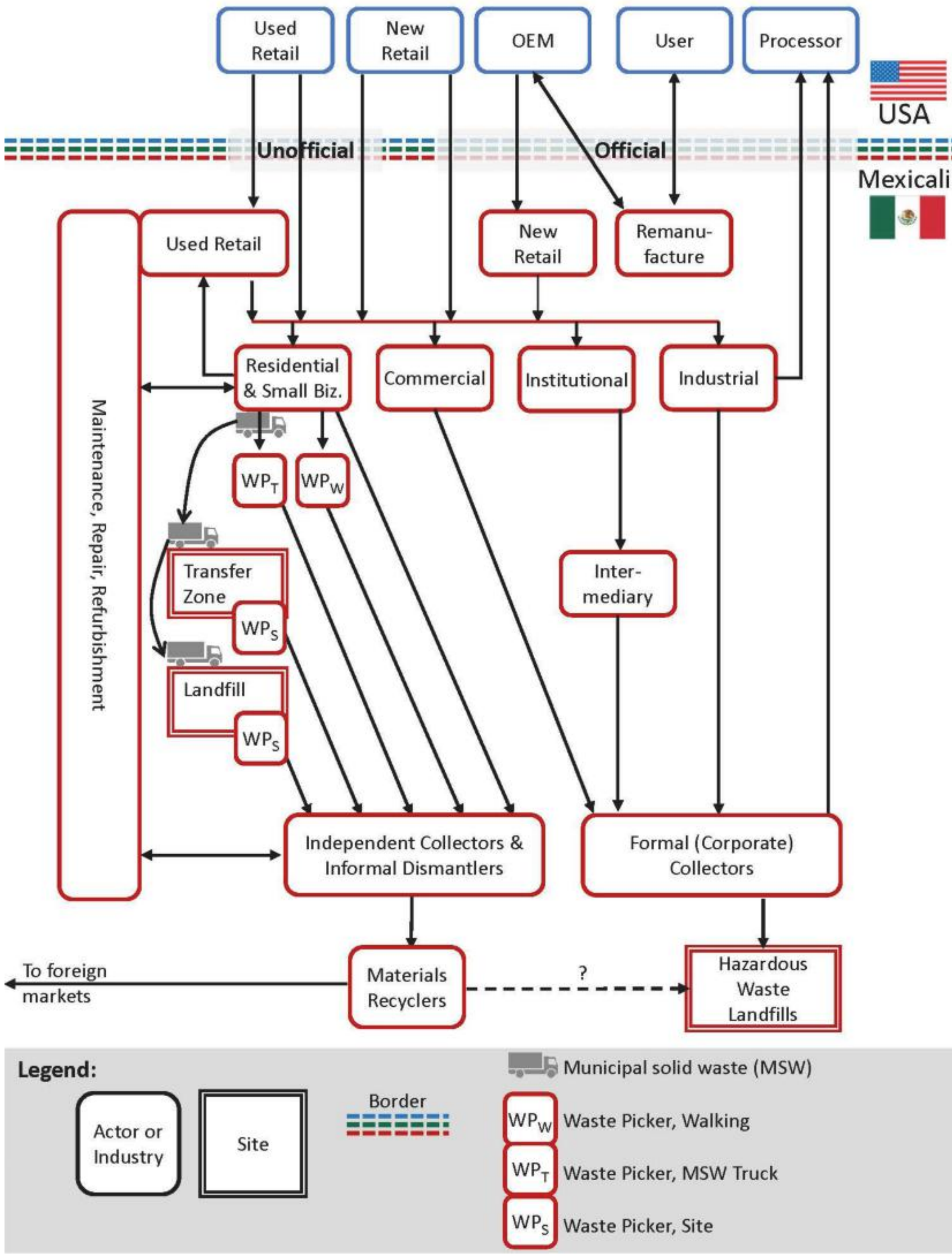

Fig. 2. Current UEP system in Mexicali.

machinery, but most primarily collect metal and prefer UEP containing metal. At the time the study was performed, WPCB were collected in Mexicali, and its flow connected to a recycling company located in Guadalajara. It is important to note that WPCB are typically the most favored type of e-waste due to precious metals, and therefore are often related to so-called "cherry-picking".

Acopiadoras can be formal or informal businesses and may deal with waste pickers or the waste generators directly (i.e., in the residential, commercial and industrial sectors, see Fig. 2). Recyclable materials handled by the *acopiadoras* are then processed by local, national or international companies (e.g., in the United States).

Second-hand markets

According to the survey results, second-hand markets are vibrant in Mexicali. UEPs were purchased by resellers either in the United States (42%), Mexico (27%) or in both countries (31%). For those purchased in the United States, the main importation strategy (about 63%) was "small importation", with only a couple of items imported at a time. Non-working purchased second-hand equipment was often repaired (50%), or was sold (14%) or returned based on the warranty agreement (36%). More than half of the stores were established by 2005.

Waste picker working conditions

Analyzing current working conditions is also important for design

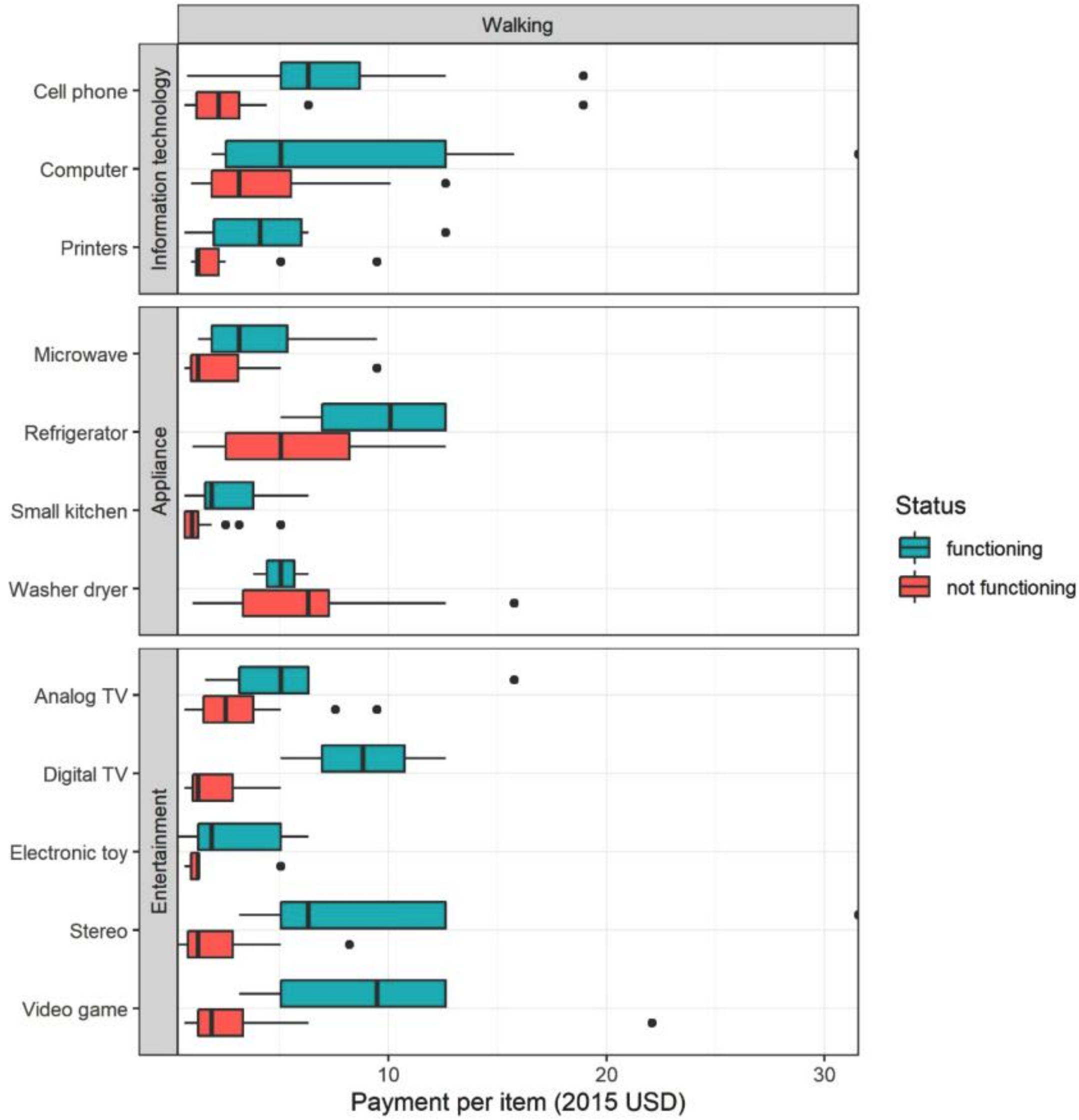

Fig. 3. Payment per UEP item, by functioning status, according to walking waste picker survey respondents. Mexican pesos converted to 2015 USD.

the proposed system, therefore income, working hours and use of safety equipment were also assessed. Fig. 5 demonstrates that the income of the waste pickers tended to be considerably higher than the minimum wage, set at 70.10 pesos (4.4 USD) per day for BC in 2015, suggesting that this is a relatively attractive occupation financially[5]. Table 1 provides summary statistics for weekly wages in comparison to the minimum wage, assuming a five-day workweek.

Regarding hours and duration in the work, most (76%) of the waste pickers from the transfer zone worked more than 7 h per 'shift', and a majority (55%) had been working as waste pickers for more than 4 years. At the landfill, 71% reported working between 4 and 9 h per day and around 38% have more than 10 years in the occupation. In the case of walking waste pickers, most (67%) work less than 8 h per day, walking on urban streets (e.g., 48% walk between 10 and 30 blocks every day), and most (72%) have less than 3 years in the activity.

After collection, the usual practice is for waste pickers to sell items to scrap dealers directly, but some perform dismantling activities before selling, which can be hazardous. Regarding the use of safety equipment in the three locations, safety gloves were the preferred safety equipment used by waste pickers: about 98% in the transfer zone, about 88% in the landfill, and about 54% in the streets. Although not common, boots, gloves, goggles and face masks were also used by some. The walking waste pickers used strollers, wheelbarrows and bicycles as the main transportation strategies to haul their items. This information is useful for the design of the new system in terms of equipment requirements and capacity, and the role of these actors.

Current hazardous management practices

While we consider this a dynamic system that encourages reuse, dismantling and recycling, some processes are a hazard to the environment and public health, and it is recommended they be mitigated. The following issues were identified: (1) unsatisfactory management of cathode ray tube (CRT) leaded glass after recovery of profitable materials or parts from monitors of televisions, (2) inadequate removal of batteries, (3) inappropriate recovery of copper from insulated copper cables by open burning, (4) landfilling of e-waste, and (5) deficient working conditions of waste pickers.

UEP generator surveys

Also, an important aspect to analyze is the one related to the use and EoU practices among the generators. Based on results from the city-level

[5] https://www.littler.com/publication-press/publication/mexico-approves-increase-daily-minimum-wage-2015-geographic-zones-and

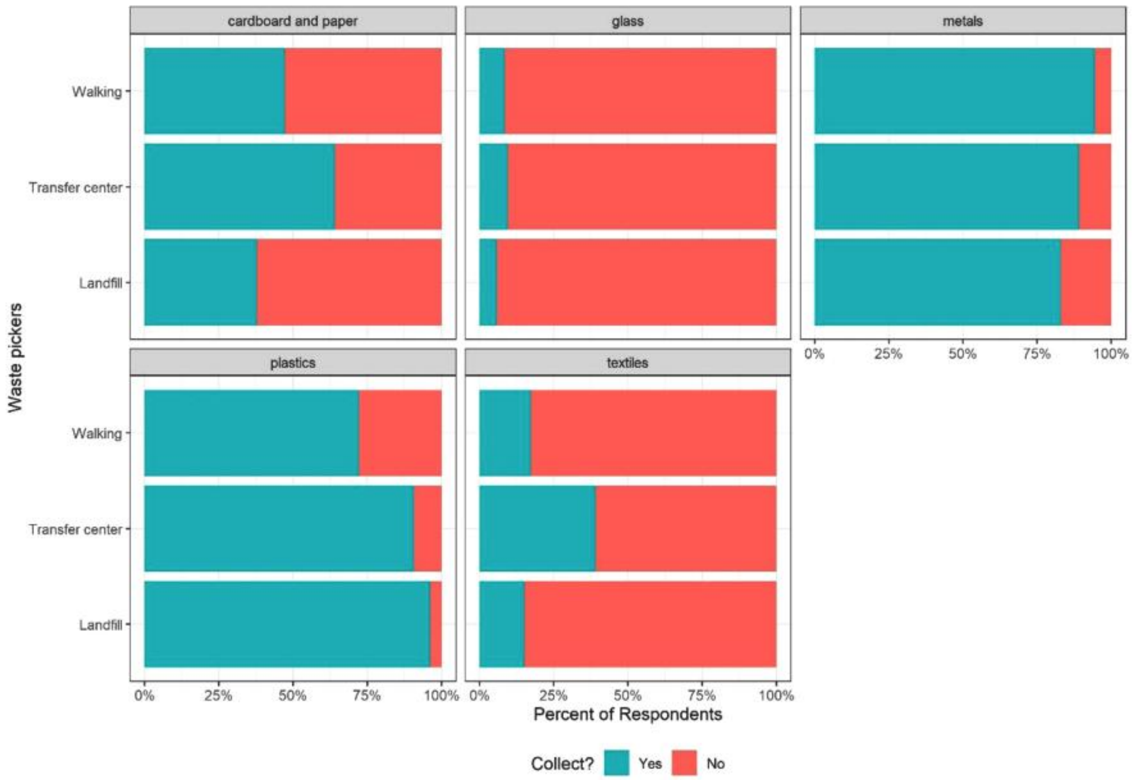

Fig. 4. Recyclable materials besides UEP collected by waste pickers surveyed.

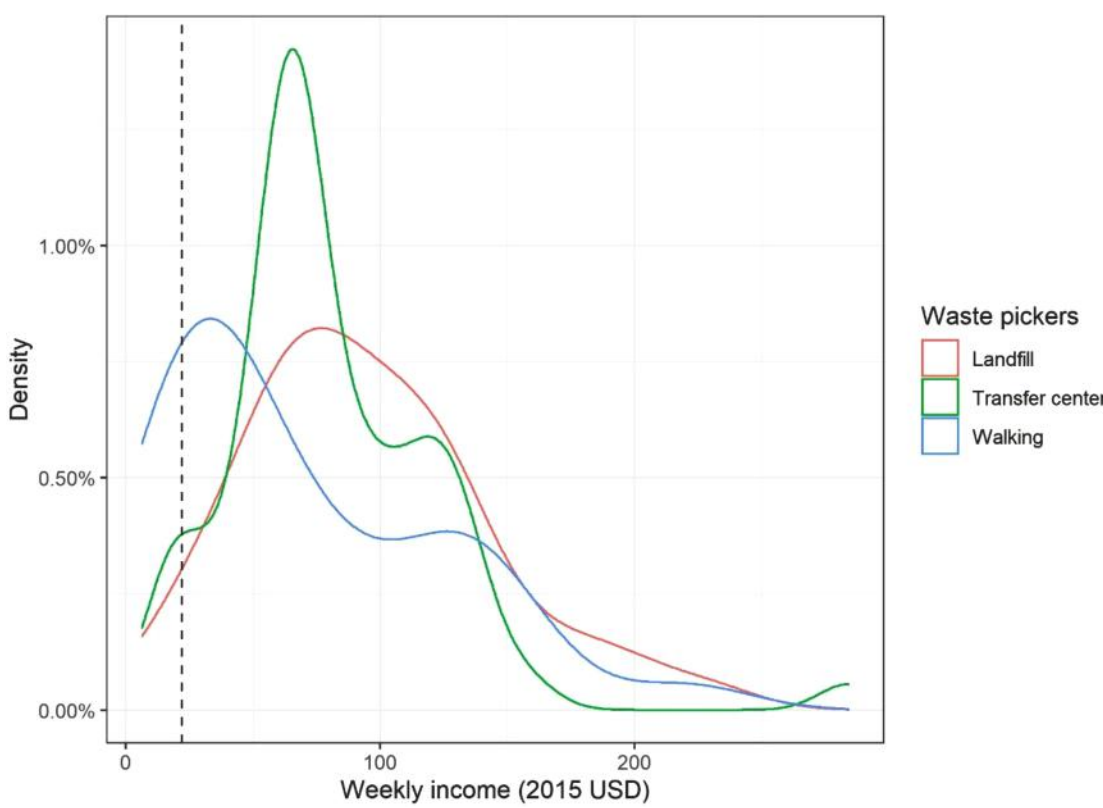

Fig. 5. Density plot of waste picker weekly income, converted from Mexican pesos to 2015 USD. Dashed line represents five days' work at Baja California daily minimum wage in 2015.

Table 1
Summary statistics of waste picker weekly income, in 2015 USD.

Waste picker type	Minimum	Maximum	Median	Mean	Standard deviation
Walking	$6.31	$220.85	$48.90	$69.94	$54.60
Transfer zone	$18.93	$283.95	$69.41	$80.77	$42.95
Landfill	$15.78	$227.16	$94.65	$94.98	$47.79
Overall	$6.31	$283.95	$75.72	$82.45	$47.84
Minimum wage	$22.12				

residential survey, the important role of the M&R sector in the lifespan extension of EEE used at homes, especially in the case of computers, refrigerators, and washing/drying machines, is confirmed. The closet effect, i.e., storing unused or obsolete electronics at home, is also present, particularly in cellphones, and the least preferable EoU options are: donate, sell or throw away. Moreover, with regard to the replacement or purchase of EEE, the acquisition of new devices from within Mexicali (especially for cell phones, and predominantly for all other devices, except game consoles and washing/drying machines), and the United States, are the most common pathways. However, buying used equipment is also an alternative, especially for washing/drying equipment and refrigerators bought in Mexicali.

Finally, it is important to note that more than 95% of the residential survey participants were willing to send obsolete devices to centralized collection points, and more than 92% were positive about self-transporting these devices. While this is a positive answer, some authors have reported shortcomings in "willingness" reported in surveys. Moreover, if a fee were required to recycle the UEP at the collection point, just under half of residents would be willing to pay, while others thought the manufacturers (28%) or government (17%) should be responsible for the cost. Further, 30% expected to be paid for the UEP brought to the collection point; their willingness might change if no payments were offered. Therefore, we still envision a role for waste pickers even if many residents state their willingness to participate.

Quantifying past and future EEE stocks and e-waste flows

The devices with the highest penetration in the residential sector of Mexicali were mobile phones, refrigerators, washer/dryer machines and TVs. Estimated EoL of the overall community of electronics for the residential sector shows that while taking into account the number of devices, mobile phones dominate by number and heavier devices (e.g., refrigerators) dominate by weight.

The growth in population and households drives the projected growth in equipment stock, which then drives expected generation of UEP. Cell phones and small kitchen items are projected to be the most numerous. The average number of people per household in Mexicali is on the decline, falling from 4.10 in 1995 to 3.13 in 2020, according to INEGI. This suggests that the number of households will increase at a faster rate than the population, and with it the number of appliances and other EEE needed for each household. The projection of EEE in residential stock in the locality of Mexicali, from 2015 to 2035 is shown in Fig. 6, based on two approaches which generate pairs of estimates, described in the SI. The upper bound estimate is based on an average stock per household (HH), while the lower bound is from an average per person. Our related estimates of device availability per household fit reasonably well with those from INEGI surveys between 2000 and 2020, as shown in the SI.

Insights from used electronics reverse supply chains around the world

Features of UEP management systems employed in other parts of the world were considered when designing the system for Mexicali. The systems have in common the goal of improving societal waste management problems, as well as improving economic feasibility in order to develop a profitable e-waste industry based on qualities such as flexibility and operative efficiency.

There are some common features in takeback systems in Europe, where e-waste management practices are adequate. For example, the

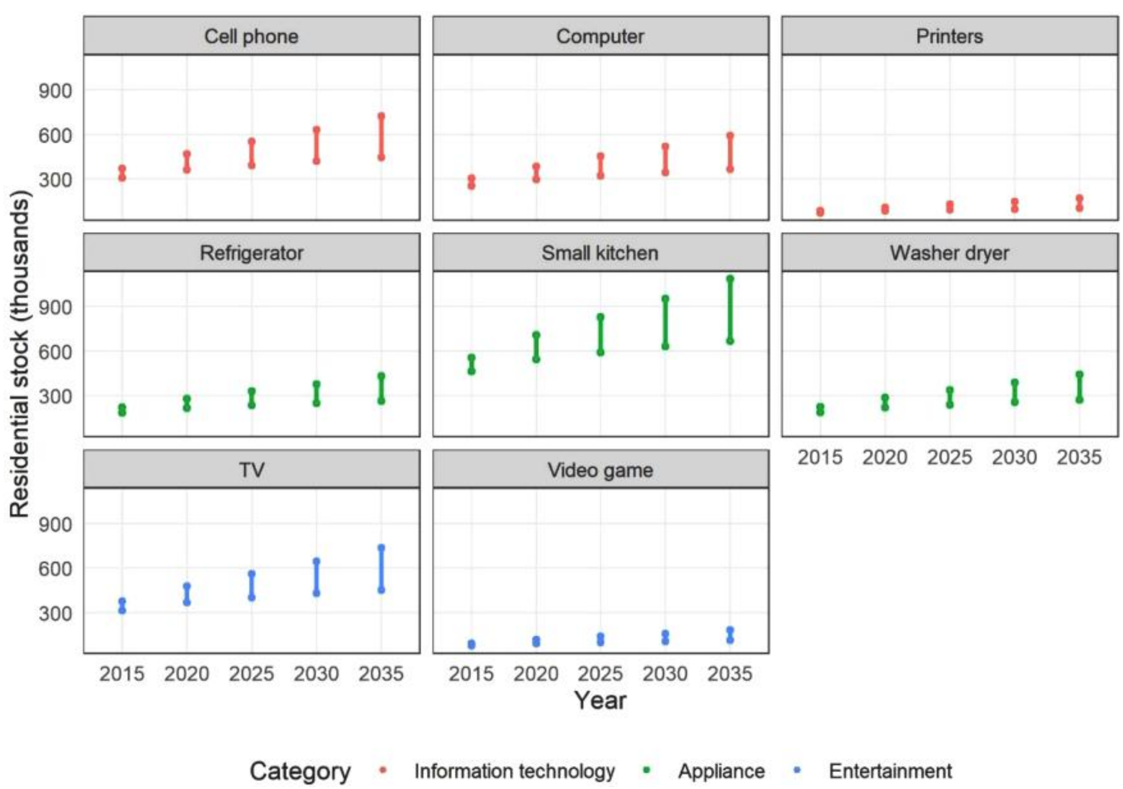

Fig. 6. Projection of EEE in residential stock in the locality of Mexicali, from 2015 to 2035. Two calculation approaches, based on average per household (HH) and per person.

systems are constituted by associations that bring together producers and local authorities. Also, the systems consider that the most important problem in collecting systems is "historic e-waste" since current disposal-fee-at-purchase systems related to electronics do not cover them. In addition, there is an opportunity for the system to improve consumer awareness and motivation via information campaigns (Kaliampakos, 2006) or by providing information about collection points (Ecotic, 2020). On the other hand, it would be advisable to implement centralized collection schemes instead of single programs, to use incentives related to targets and due to the necessity of an authority to report to.

North America is characterized by state- or province-level approaches that rely on diverse legislation (mostly EPR-oriented and one with an Advanced Recovery Fee), landfill bans, retailer requirements and others (Schumacher, 2016). Different strategies to collect UEP, such as the use of local chain stores or non-profit organizations as drop-off locations and pick-up services have been developed (Manufacturer Takeback Programs in the U.S. – Electronics TakeBack Coalition, n.d.). In addition, developing a second-hand online marketplace could lengthen the lifespan of electronics, and are used in the North America, for example, Craigslist or ebay (Craigslist, 2020; Ebay, 2020) and there is a notable increase of repair practices and right to repair movements (Lepawsky, 2020).

Regarding Asia, formal and informal systems coexist (Shittu et al., 2021). In the case of China, the capacity of the informal sector to self-organize in order to be efficient in management has been observed, which, added to low labor costs and the size of the collection system, also makes the informal system competitive (Li et al., 2012). Moreover, approaches to eliminate informal e-waste activities have proved unsuccessful (Ignatuschtschenko, 2017). Also, collaboration between small e-waste recyclers integrated into industrial parks has been reported in Guiyu, China (Awasthi et al., 2019), as have been solutions to interconnect different actors in the reverse supply chain (e.g., Baidu Recycle App) (United Nations Environment Management Group, 2017). A similar situation is found in Dhaka, Bangladesh, where there is a whole industry related to the final disposition of UEP, either for refurbishing or for dismantling. Although it can be true that profits increase with increased breakdown, it is important to ensure acceptable work conditions, such as fair wages, and avoid child labor (Lepawsky and Billah, 2011). In addition, the concept of a circular economy is contemplated in countries like Japan, where there is a scarcity of raw materials and an opportunity for small and medium e-waste recycling enterprises (Yolin, 2015).

Some of the imported UEP into Africa may contribute to close the digital gap, but others create other waste management problems (Asiimwe and Åke, 2012). There are several good initiatives for adequate e-waste management but problems remain. In South Africa, Pikitup, a private company, allowed 'site entrepreneurs' to operate in its facilities, called 'Garden Sites', to segregate different types of recyclable materials (Finlay and Liechti, 2008; Pikitup, n.d.). Moreover, in Agbogbloshie, a dumpsite/informal recycler site located in Accra, Ghana, cooperation between the various interest groups has, with the help of technology, reduced contamination due to e-waste recycling (Pure Earth, 2015). The Agbogbloshie Scrap Dealers Cooperative was established to obtain better labor and economic conditions through cooperatives (Ghana - Pure Earth, n.d.).

Finally, there are several approaches throughout Latin America for addressing recycling. Cooperatives are for-profit organizations in which the owners are the same people that work in them, thus avoiding exploitation. Non-profit recycler associations are important to obtain better prices and to improve work conditions. Such organizaitons have been successful in countries such as Brazil, with the *Associação dos Catadores de Papel, Papelão e Material Reaproveitável* (ASMARE), and Colombia with the *Asociación de Recicladores de Bogotá (ARB)* (Pure Earth/Blacksmith, n.d.). Moreover, waste picker cooperatives in Brazil have been shown to successfully collect and dismantle e-waste, after receiving training from *Insituto GEA* (Instituto GEA | Ética e Meio Ambiente, n.d.). Other experiences in Latin America are related to donation and refurbishment programs that extend the life of electronics while employing local refurbishers. For instance, the Colombian program *Computadoras para Educar (CPE)* enables children to use computers at school (Computadores Para Educar (CPE) - Ministerio de Tecnologías de La Información y Las Comunicaciones, n.d.; ITU, 2018), while the *Telecentros* in Belo Horizonte, Brazil, uses old computers to equip community centers for improving digital inclusion as government policy (Câmara, 2005). Finally, developing itinerant collection campaigns is useful to improve consumer awareness, especially if they are organized jointly by the environmental authority and the private sector (MINAM, 2019).

Proposed UEP management system

The proposed UEP management system that we envision contains two phases, decentralized and centralized, which will allow immediate action toward the management of e-waste and sufficient time to allow this system, including legislation, to evolve. The two phases are explained here.

Proposed decentralized phase

The initial decentralized phase (see Fig. 7b) requires very little capital investment, promotes visible trade relationships among actors, and applies several practices that reduce the environmental and human health impacts related to all activities involved in the reverse supply chain. Several fixes to the current system are proposed (e.g., strategies to decrease landfilling and improve management of UEP) to achieve these goals and reach financial sustainability. These fixes rely on several strategies, some taken from the literature or already adopted in other systems. For example, waste pickers that take part in the system are expected to perform dismantling activities in special workspaces located at partner *acopiadoras* (i.e., small collection establishments). Importantly, around ¾ of waste pickers surveyed were willing to take part in a training workshop related to adequate management of UEP that would lead to certification to deal with UEP. However, careful attention needs to be paid to the shortcomings of reported "willingness" obtained in surveys, as previously mentioned.

As a disincentive to the open burning of copper cables, special machines (i.e., chopper machines) will be incorporated into the system (e. g., as part of the centralized facility) and a superior market price for copper cables will be mandated; waste pickers will get this higher price if they do not separate copper from the cables. Based on previous unpublished work by some of the authors of this paper, in some situations the market provokes the burning of copper cables, due to recyclers' unwillingness to buy insulated copper cables or the lower prices paid for them. Also, considering that burned copper cables typically have a lower price than copper obtained by other separation practices, as reported by Davis & Garb (2015) for the Israeli-Palestinian e-waste sector, this solution provides a clear intrinsic economic incentive. However, to avoid a negative response to this strategy due to a misunderstanding of how "superior market price" is calculated, viewed as less profitable by informal recyclers, or issues related to copper price fluctuations and payback periods (Davis and Garb, 2020), it is important to correctly disseminate information linked to copper cable strategy and to understand the nature of economic transactions in this sector.

After initial training, which includes transmission of knowledge regarding adequate management of UEP (e.g., adequate use of tools and safety equipment, recommended and non-recommended dismantling practices, potential risks), waste pickers will receive safety equipment (e.g., safety gloves, goggles and shoes). The systems will not require the formalisation of waste pickers, (i.e., government recognition for taxes and other purposes), just their agreement to adequately perform their activities. The route of "formalisation" of the informal sector has been proposed by some authors, though, as part of an enhanced ERP-based

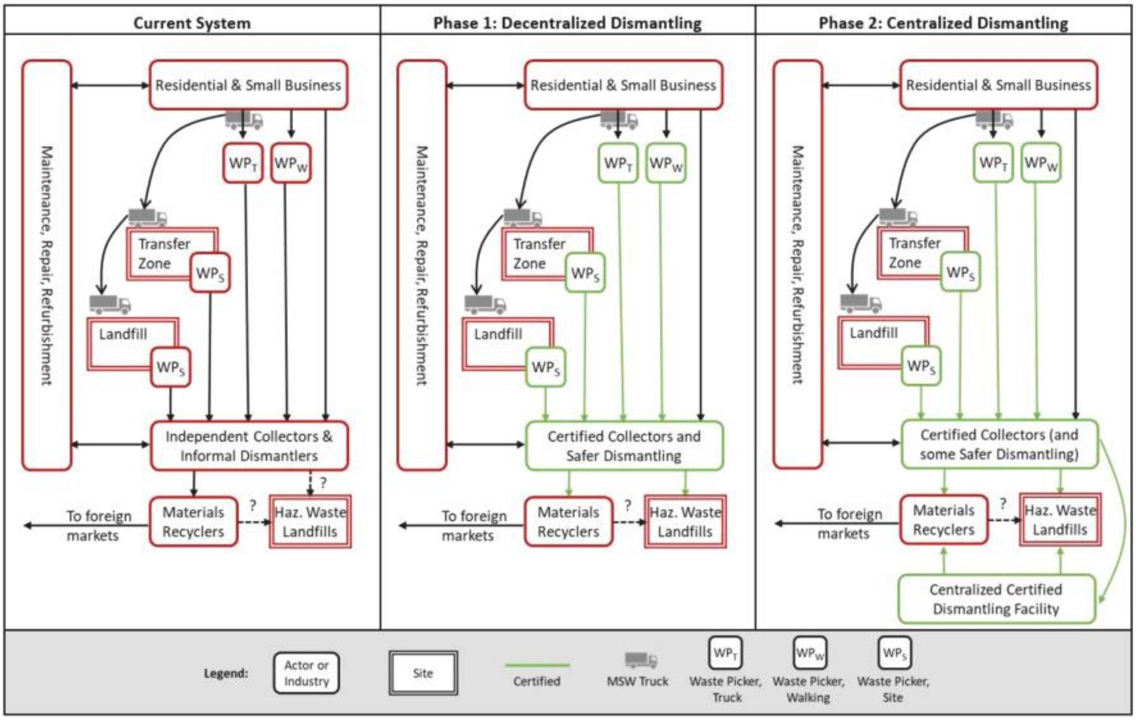

Fig. 7. (a) Summary representation of Current system (b) Decentralized Dismantling and (c) Centralized Dismantling. In the decentralized system, acopiadoras are connected to certified waste pickers, who perform the collection and dismantling of e-waste. In the second system, a centralized dismantling facility is connected to both: certified waste pickers and certified partner acopiadoras.

strategy for the Global South (Davis, 2021). Besides, the line between the formal and informal is sometimes blurred or difficult to define (Davis and Garb, 2015). In addition, *acopiadoras,* already dealing with e-waste, will enter a certification process and, if certified, be invited into the system as authorized partners. A link between the two types of sectors, formal and informal, is desirable for places where typical command-and-control strategies have proven to fail (Williams et al., 2013). Interface organizations (Williams et al., 2013) and the formation of cooperatives (Ignatuschtschenko, 2017), are two strategies that can be used to achieve this indispensable connection.

Another important issue is related to the selection and engagement of *acopiadoras*. There are important criteria to consider when selecting these small collection establishments. First, to be able to cover the entire city, geographic location is important to achieve an adequate distribution within city boundaries. Second, selected companies need to agree to accommodate the dismantling workstation, as well as certified collectors/dismantlers or certified waste pickers. No labor liability of *acopiadoras* to certified waste pickers should exist, so special emphasis should be placed on solving any domestic legal aspects. Third, only *acopiadoras* with documented experience in dealing with e-waste will be selected, and finally, proof of adequate handling of recyclables and financial management will be required.

To promote the system's performance, a periodic assessment is proposed, especially for *acopiadoras*. The assessment will be based on performance indicators that could include for example the number of collectors/waste pickers that use the new arrangements, amount of CRT glass collected, and plastics recovered from insulated copper cables. Subsequent incentives (e.g., upgrade of the certification label) or penalties (e.g., expulsion from the system) could be put in place to ensure attainment of the systems goals.

While *acopiadoras* will continue to act as collection points for e-waste, as part of the creation of the system, other non-typical generators will be able to use them as certified drop-off points for e-waste. Some collection points for e-waste already exist in Mexicali (Fundación-Helice, 2021) and will be linked to the proposed system.

To increase the collection of electronics at EoU, especially in the residential sector, the proposed systems include a simple text message system that connects waste pickers with residents. Residents will be able to send a message to the 'system' phone number and via an autoreply mechanism, required information about the item, condition, residents' address, etc. will be gathered and distributed to a group of certified informal collectors/dismantlers. The collector that claims this item will reply to the text and simultaneously the system will inform others. This simple option reduces the barrier that often exists between the generator and the second-market or EoL provider (Cruz-Sotelo et al., 2017). Connecting generators with the reverse supply chain, especially in the residential sector, has been recognized as an activity important for the success of a system and some strategies have been proposed in the past. Moreover, this will favor practices related to M&R, refurbishment, repurposing and reuse of electronics deemed obsolete by the user. This therefore promotes the life extension of products as opposed to merely allowing resource recovery from e-waste, something that could be detrimental to the system (Lepawsky et al., 2017; Williams, 2005). The initial phase requires an investment in the following: capital investments (i.e., dismantling tables, storage lockers, and tricycles for waste pickers, chopper machines), public awareness campaign, and defraying the cost to deal with hazardous materials (e.g., CRT glass).

Due to the characteristics of small businesses (about 16% of employers) we considered them to be part of the proposed program as they may behave similarly to the residential sector.

Proposed centralized phase

After the decentralized transition phase, the centralized system is proposed (see Fig. 7c). The main change from the decentralized phase is that a centralized facility will be installed to improve the technical aspects related to reverse logistics of WEEE, especially the recycling processes. We envision the UEP management process as one that requires different phases in its evolution. This is because, for many reasons, directly starting with the centralized system is not feasible, as it will require legislative action and a significant capital investment, which will require more time. As in the decentralized systems, the four objectives of the program remain. Results from the financial feasibility calculations (shown in the Supporting Information) indicate that without legislative actions that lead to a continuous external source of income, this model will not be economically feasible.

With regard to reuse, refurbishment and M&R activities, the proposed system avoids interference with current practices which are found to be critical for the life extension of consumer electronics and white goods, and provide social benefits to both employees in the sector and consumers requiring these services. In both phases, the system will prioritize the reuse of used parts, obtained after dismantling, for M&R and repurposing activities.

Conclusions

Considering that Mexicali currently does not have a UEP management system, the proposed two-phase alternative will benefit the city, ensuring proper management of UEP that incentivizes the circular economy, mitigates environmental and human health negative impacts, and enhances current employment opportunities and conditions.

Based on the methodological strategy followed in this project and its findings, an e-waste management system has been proposed for the city of Mexicali, Mexico. The main findings demonstrate the importance of waste pickers in the streets, transfer stations and landfills in the waste management system, including UEP, the important role of *acopiadoras* in the collection of recyclable materials and the value of UEP-related M&R activities. However, the reduction of some environmental impacts linked to inadequate recovery of materials from e-waste, such as open burning of copper cables are also noteworthy. Also, there is an opportunity to enhance the working conditions of some actors, especially waste pickers, in the reserve supply chain.

These findings and other specific characteristics of this location (e.g., a border city) have been considered in development of this alternative to manage UEP. A hybrid approach that connects the informal and formal sector and that ensure social, environmental and human health benefits has been proposed. Ignoring the informal actors will lead any new system to failure.

While the authors consider that it is important to preserve the opportunities related to waste-picking activities, the system provides mechanisms to ensure proper labor conditions and the mitigation of environmental impacts (e.g., dioxins and furans emitted due to open burning of copper cables). Formal collectors or asset management companies are also important and the proposed system reinforces their activities and established agreements with, for example, the industrial sector.

The financial sustainability of the system is a critical aspect that also needs to be considered. It is desirable to transition to a centralized system and simultaneously pursue of the establishment of some kind of fee related to the purchase of EEE. In a city where an important portion of these devices are bought in the United States, with some directly imported by the residents of Mexicali, a purchase fee program is complicated. However, since most of these devices are bought in a United States state that requires an advance recycling fee for electronics (i.e., California) (Cal Recycle, n.d.), the transfer of this fee could be a possibility, if international legal flexibility is reached.

While the focus of this research is the city of Mexicali, the outcome has broader implications for cities around the world. It is quite common in many developing countries for informal workers to be engaged in UEP management, and yet few proposed solutions address waste management efficiency and worker safety. We hope that our proposed transition from decentralized to centralized phases will inspire a new wave of creative policy solutions to this complex issue.

Supporting Information

Section 1: Images from Mexicali
Section 2: Methodological approaches
Section 3: Entire current system
Section 4: Mexicali projection approach
Section 5: Additional results

CRediT authorship contribution statement

Ramzy Kahhat: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **T.Reed Miller:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Project administration. **Sara Ojeda-Benitez:** Conceptualization, Investigation, Methodology, Project administration. **Samantha E. Cruz-Sotelo:** Investigation, Data curation. **Jorge Jauregui-Sesma:** Investigation, Data curation. **Marco Gusukuma:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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