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Decision factors for e-waste in Northern Mexico: To waste or trade

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ABSTRACT

Currently, around the globe, environmental and social problems derive from the inappropriate recycling of electronic products. Moreover, improper recycling is not the only issue to address in electronic products. Others include: energy intensity in their manufacture, employment generation related to the international trade in used electronics, and access to technology by low-income communities. Nevertheless, policies and controls created to provide socially and environmentally sound management of used electronics do not match the complexity of the system. In order to understand the e-waste system, particularly used computers, as a whole, a field study was done between 2010 and 2011 in ten Mexican cities. Ninety-five diverse stakeholders were interviewed to uncover factors regarding the decision to waste or trade still-usable computers. Structured analysis was used to create Data Flow Diagrams (DFDs) to describe the critical parts of the system. The results show that perceived value and geographical location determine the rate in which computers are disposed and the opportunities to waste or trade them, including the trade of their materials. Among businesses and other organizations, legislation has a stronger effect. Technological change is another important factor, largely driving the change in materials and new products. Designing policies responding to this diversity may prevent unforeseen problems and stimulate solutions.

1. Introduction

Wastes generated by human society are as complex as the social and technological systems that create the goods from which they originate. The massive quantities of anthropogenic waste surpass the capacity of natural and human systems to process them and waste management systems created to handle anthropogenic waste still do not match its complexity. An example can be seen in the increasing quantities of unwanted or obsolete electrical and electronic equipment known by the acronym of WEEE (for Waste Electrical and Electronic Equipment), or e-waste (Bhuie et al., 2004). Numerous, and dissimilar devices, such as refrigerators, computers and mobile phones, are classified as e-waste. End-of-use management requires different strategies for each.

In recent times, problems derived from e-waste handling by informal recyclers in poor communities in developing countries have garnered worldwide media coverage (e.g., Subramanyam, 2004; Solly and Granastein, 2008; Overlar, 2010; Vinicio, 2010; Lambert, 2011; Brown and Terra Blight, 2012; Macquarie, 2013). Informal recyclers are driven by the valuable resources contained in e-waste, such as gold and copper. The value of these materials is a powerful incentive for people to recycle them, even without technology or proper consideration of the environment and public health. Typical practices to recover valuables by informal stakeholders across the globe include: (1) open burning of insulated wires to recover copper (Umair et al., 2013); (2) soaking of printed circuit boards in acid (Ren et al., 2011; Bi et al., 2010) and (3) smashing of CRT monitors to recover copper, leaving leaded glass at the landfill site (Niu et al., 2012; Torzewski, 2009). The problems caused by these types of informal recycling methods have been widely documented. For example, in the recycling town of Guiyu, China, open burning activities have produced high air and soil concentrations, of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) and polychlorinated dibenzo-p-dioxins (PCDD), while leaching processes have led to heavy metal contamination of water bodies and sediments (Wong et al., 2007; An et al., 2011). In addition to China, e-waste informal recycling has also lead to health and environmental problem in countries like Nigeria (Osibanjo and Nnorom, 2007), Ghana (Oteng-Ababio, 2010) and Pakistan (Umair et al., 2013), among others.

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Developing e-waste management solutions requires a larger vision, encompassing more than just the problems derived from the inappropriate recycling of materials. According to one Earth Systems Engineering and Management principle, before proposing any potential solutions to the system, "the system itself, including relevant stakeholders, [must] be understood as a whole" (Allenby, 2005). E-waste management includes a number of stakeholders, some of which are often excluded or underrepresented in decision-making spheres. Although informal recyclers are recognized, regulations are often targeted to eliminate their source of revenue instead of improving their recycling practices with environmentally friendly technology. Also, the used electronic equipment trade to developing countries is erroneously understood as trade of hazardous waste, due to an incorrect interpretation of the Basel Convention, and some used computers that are considered hazardous waste are, in reality, safe to use. In fact, not only does the used electronic equipment trade create jobs in the refurbishment sectors, it provides access to technology in low-income communities around the globe (Kahhat and Williams, 2009).

Management of e-waste is complex because multiple factors and dimensions affect how it can be handled. E-waste management encompasses not only the proper recycling of the materials, but also social and environmental dimensions. Additionally, cultural, social and economical decision factors (varying among communities around the globe), define access to resources and opportunities to manage e-waste. Hence, the main goal of this study is to understand these decision factors from a systems perspective. The study region is the north of Mexico. This region presents a unique opportunity to assess how decision factors considered by various stakeholders located there are affected by proximity to the United States (US).

This article focuses particularly on used personal computers, with or without reuse potential, at Mexican cities near the US-Mexico border. There is a continuous flow of people and products in the study region. Every hour, 20,000 people from Mexico enter the United States at border crossings, and around goods worth 38 million dollars are traded (Del Castillo et al., 2007). Moreover, the strategic location of cities like Tijuana, Nogales, Juarez and Chihuahua make them important manufacturing centers of new electronic equipment, such as televisions, mobile phones and computers, which are shipped to the United States after assembly. For example, 30 million televisions sets are assembled in the Mexican state of Baja California every year. In addition, numerous factories in Mexico manufacture electronic parts that are then shipped to the United States for final assembly. According to the Mexican Manufacture and Exporters Association, there are around 350 electronic manufacture plants in north Baja California, Chihuahua and Nuevo Leon (Roman Moguel, 2007).

In addition to this trade, there is a dynamic trade of used products, mainly from the United States to Mexico. Unfortunately, data related to this commerce is scarce, primarily because of the special characteristics of these activities (importation, refurbishment and resale), such as informality, and the small size and large number of companies involved, which make it a challenge for tracing by government organizations. However, the importance of this informal commerce can be inferred by the quantity of vendors that gather in flea markets in northern Mexico as well as the many years they have been in operation. For example, the *La villa* flea markets in Tijuana gathers more than 5000 vendors every Sunday, and flea markets like "*La Chaveña*" in the city of Juarez have been continuously operating for more than 30 years. At flea markets, significant numbers of used electronics dealers are present, as are small electronic refurbishers operating in the geographic area. In addition, in all cities studied, informal collectors (*pepenadores*) or scavengers are present. These informal collectors sort recyclable materials and used products out of the municipal waste stream for further sorting and dismantling. Also, in cities like Juarez and Nogales, formal collectors with experience managing ewaste from international companies provide services to dispose electronics for the public.

2. Methods

This research uses a bottom-up approach to study the systems that manage e-waste at each city. One way to overcome the complexity of describing a system which has several dimensions and in which stakeholders interact with one another is to classify, for analytical purposes, the interactions in three different levels: micro, meso and macro (Svedin et al., 2005). The first, (micro-level) represents the actions taken by individuals, the second (meso-level) represents the flow of information among organizations, while the macro-level encompasses national characteristics. The reason for including a multilevel analysis is that the decision factors which drive the flows of e-waste among stakeholders do not operate at a single level, but have impacts at all levels.

We began at the micro-level, conducting interviews with stakeholders, participants in the e-waste supply chain management system in each city.

The general procedure was: learn from each stakeholder where they acquire their material, where their products (e-waste or computers) are sold and where they dispose of their waste materials. Through this information, it was possible to identify alternatives to trading or wasting materials in each city. The interviews also provided information from stakeholders about the reasons behind their decision-making on how to deal with their e-waste. The reasons provided from these stakeholders varied from the availability of choices at their location, to more complex factors that drive the behavior from their customers and suppliers. Therefore, since their analysis of the reasons behind their decisions move from the micro-level to the macro-level, it was necessary to organize these at the meso-level and the macro-level in order to capture the emergent behavior derived from complex systems.

2.1. Study region

In order to understand, the decision factors which drive e-waste management, field studies were performed between January 2010 and July 2011 in ten Mexican cities located within a maximum distance of 200 miles from the US-Mexico border. Fig. 1 shows the Mexican border area as well as the studied cities. Some of their characteristics, such as population and main economic activity are also shown on this figure.

The selection criteria are based on geo-political, social and economic differences, as shown in Table 1. Some of the characteristics include: main ports of entry to Mexico (from California, Arizona and Texas); most populated city in the state; agricultural cities; touristic cities. The following cities were studied: Chihuahua, Cuauhtémoc, Fronteras, Hermosillo, Juarez, Mexicali, Monterey, Nogales, Rosarito and Tijuana.

2.2. Stakeholder selection process

Approximately 95 interviews were completed with different stakeholders: users (residential and business), electronic retailers, computer refurbishers, street sellers of used computers, owners of used-computer shops, Internet kiosks, electronic waste recyclers, metal recyclers, scavengers, a CRT glass recycler, and landfill operators. The study included both informal and formal stakeholders. Formal recyclers were located through e-mail to set up an appointment. Personal interviews in the field were scheduled with those which accepted to be interviewed. Informal recyclers had to be

Fig. 1. Field studies about e-waste in Northern Mexico.

Table 1
Selection criteria for field studies.

City	Main characteristic	Reason for choosing the city
Chihuahua	Capital of the State	Second most populous city and capital of the State of Chihuahua. State capitals cities are more strongly influenced by state governments, and Mexican laws classify e-waste as special residues which municipalities are required to manage
Cuauhtémoc	Small city located in border state	Cuauhtémoc is an agricultural city. Peasants and farmers have strong ties with the US; therefore, it is important to understand how this relationship affects e-waste management systems
Fronteras	Small city near the border	Location of an e-waste recycling plant
Hermosillo	Most populated city in border state and capital of the State	Hermosillo is also an important industrial city. For example, Ford Motor Company assembles cars for worldwide markets here
Juarez	Border city and main port of entry from Texas, US	Proximity to the United States-Mexico border and main port of entry of electronic waste coming from Texas. Important presence of informal commerce. Juarez is the second largest city in terms of population and commerce along the US-Mexico border
Tijuana	Border city and main port of entry to Mexico from California, US	Proximity to the United States-Mexico border and main port of entry of electronic waste coming from California. Important presence of informal commerce, the largest city in terms of population along the US-Mexico border
Mexicali	Border city and state capital	State Capital of Baja California Norte. Headquarters of a CRT glass recycler and presence of refurbishers and recyclers
Monterrey	Industrial city and most populated state	Monterrey is the third largest city in Mexico and the most industrialized city in the north. It is also the home base of important Mexican industrial groups
Nogales	Border city and main port of entry to Mexico from Arizona US	Proximity to the United States-Mexico border and main port of entry of electronic waste from Arizona. Important presence of informal commerce
Rosarito	Small city located in border state	Small and touristic city, near Tijuana. It was deemed important to understand if small cities are connected with big cities, or if they have their own e-waste management systems

located on each site; they were traced through the following multi-step method:

1. The oldest and traditional commercial area was located at each city because it is usually more closely connected with the community.
2. Electronic shops (stores selling electronics, repairing computers or selling computer spare parts) were identified. These shops were visited, and the owner was asked for permission to perform an interview, explaining the study objectives and its academic purpose.
3. Stores leasing Internet access and computers in the same commercial area were located and visited, and a similar request for permission to conduct an informal interview was made.
4. The next stakeholder in the e-waste system was traced at each interview by requesting help from the initial participant to locate a supplier/recipient who was next on the e-waste chain.
5. Stakeholders along the chain, from acquisition to disposal, were located and interviews scheduled.
6. Visits to city landfill sites were scheduled. Scavengers (*pepenadores*) and landfill managers were interviewed about disposition of e-waste at this sites, and e-waste buyers.
7. E-waste and used-computer buyers were located, and asked for permission to an interview.

Finally, certain stakeholders were selected to represent various socio-economic groups (e.g., users) and business size (e.g., from small refurbishers/recyclers to large asset management companies).

2.3. Interview methods

The problem of including diversity is that it may lead to the sacrifice of detail; however, it is possible to overcome this limitation with a careful selection of the type of interviews. There are two general categories of interviews: structured and unstructured. The former is used to test a theory, while the latter is used to understand the behavior. An unstructured interview is a qualitative tool used in social sciences to collect rich and deep information from participants. Because it is closer to an informal conversation, it elicits more confident and open responses from participants; thereby allowing new information to emerge (Denzin and Lincoln, 2011). Because the objective of this research is to understand the complexity of multiple stakeholders and there is a need to understand, from an open perspective, the factors that drive their behavior, unstructured interviews were used.

Despite being developed in an informal way to avoid stressing the participant, unstructured interviews required careful preparation to maintain the focus of the conversation. The method for a deep/unstructured interview encompasses the following sequence (Wengraf, 2001):

$$\text{Central Research Question (CRQ)} \longrightarrow \text{Theory Question (TQ)} \longrightarrow \text{Interview Question (IQ)}$$

Accordingly, Table 2 shows the research question framework for the deep/unstructured interviews that took place in the field studies.

The interviews addressed five points (Table 2):

(1) Equipment characteristics
(2) Market characteristics
(3) Waste destination
(4) Perceived trends regarding their customers/activities and
(5) Main problems faced in their daily activities.

Table 2
Research question frame for interviews.

CRQ – What factors drive the flows of used computers and e-waste in Northern Mexico?
TQ1 – Equipment/waste characteristics
TQ2 – Market characteristics
TQ3 – Stakeholders waste destination, based on geographical location
TQ4 – Perceived trends regarding their customers/activities
TQ5 – Main problems faced in their daily activities

Through this research frame, it was possible to develop open conversations with the stakeholders and learn: (1) types of used equipment traded, (2) e-waste origin and destination, and (3) electronic consumer adoption and disposition, used equipment values and difficulties stakeholders faced in performing their activities. Unstructured interviews allowed stakeholders to comment on how they perceive the e-waste system and their problems; this freedom allowed for the collection of deeper information about how stakeholders perceive the e-waste system.

2.4. Analysis methods

This study uses structured analysis to create Data Flow Diagrams (DFDs) and Ishikawa diagrams to organize the information provided by unstructured interviews in order to understand the system from a bottom-to-top approach with emphasis on the cultural and geographical differences.

Structured analysis is a method used in computer science to create a model of the "real world" using DFDs (Yourdon, 1988). A DFD is a graphical representation of the information flow; it can also be used to represent the flow of activities in a process. A DFD shows the decision processes and the flow of information. Because of these characteristics, the DFD is a useful tool to represent the decisions that control the flow of materials and information in factories; consequently they are widely used by industrial engineers. In the same way that a DFD can represent the flow of materials in a factory, it can represent the flow of used computers and e-waste materials.

However, the system which these DFDs describe is complex, and in continuous evolution. Diverse stakeholders interact with one another, and at the same time are affected by factors caused by stakeholders at different geographical locations. These factors also derive from characteristics that emerge at an aggregated level and from the close relationship e-waste has with information and communication technology (ICT).

Common reasons that drive e-waste flows emerged from the interviews with stakeholders; therefore, this information was organized in Ishikawa diagrams. The Ishikawa diagram is a tool used in quality control and design for engineering. They are commonly used by industrial quality teams to analyze the causes of a given phenomenon. The methodology, as well as other tools, were created by Kouru Ishikawa to improve processes (Ishikawa and Loftus, 1990) because they permit the viewing of causes and effects of a given phenomenon; in the current study, these reasons, named *decision factors*, were reviewed against the literature and available statistics at an aggregated level to compare the findings at the interviews with other studies, to avoid bias in the process of analyzing the unstructured interviews.

3. Results and discussion

DFDs permits an understanding of the decisions available at an individual level (micro-level), institution level (meso-level) and, finally, the macro-level. For example, an individual has the choice of either disposing an old computer or storing it. A city waste manager may have the choice to either accept e-waste at a landfill site or not (Meso-level); finally, social characteristics, such as Internet availability and poverty affect the potential of a society to manage e-waste. How these decisions are generated is discussed through Ishikawa diagrams that show factors that usually have an impact at all levels.

3.1. Purchase-to-disposal DFD (micro-level)

Fig. 2 shows four decisions blocks. The first two: (3.3.1) Decision factors to change/purchase a computer and (3.1.2) Decision factors to dispose or store a computer, are decisions that computer users take. On the other hand, the third (3) Is there a market for the equipment, and fourth (4) The disposal represents a cost decision factors, are external to users. They will be reviewed in Section 3.3 (Factors for computer collection and end of life).

It is important to point out that, although the DFD in Fig. 2 represents the system at the micro-level, decision factors cannot be separated from the complexity of the system; hence, the factors presented in Figs. 3, 4 and 6, operate at all levels.

3.1.1. Decision factors for replacing a computer

Block 3.1.1, in Fig. 2, shows the two possible decisions made by the computer user: to change or continue using a computer. From interviews with stakeholders, the decision factors emerge. Fig. 3 shows the Ishikawa diagram illustrating decision factors for replacing a computer. Fig. 3 relates to Fig. 2 because it enumerates the factors leading to replacing a computer; however, the DFD at Fig. 2 shows the system at the micro-level individual decision while the factors operate at all levels. Fig. 2 shows the decision at the micro-level, but these decisions may be affected by meso-level structures like legislation and the presence of markets for used computers. For example, technological obsolescence is a result of technological change. Attachment is a factor that also operates at several levels. For example, depending on the socio-economic level and culture, it will have stronger influence. High income teenagers may experience stronger peer pressure to change their computer due fashion.

Factors that promote the action to purchase a new computer can be grouped into three categories: failure, technological obsolescence and fashion. On the other hand, price, attachment and repair costs are factors that prevent a positive purchasing decision from taking place. These factors are briefly explained below.

3.1.1.1. Technological obsolescence. According to interviewees, one of the factors leading to changing a computer is obsolescence.

The literature indicates that *technological obsolescence* is when the benefits gained from purchasing a new computer minus the incurring costs from this purchase are more than the benefits generated by the present computer (Benefits from new computer – Costs to buy a new computer > Benefits from present computer) (Saleh, 2008). *Optimum obsolescence* is a concept that proposes that a computer must be changed when the benefits from a new computer are higher than the associated costs to replace the old one (Benefits from new computer > Costs to replace the old computer) (Carlaw, 2005).

Obsolescence can be also caused by factors other than the device's internal characteristics, e.g., the conversion of broadcast television signals from analog to digital. However, this example is not typical. Engineering changes are usually caused by new technologies displacing old technologies, e.g., laptops displacing desktops (or tablets displacing laptops). This tendency is supported by statistics: according to information from International Data Corporation (IDC), "...tablet shipments will surpass desktop PCs in 2013 and portable PCs in 2014. According to sales projections, desktops computers are decreasing in global markets by 4.3%. Laptops and portable computers sales growth remains steady at 0.9%. On the other hand, tablet sales are increasing. The latest sales figure was 190 million units annually, which represents a double-digit growth of 48.7%."

However, these impressive sales are modest compared with the Smartphone's market, which is expected to reach sales up to 918.5 million units. It is clear that new technologies do not immediately displace old ones; instead there is a process in which new devices with emerging characteristics compete with the old ones. Mexican consumers also reflect this tendency; when interviewed, computer refurbishers declared that used computers now must compete with new emerging devices like tablets, making it difficult to trade them.

Technological change is a more complex phenomenon, and has been the subject of analysis from several disciplines. For example, Marx, and later Schumpeter, proposed that in order for new structures, technologies and systems to emerge, there is a need to destroy the old ones. This concept is called creative destruction (Marx and Engels, 1848; Schumpeter, 2008). Analysis of the creative destruction in computers is beyond the scope of the present work, but according to information gleaned from our surveys, the concept of obsolescence in computers is not absolute, it relates to a particular, intended use. For example, computers deemed obsolete by a company are important assets for Internet kiosks and cafes that provide access to the Internet to consumers whose access needs are limited. Some of the reasons stakeholders report computers becoming obsolete are: (1) Mandatory changes: e.g., a change in engineering standard, a lack of memory to run programs. (2) Connectivity: computers that cannot be connected to Internet or to new devices.

3.1.1.2. Computer change promoted by fashion. The purchase of a new computer to replace an old one is not always the result of technological change or creative destruction. Some changes are due to "cosmetic" upgrades, like a new exterior color, and more attractive design. A change due to these types of factors can be defined as a change promoted by fashion. According to interviewees, computers are often changed because of new designs. However, interviewees acknowledge that change promoted by fashion was not common at companies, but was for individual users, especially teenagers. At the corporate level, a quantitative economic analysis can be made about the advantages to change equipment, but at the individual level, changes for fashion are more common. For example, according to stakeholders that refurbish and sell used computers, teenagers at a certain economic level buy new equipment instead of a used unit because of pressure from their peers to have the latest version. Teenagers are a powerful driver toward the adoption of new technology: in the United Kingdom, teenagers between 12 and 16 years of age expend a total of 3 billion pounds a year on new technology (Spero and Stone, 2004).

3.1.1.3. Computer change due to failure. Probably the most powerful reason to purchase a computer is equipment failure or malfunction. Failure can be caused either by hardware or software. Failure from software includes slow Internet connections and the lack of capacity from the equipment to support new software applications. Failure due to hardware includes the failure of components (e.g., hard drive) in the computer. However, while some factors promote the purchase of a computer, other factors promote the continuous use of a computer and serve as a deterrent to buy a new one. As explained below, these factors are: repair costs, attachment and the price of new equipment.

3.1.1.4. Repair costs. Repair costs can have an impact in both ways, as a deterrent and as promoter of new equipment purchasing. If the cost to repair is cheaper than the cost to purchase a new one, the lower cost becomes a powerful deterrent from buying a new computer. This is especially important because the differences in repair costs in developing (e.g., Mexico) and developed economies

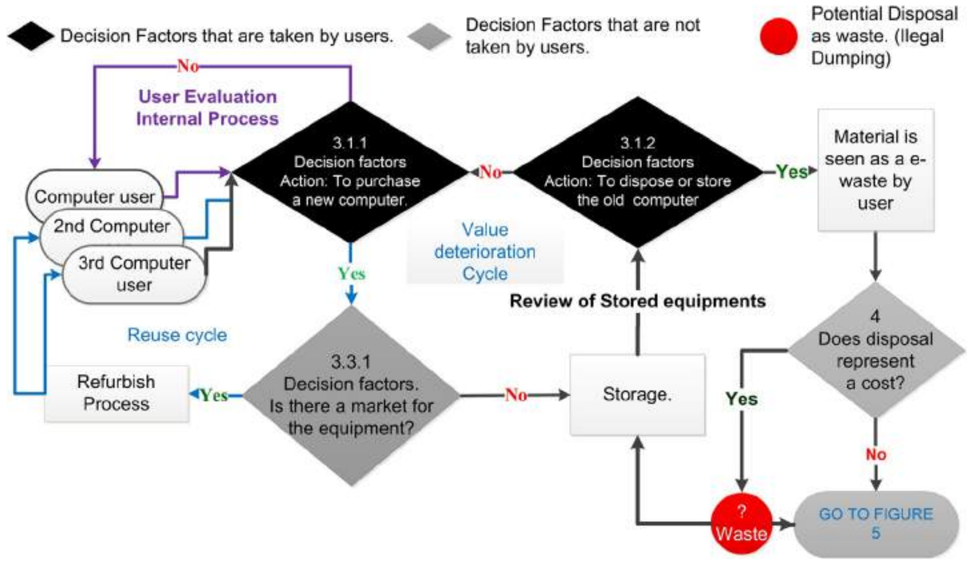

Fig. 2. DFD, decision factors from purchase to disposal, as defined by users.

(e.g., United States) lead to the export of used computers to the former (e.g., to Mexico) from the latter (e.g., United States).

3.1.1.5. Attachment and environmental awareness. Corporate users and individual users develop attachment to old computers for different reasons. In the case of corporate users, attachment is related to data security and accessibility. Some individual users have subjective feelings of attachment to old equipment beyond their practical use. Some factors that can cause attachment to old equipment are: perceived value, resistance to change and environmental awareness. Perceived value is a factor that impacts the decision to purchase a new computer, and also impacts the decision to store an old computer once it has been replaced.

Because computers are technological innovations, storage is also a reflection of the technology adoption curve. In 1962, Rogers suggested five categories of people depending on their location on the technology adoption curve: innovators, early adopters, early majority, late majority and laggards (Rogers, 2010). *Innovators* comprise about 2.5% of the population and are the first to adopt new technologies and products. *Early adopters* are less tolerant to risk than innovators and make up 13.5% of the population. The *early majority* is 34% from the population adopting technology more slowly than early adopters. The *late majority*, about 34% of the population, are highly conservative. Finally, about 16% of the population are classified as *laggards:* individuals forced to adopt the technology once it has been widely accepted by the majority of the population. According to this model, 16% from the population will keep their old equipment as long as they can before changing it.

Additionally, some individuals keep their old computer because they know about the environmental impacts of computer disposal. Such environmental awareness is high among users. For example, in a Lima, Peru survey about adoption and disposal of computers, seven out of ten households responded that they know that the improper disposal of computer creates an environmental risk and consider reuse to be a preferable option (Kahhat and Williams, 2010).

3.1.1.6. Price of new equipment. Cost is an important deterrent, especially for people of low-income. Price comparisons are made not only with other computers, but also regarding the services provided since less expensive devices have emerged that compete with computers in providing a specific service. For example, smart cell phones provide Internet access. Therefore, such equipment can compete, for some applications, directly with used computers. This was learned in interviews at used computers shops, and the tendency can be also seen in the national statistics. For example, according to data from the *Instituto Nacional de Estadística y Geografía* (INEGI, Mexico's national statistical institute), computer

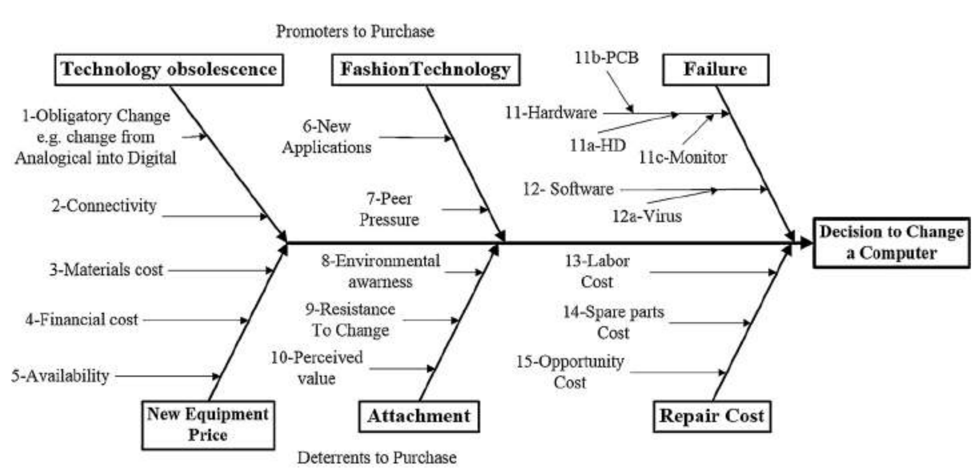

Fig. 3. Decision factors to purchase/change a computer.

ownership in Mexican homes grew from 19.7% in 2004 to 29.7% in 2010, while telephone access (both cell phones and land lines) grew from 59.9% to 80.1% during the same time period. This growth in telephone access can be attributed to cell phones because of all the telephone users, 49.8% have only cell phones, 8.7% only land lines phones and the rest have both cell phones and land lines.

3.1.2. Decision factors for computer storage or disposal

When a new computer is purchased, the old computer is either stored or disposed. According to an Irish and a Japanese study, individuals store old computers an average of three years, called the *closet effect* (Hickey and Fitzpatrick, 2008; Williams and Hatanaka, 2005). Organizations, on the other hand, store more equipment, and storage for their equipment lasts from months to two years. The fate of these computers varies: either re-used for equipment, disassembled within the company for parts, or sold (Babbitt et al., 2011). A stored computer decreases in value overtime: the longer the storage time, the greater the obsolescence. Fig. 4 shows the decision factors for computer storage. Fig. 4 relates to block 3.1.2 in Fig. 2. However, the factors shown at Fig. 4 operate at all levels while Fig. 2 reflects only the DFD at individual decision level to either store a computer or dispose it.

3.1.2.1. Perceived value of computers. According to interviewees, sometimes people perceived the value of their equipment to be higher than the actual market price. Also, used computers were perceived as low quality equipment. Perceived value is a factor that impacts how users purchase, store and dispose of their computers. *Customer perceived value* has been defined as how a consumer perceives the benefits and other factors of a product compared to its inconveniences or tradeoffs (Lapierre, 2000; Slater and Narver, 2000; Ulaga and Chacour, 2001; Woodruff, 1997; Zeithaml et al., 1996). Interviewees indicated that perceive value has a great impact on the decision to dispose computers. The decision to store impacts the collection of units, and later the possibility to refurbish old computers for trading. Used computers are perceived to have higher risks of failure, so they are perceived as being of lower quality (Snoj et al., 2004). This is corroborated by the findings of surveys done in Lima, Peru and Ireland, where only 11% and 41%, of respondents, respectively, perceived used computers as reliable (Kahhat and Williams, 2009; Hickey and Fitzpatrick, 2008).

3.1.2.2. Inconvenience of computer disposal. According to interviewees, if computer disposal is inconvenient, users may prefer to store their computers. Interviewees provided two main reasons. The first is the value of the information kept in the device and the lack of data backup practices. The second is the difficulties faced in disposing of a computer. Such difficulties can be caused by geographical and temporal reasons. An example of a geographical reason is that small towns, such as Cuauhtémoc, have no infrastructure to dispose a computer. Sometimes the problem is that collection points, if available, are far away from users. Finally, instead of permanent collection points, in some places only, collection events scheduled at different times of the year are available, meaning users have to store their equipment until they can take it to a electronic collection event later.

3.1.2.3. Disposal costs. The implications of adding fees to dispose computers were discussed in conversations with interviewees. Consumers incur costs to dispose of a computer. Depending on the location, computers can be disposed via take-back systems, collection events, e-waste collectors, *pepenadores* and metal collectors, etc. A take-back system encompasses a complete infrastructure, including creation of facilities to receive, transport and process e-waste, including transferring of equipment from users to recycling centers and other facilities that provide an environmentally friendly means of disposal. The financial costs to maintain the system infrastructure must be funded through mechanisms such as: revenue (i.e., the intrinsic value of the materials in a PC) or based on legislation (requiring the charging of users a disposal fee which is used to fund the equipment disposal system). Jurisdictions like Japan and California have created a disposal fee, which is charged to consumers at the time they dispose of their equipment (Williams and Hatanaka, 2005; State of California, 2003). On the other hand, a system can be based on a kind of gray market, with for-profit collectors, e.g., Mexico's *pepenadores*, looking for these materials where users dispose of them. Finally, governments and NGOs organize collection events in which, at particular dates, users can dispose their waste at temporary sites. Success of the latter collection system greatly depends on help from media to advertise the event.

In Mexico, according to the *Ley General Para el Aprovechamiento y Gestión de los residuos* (general law for waste management), e-waste is deemed to require special handling and the states are responsible for its proper management and disposal (SMAyRN, 2013).

On February 1, 2013, a standard enacted by the Mexican government, Mexican Norm NOM-161-SEMARNAT-2011, came into effect. This standard establishes that the special handling of such residuals requires a waste management plan (SMAyRN, 2011). The aim of such plans is to ensure proper handling in an environmentally friendly way and as well as economic benefits from recycling through the recovery of valuable components. During interviews, the impact of the new laws enacted in Mexico, the gray market and possible fees were discussed. Interviewers indicated they were concerned that the legislated fee system would create corruption. In addition, costs will increase as a result of the need to support a larger bureaucracy to maintain the system and the governments will use these mechanisms as a way to disguise new taxes, using the additional funds collected to support other expenditures. For users, a fee will increase the possibility that equipments may be illegally disposed to avoid payment of the fee.

3.1.2.4. Computers disposed in socially beneficial way. Interviews revealed that computers are not always disposed for economic benefits, instead many are given away. Individual users often donate or sell their old equipment to family members or friends. Some corporations donate or sell old equipment to schools, employees and other organizations. Reuse of computers is important worldwide. In 2010, 14% of acquired computers in the United States came from secondary markets [47]. In addition, donation of computers to friends and family members is a popular end-of-use management option: 20–36% and 16% of computers were donated in Mexico and Peru, respectively (Kahhat et al., 2011) (Kahhat and Williams, 2009).

3.1.2.5. Inconvenience of storage. Interviewees agree that it is more difficult for a company to store its old equipment than individual users because storing large quantities of computers represents a cost for companies, in terms of space. In addition, the market value of used computers and their materials is a factor that promotes their disposal, as well as collection by others. This is discussed in Section 3.4.

3.2. DFD: from user disposal to waste or trade by individuals (micro-level)

The DFD at Fig. 2 ends with the decision by users to dispose of their old computer. Once a computer is disposed, other decision factors determine the viability of collection. Used computers are collected by different stakeholders, through different mechanisms. e.g., collection events, collection points and direct pick-up. The DFD in Fig. 5 starts when users in Mexico or the United States dispose

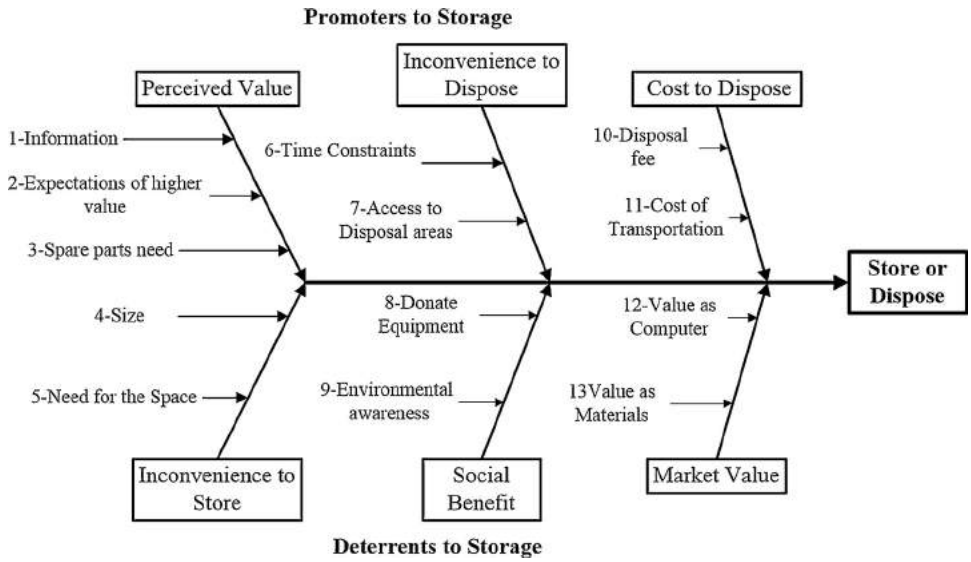

Fig. 4. Decision factors related to computer storage or disposal.

their computer. Fig. 5 shows seven decision blocks that represent the decision factors for a computer to be traded or wasted:

The first decision factor (block #1) relates to the possibility of trading a computer in the market. The second decision factor (block #2) represents the decision taken by market participants to collect or not collect a computer. If there is a profit, collection takes place, and the decision process continues to block #4. On the other hand, if the market price does not generate revenue, the material is disposed as waste, and the decision process continues to block #3.

Block #4 shows the decision process to trade a computer. Potentially, a used computer can be traded in three different ways: 1-secondary markets for computers, 2-market for used parts, and 3-market for recyclable materials. This fourth decision factor separates the flow of used computers into two different streams: Those units which can be trade as used computers and those which will be sent to a disassembly process. Two streams emerge from this process: Spare parts and materials. Spare parts are closely related to used computers; therefore, they are traded together. Materials on the other hand undergo a fifth decision factor (block#5), which determines if the specific material has a value in the market. If there is no market, the materials are disposed as waste and the decision process reverts to block #3.

Otherwise the next decision process take place at block #6, which defines the transportation cost. At the landfill site, another examination for valuable material is done by *pepenadores* who salvage any remaining valuable material. Therefore, block 6 shows two sources of materials: Materials rescued by scavengers and the materials generated by the separation process. In block 6, materials are accumulated until the volume covers the transportation costs. Residual materials go again to block #3 where a final decision is made: This decision defines if material can be disposed through the landfill process or not. If these materials are processed through the landfill process, scavengers rescue any valuable material and sell these materials to a collector (block # 7).

If there is no place to legally dispose of a material, it is disposed illicitly or stored. This problem was revealed in interviews with

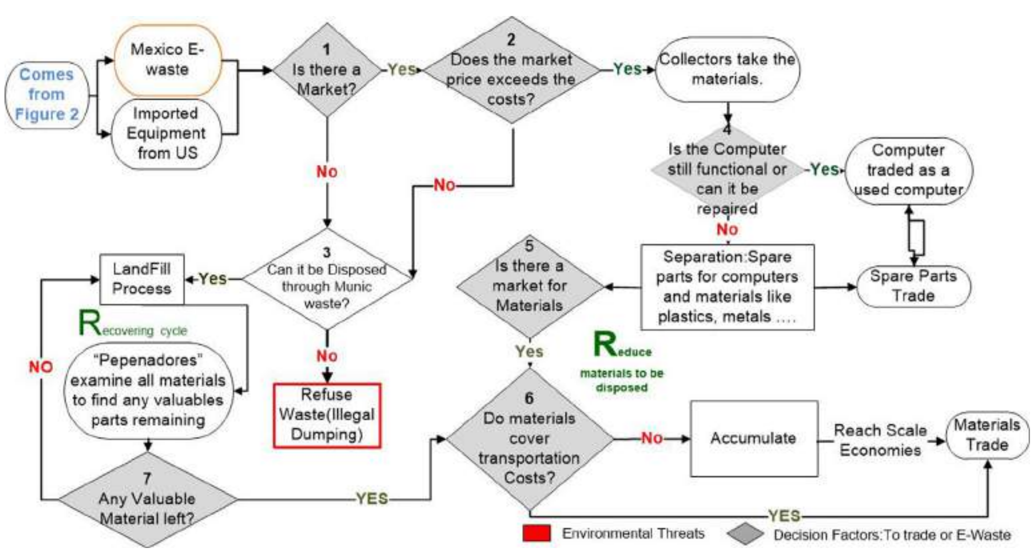

Fig. 5. DFD decision factors that drive the flows of e-waste.

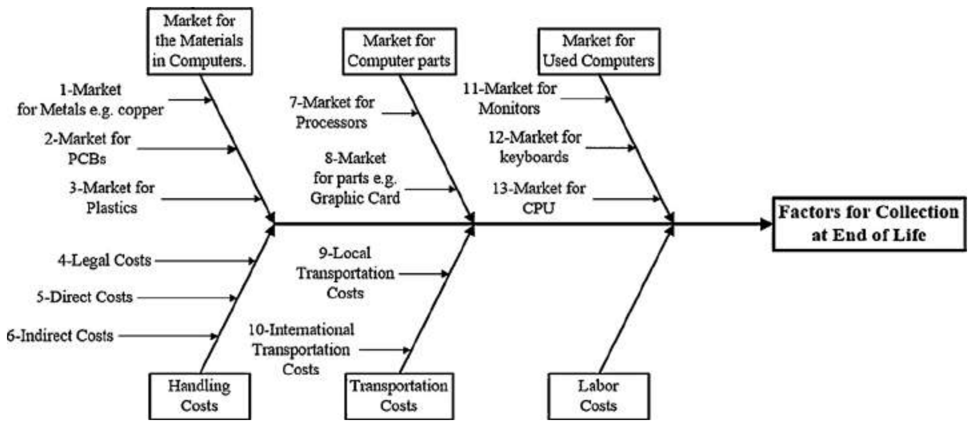

Fig. 6. Decision factors to collect or disposed as waste “And End of Life”.

pepenadores, who indicated that when a landfill site bans a particular waste and there are no options to dispose of such materials, they may be dumped in waterways, abandoned in the wilderness, or stored.

DFDs are powerful tools to uncover the relationships and the flow of information from stakeholders. While DFDs at Fig. 2 show the flow of a decision take by one user, Fig. 5 shows decisions take by several stakeholders; nonetheless this DFD is also at the Micro-level. For example, there is a decision block that formulates the question related to whether a market exists. This single decision block represents a very complex, large system which is more comprehensively described at Fig. 7.

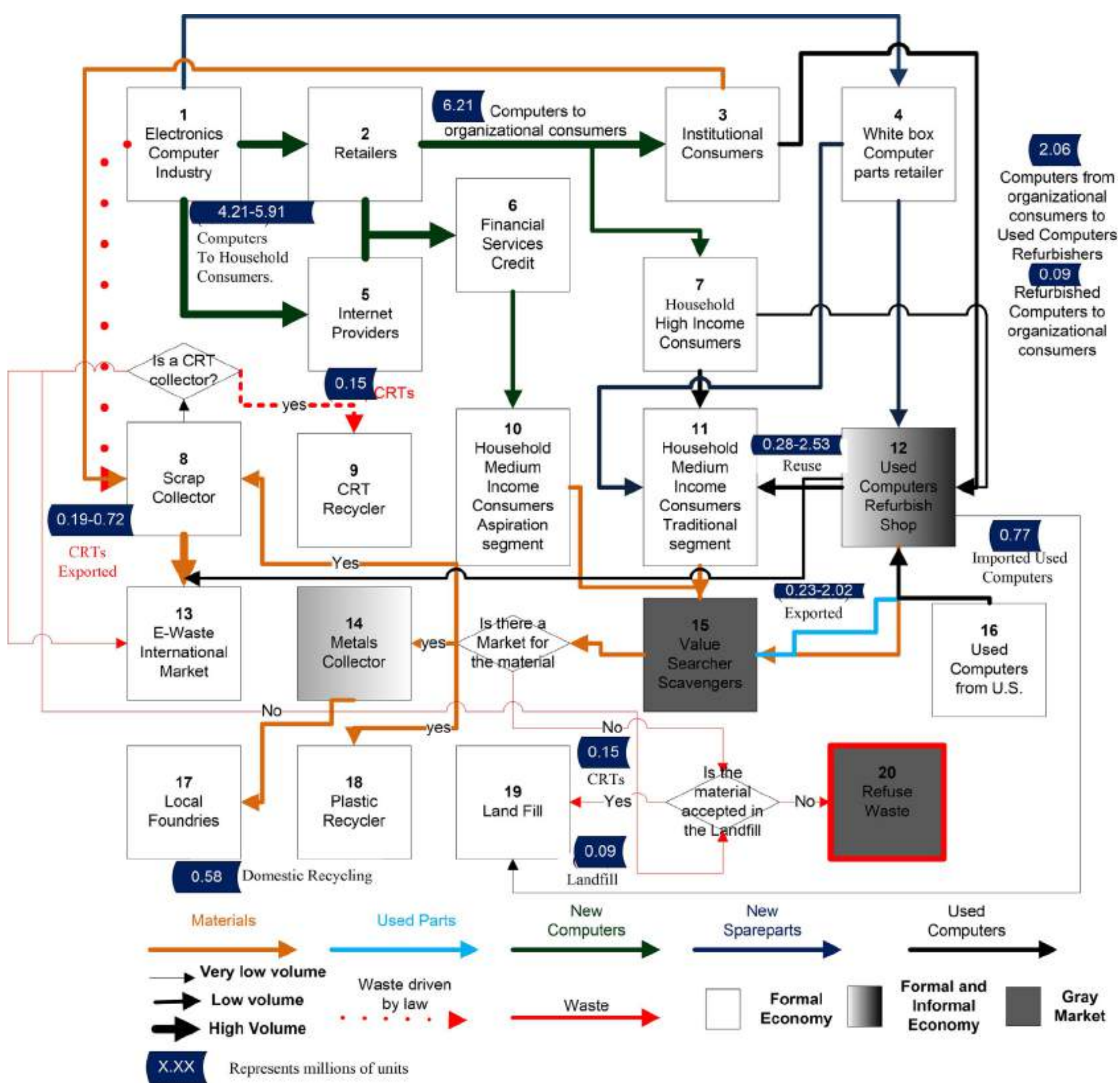

Fig. 7. DFD stakeholders from the life cycle of computers in mexico. (The numbers shown in X.XX are in millions and are data from known Materials Flow Analysis (MFA).)

Table 3
Stakeholders in the computer life cycle in Mexico (numbers correspond to the place they appear in Fig. 7).

Place	Stakeholder	Description
9	CRT recycler	Because of the lead included in CRT monitors, this activity is carried out under a license provided by the Mexican Environmental Secretariat, SEMARNAT
1	Electronic Computer Industry	Manufactures computers and their components. While many of these components and computers are assembled in Mexico, most of them are sold in the U.S.
13	E-waste International Market	Demand from international markets like China, and Europe
6	Financial Services Credit	Banks, retailers, and Internet providers offer credit to consumers to purchase new computers
7	High-Income Consumers	These consumers can buy brand new computers without credit. In addition, they can purchase computers locally or in the United States
3	Organizational Consumers	Companies, large and small, and governments as computer consumers
5	Internet Providers	Internet providers offer computers, along with their service, through long-term contracts
19	Landfill Administrators	Depending on the city, some landfill sites are managed by private companies, others by municipal authorities. Some landfill sites already ban electronic waste disposal
17	Local Foundries	Due to the long tradition of mining industries in Mexico, including the steel and copper industries there are several local foundries. The largest in Mexico are located in Monterrey, where WEEE recyclers prepare materials for them (see Fig. 6)
10	Medium Income Consumers Aspirations Segment	These consumers prefer to buy brand new computers, but the only way they can access such computers is on credit
11	Medium Income Consumers Traditional Segment	These consumers prefer to buy an affordable computer and do not hesitate to buy used computers
14	Metal Collectors	Also known as *Yonques*, their core business is to collect metals, mainly from automobiles, but some, like Yonque Phoenix in Juarez, may also take electronics
18	Plastic Recyclers	These businesses buy plastic from scavengers and collected a sufficient amount for them to recycle. Because of the mix of plastics used in computers, separation is key, and accumulation for economy of scale (as seen in Fig. 8) is necessary
20	Refuse Waste	When waste does not hold any value and there are no suitable places to dispose the probability increases that this waste will be dumped illegally
2	Retailers	Big commercial retail stores, which sell brand computers, but also small dedicated computer stores. Due to the proximity to the border, retailers can be either national or from the United States
8	Scrap Collectors	These businesses collect scrap from foreign industries established in Mexico to assemble products; they are also starting to provide the service to collect domestic e-waste. Some of these business export e-waste to the international market, but some also integrate the materials into the national industries. For example, recycled plastic is used to make heels for shoes, and metals are separated and sold to foundries
16	Used Computers from United States	Because of NAFTA, used computers can be bought in the United States, imported and sold in Mexico
12	Used Computers from refurbishers shop	This kind of business sometimes assembles and sells new computers, but most of the time they refurbish and sell used computers. In addition, some provide Internet and computer services to the public, through Internet Kiosks (also called cyber stores)
15	Value Searcher (*Pepenadores*)	There are several types of *pepenadores*, ranging from the ones that collect all kinds of waste left on the streets and occasionally collect e-waste, to the ones that specialize in e-waste. In some places the government organizes collection events
4	White-Box Computer parts retailers	This business sells new spare parts, they are known as white-box computer sellers because their parts are used in the assembly of non-branded computers

3.3. *Waste or trade: decision factors for collection and end-of-life management options*

Based on the legal structure and the different elements presented in the e-waste management system in Mexico, decision factors for collection and end of life are largely determined by market forces. Fig. 6 shows these factors. Market forces are shaping an emerging supply chain as Lepawsky and Billah found in their research in Bangladesh. Value is created through the ingenuity of stakeholders dismantling computers (Lepawsky and Billah, 2011). It is important to add that interviewees in the field studies agreed that computers were managed according to the market demands. For example, while the market for copper is widespread at all locations, the value of specialized parts such as printed circuit boards was not recognized in small cities. Computer re-use, on the other hand, was more prevalent in small cities where the access and cost of new computers were worse.

Fig. 6 relates to Fig. 5 in that it describes the factors that affect decisions taken by collectors and recyclers.

3.3.1. The market for used computers and spare parts

The trade in used computers and spare parts in the north of Mexico is strongly influenced by the importation of used computers from the US. Small computers merchants buy used computers in the United States, refurbish them and sell them in Mexico. Kissling et al., 2012 have identified four reuse models: (1) The networking equipment recovery model, (2) the IT asset management model, (3) the close-the-digital-divide model and (4) the social enterprise model. The first two are profit-oriented, the last two, non-profit-oriented. The for-profit models are differentiated by the kind of devices they re-use; e.g., networking is related to the infrastructure to support communications, while IT assessment management relates to devices like computers. On the other hand, the non-profit models differ on the final goal: either providing computer access, or creating jobs.

The stakeholders interviewed in the field studies represented a mix of all these models. For example, recyclers providing e-waste management services to *maquiladoras* are similar in their operation to the network model. However, these entities do not manage IT infrastructure. On the other hand, small used computers importers create jobs, but at the same time are profit-oriented. Purely social enterprises do not exist, but there is a fair trade of electronics case: *Las chicas bravas*, a recycling enterprise at Fronteras Sonora. The close-the-digital divide model is implemented in certain cities as a mix of the social enterprise model and the IT asset management model. Used computers refurbishers create jobs and provide used computers to Internet kiosks that sell Internet and computer time to low-income populations.

The market value for a used computer is related to characteristics like Internet connectivity, and capability of supporting software requirements. Literature reports that, for example, up to 61% of computer use in Lima was for Internet browsing (Kahhat and Williams, 2009). At study-area flea markets, used equipment with a Pentium III is priced between 20 USD and 30 USD. However, the window of opportunity to trade a used computer narrows over time. Nonetheless, used computers trade is successful because of the enormous economic and social diversity of Mexican society. Information about the flows of used computers trade is scarce because a huge part of this trade is made in informal markets and between individual users.

The demand for spare parts for used computers is closely related to the computer models currently being used. Once a particular model is outdated, the market for its parts ends. Also the size of cities generates different market dynamics. Specialized computer stores are more common in big cities than in small ones. In big cities, such retailers collect used computers for dismantling and consequently, they are able to trade computers parts. On the other hand, in small cities stores combine used computers parts with other used electronics because only through this diversification are they able to manage inventory costs. When complete disassembly occurs, even the parts most difficult to dismantle are extracted from computers, as long as there is a market for them.

3.3.2. Markets for materials in the computers

The biggest incentive to collect non-working computers is their metal content. E-waste contains a variety of ferrous metals, base metals like copper and aluminum, precious metals like gold, silver, platinum, and technology metals like indium, gallium and cobalt; but they also contain toxic heavy metals like mercury, lead and chromium. The value of e-waste as a source of metals has been extensively reported in literature (Hagelüken et al., 2005) (Oswald & Reller, 2000) as have as the environmental impacts related to printed circuit board recycling (Bi et al., 2010). However, material value is not the only driver, the difficulty of dismantling and market demand are as well. For example, complete CRT end-of-life management is complicated because of its characteristics: while the copper can be separated easily, there are environmental risks related to leaded glass (Ren et al., 2011). In addition, the technical change from CRT monitors to flat screen (LCD monitors) makes it difficult for CRTs monitors to be traded and re-used. Materials like plastic, glass and lead are also difficult to trade (Qu et al., 2006). This was confirmed by interviews of recyclers in Monterrey, who indicated that plastics from computers have to be stored to make transport feasible for later recycling. Despite the just-cited emergent research on how to recycle plastics, important logistical issues with plastics remain. This is a common characteristic of all materials less valuable than metals.

3.3.3. End-of-life costs

The feasibility of end-of-life recycling depends on three items: (1) processing costs, (2) transportation costs, and (3) labor costs. While the latter two are self explanatory, process costs deserve further discussion. The process to recycle obsolete equipment requires expenditures for energy, infrastructure and materials. There are costs to store large quantities of computers for recycling. They first have to be sorted into two parts: computers to be dismantled for materials and computers to be refurbished and sold as used computers. In addition, administrative and regulatory costs, such as taxes, are part of the overall costs of these operations. Costs to recycle materials from computers can be in different scales: from medium-sized technologies to integrated refineries such as Umicore in Belgium and Dowa in Japan (Hagelüken et al., 2005). Informal recyclers often do not benefit from the new recycling technologies. In addition, the economic returns from the appropriate recycling of metals due to better technology should be distributed to other participants in the reverse supply chain.

3.4. DFD: from production to disposal, a meso-level view of the materials flow

Decision Factors for e-waste management goes beyond the individual, because local and national organizations impact these decisions. In addition, global tendencies and cultural characteristics are also important and must be mentioned to provide a comprehensive systems view of the e-waste management system in northern Mexico. At the aggregated level, new characteristics emerge. The e-waste system is complex, not because of the methods to manage e-waste but because of their continuous evolution and the complex behavior of human society. However, the DFDs presented in the previous figures show only the decision information flows for individuals. There is a need to review the system at two additional levels, meso- and macro. While the micro-level is at the perspective of individuals, the macro-level encompasses entire countries. Between the micro and macro, is a meso-level, formed by organizations, such as governments and companies, large and small [25]. Fig. 7 shows a simplified view, at the meso-level, of the flow from computers through the different stakeholders in northern Mexico.

It can be seen in Fig. 7 how new stakeholders emerge at the meso-level, e.g., the computer industry, and retailers. At this level, the influence of legislation is more clearly seen. A brief explanation by stakeholders appearing in Fig. 7 can be seen in Table 3.

At the meso-level, (Fig. 7) four characteristics of system that do not appear at the micro-level emerge:

1. *Formality of operations*: Formality is defined as the need to be registered by law and adhere to existing rules and regulations.

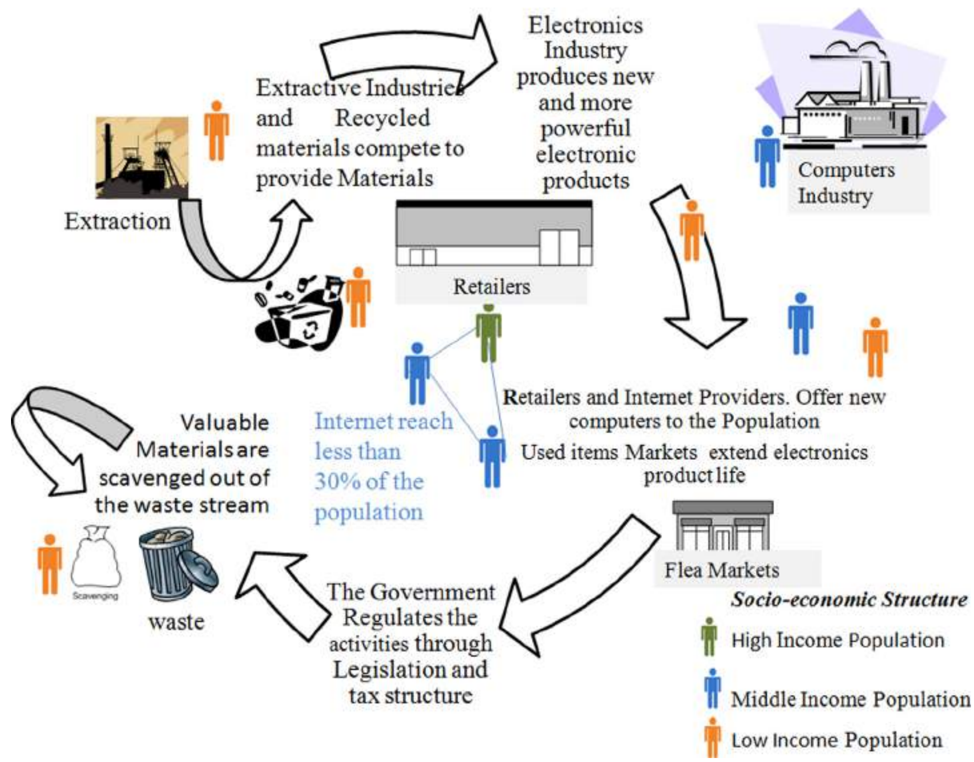

Fig. 8. Computer life cycle and technology and social structure in Mexico. This figure includes: the life cycle, socio-economic structure (represented by 10 persons with their economic level shown in varying colors), and finally Internet access. (Both Internet access and socio-economic level quantities are derived from INEGI statistics.)

Formal stakeholders are shown in white, and informal stakeholders in black (black and white gradient boxes represent the existence of various informal and informal stakeholders for the same activity). It is important to point out that informality can be derived from two main components: The first is the lack of specific regulations, the second from the difficulties of informal collectors (e.g., *pepenadores*) to become formalized and meet complex regulations.

2. *Material flow*: Fig. 7 shows how materials are moved from one stakeholder to the next with the volume from these materials shown by *the thickness of the lines*. The figure includes known data about the materials flows in Mexico, derived from a study by Arizona State University (Kahhat et al., 2011) For example, the flow of new computers from the electronic industries to household consumers in Mexico ranges from 4.21 to 5.91 million units (desktops and laptops). The flow of new computers from the electronic industry to organizational consumers (business and public sector) is about 6.21 million. O*rganizational consu*mers sent 2.06 used units to refurbishers, but received 0.09 million units from them (because some small companies buy used computers). Household users sent 0.98 million used units to refurbishers, but may in addition receive from them from 0.28 (low reuse scenario) to 2.53 (high-reuse scenario) million units. About 0.58 million units are recycled in Mexico (desktops and laptops) and from 0.23 to 2.02 million units are exported. Finally 0.15 millions of CRTs are recycled domestically, and 0.19–0.72 CRTs are exported.
3. *Socio-Economic Characteristics:* interviews with stakeholders working directly with consumer users revealed important social and economic differences among their customers. High-income consumers traditionally prefer to buy new computers, but middle-income consumers are divided into two different segments. The first segment is comprised of middle-income consumers who try to imitate high-income consumers and buy new computers through credit schemes. In the second segment, middle-income consumers buy used computers. Low-income consumers find access to computers and the Internet from entrepreneurs that buy used computers and rent them to consumers for short time periods at kiosks.

Expressed as a DFD, the systems view at Fig. 7 allows three important characteristics of the system to be identified.

1. Importance of informal recyclers: Small cities and towns have higher risk related to disposal of e-waste. For example the absence of CRT collectors increases the risk of non-environmentally sound disposal. *Pepenadores* are the last line of defense for the system to recover valuable materials.
2. Importance of markets: Most of the system runs on profit; hence, any material that does not have a market value will be sent to the landfill site.
3. Regulatory framework: Regulation that prohibits disposal at landfill sites does not solve the problem of waste generated prior to the regulation and also promotes illegal dumping.

3.4.1. Decision factors at a macro-level systems view

Factors like culture and the socio-economic structure are still not easy to see, both at the micro-level and at the meso-level. For example, the role of *pepenadores*, who scavenge electronic waste as it enters the landfill site, cannot be seen clearly in Figs. 2, 5 or 7. At a larger systems view (macro-level), *pepenadores* are the last part of an e-waste system that includes a great many stakeholders in the supply chain, a few of whom are: raw material extractors, material transporters those who transform these materials into products, distributors of these products to markets, the consumers who used and dispose these products, and end-of-life management operators.

However, none of these stakeholders operate in a vacuum; they are part of a socio-technical system (Odum and Barrett, 2005) that includes Internet, radio stations, TV networks and emergent communication systems (see Fig. 8). It is at this level that social and economic characteristics emerge. These characteristics are not shown in Fig. 7. In Fig. 8, the population in Mexico is represented by 10 persons with colors representing socio-economic level. (The number of stick figures included is proportional to national statistics provided by INEGI.) It can be seen that only 1 out of 10 people is a member of the higher socio-economic level and half of the population belongs to the low socioeconomic level. (Poverty or extreme poverty according to international standards.) Only 3 out of 10 are connected to the Internet.

4. Conclusions

DFDs with the combination of Ishikawa diagrams are a useful tool that portrays processes, information and materials flows within a system. These characteristics made them a valuable tool to uncover relationships between stakeholders, and identify obstacles and opportunities in the e-waste management system. An example is the direct correlation between the subjective value of electronic equipment and its end-of-use management option or how the market requirements of materials determine the way they are handled at the end of life. The emergence of markets for electronic parts or materials depends on factors that include the transmission of information between the principal stakeholders, available technologies, resource scarcity and varying requirements of society. If value is found for parts/materials, a market will be created, and collection, dismantling and recycling practices will emerge.

Decision factors for e-waste systems operate at different scales, at the macro-level, where technological change is the most important factor, the meso-level where legislation is the most important factor, and the micro-level, where perceived value and geographical location drive the rate at which computers are disposed and the resources available to trade or dispose a computer.

However, decision factors have different weights according to these levels. For example, technological change is a powerful driver at the macro-level, but its impact on individuals with low acquisitive power is limited. Also, legislation is only effective as long as there are meso-level structures that support it.

Legislation is the most important factor at the meso-level, because it defines e-waste management responsibilities; however, its impact level depends on the structures that support application. For example, more restrictive laws may not be effective if the resources to implement them are not available. In addition to legislation, knowledge is also an important factor, with a wide influence at different levels. For example, culture and knowledge about electronics play an important role in how computers are managed. Furthermore, the presence of the *maquiladora* industry creates knowledge about electronic processes, and dismantlers find a qualified labor force, which is not always present in communities without *maquiladoras*. This qualified labor force is able to properly disassembly even the most difficult electronic components, if there is a market for them. This is an important characteristic because it allows the recovery of parts. Such re-use would reduce the high energy intensity, estimated to be about 6400 MJ to manufacture a computer (Williams, 2004).

The use of DFDs in this paper illustrates the seldom-acknowledged complexity of managing e-waste. This complexity derives from multiple stakeholders, who are affected at multidimensional levels by multiple factors. Therefore, it allows focusing on potential solutions according to the level at which a problem presents. For example, regulatory legislation is only one of many factors that are important in the disposal of e-waste, other include technological change and the availability at a specific geographical location of resources and knowledge. This supports the thesis that it is important to include this diversity when designing policies for managing the disposal of computers. The use of DFDs may also be important when exploring the behavior of this complex system as a consequence of legislation and different policies. Moreover, the use of DFDs can identify obstacles in the system and propose the implementation of mechanism to solve them. In addition, the multi-level analysis allows for a focus on the mechanisms which may be appropriate. Thus, DFDs show this complexity and Ishikawa diagrams are the tool to understand how decisions are made.

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