CIRRELT

Centre interuniversitaire de recherche
sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre
on Enterprise Networks, Logistics and Transportation

Computer Hardware Reverse Logistics : A Field Study of Canadian Facilities

Suzanne Marcotte
Marie-Eve Hallé
Benoit Montreuil

August 2008

CIRRELT-2008-41

Bureaux de Montréal:
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone: 514 343-7575
Télécopie: 514 343-7121

Bureaux de Québec:
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
Téléphone: 418 656-2073
Télécopie: 418 656-2624

www.cirrelt.ca

UNIVERSITÉ LAVAL UQÀM HEC MONTRÉAL ÉCOLE POLYTECHNIQUE MONTRÉAL Université de Montréal

Computer Hardware Reverse Logistics: A Field Study of Canadian Facilities[†]

Suzanne Marcotte[1,2,*], Marie-Eve Hallé[1,2], Benoit Montreuil[1,3]

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT

[2] Department of Management and Technology, Université du Québec à Montréal, C.P. 8888, succursale Centre-ville, Montréal, Canada H3C 3P8

[3] Département des opérations et systèmes de décision, Pavillon Palasis-Prince, Université Laval, Québec, Canada G1V 0A6

Abstract. This paper reports Canadian field based evidence and insights on computer hardware refurbishing and recycling facilities. The key findings lie at multiple levels: double-sided environmental and business motivation, complex network with many bi-directional relations and many relational loops and similarity of the operations no matter the facility size. Two complexity factors are the high uncertainty of both demand and offer, and the hard-to-assess and fast-decaying value of returned hardware. These generate many sources of uncertainty and variability along the refurbishing and recycling process.

Keywords. Reverse logistics, network, waste management, computer, operation management.

Acknowledgements. The authors thank the Creation and Research Financial support program (PAFARC) from Université du Québec à Montréal.

[†] This article was presented at the “2008 International Material Handling Research Colloquium”, Dortmund, Germany.

---

* Corresponding author: Suzanne.Marcotte@cirrelt.ca

Dépôt légal – Bibliothèque et Archives nationales du Québec,
Bibliothèque et Archives Canada, 2008

1 Introduction

The industrial era brought great advances in human health but also its share of problems. As facilities increased productivity, they also offered products at cheaper price and thus contributed to an increase in consumer goods purchase and utilization. Then a cycle started: as more people buy, more facilities want their share of market and thus offer more products which thereafter increase consumer expectations. To keep their market share, businesses encourage consumers to get newer and better products. Then, these products's life gets ever shorter, thus generating ever increasing waste. This leads to two major environmental problems. First, the high consumption rates lead to pollution and depletion of natural resources. Second, waste management becomes more complex, with higher variety and volume. Indeed, the waste increase leads to landfills becoming quickly saturated. Cities must find new landfill sites. This creates turmoil among environmental consciousness pressure groups. As a countermeasure, increasing recycling prevents, or at least delays, the need for new landfills.

On the private side, some retailers and manufacturers offer to clients the possibility of returning products at the end of their useful life through reverse logistic initiatives. The automotive, electronic, pharmaceutical, and soft drink industries are among those having leaded the way. Individual companies have put in place reverse flow networks. Examples include Coca-Cola for its recyclable bottles [2], Phillip Morris for its pallets [1], Kodak for its cameras [13], Hewlett-Packard for its ink cartridges [11], L'Oréal for its beauty products [15]. Reverse logistics is thus becoming a key competence for modern supply chains [3].

One the public side, many cities have put in place recycling programs, legislations and facilities. Early recycling facilities focused on products including significant amounts of materials with a higher salvage value, such as ferrous metals, paper and cardboard. This has resulted in a decreased dumping of many such materials in landfills in recent years [12]. As recycling facilities treat ever more variety of products and materials, a new reality is being shaped, involving as a normal behaviour the return of discarded products or raw materials in the value chain network.

The recycling effort is having trouble dealing with high-volume short-life technological products such as cellular phones and computers. Such products have registered a steady increase of quantities discarded in landfills. Environmental consciousness group raise emergency flags. The environmental impact of discarding such products in landfills is deemed unbearable. On one side they contain many very long lasting components. On the other side they include materials which are detrimental to the environment. Both industry and governments recognize the importance of the issue. Several businesses are becoming more responsible regarding the role they have to play regarding these products at their end of their use. New players specialize in the flow management of discarded computers. Some aim for environmental protection. Others aim for profitability and computer secondary market.

This paper focuses on computer hardware reverse logistics, and particularly on computer hardware recycling and refurbishing facilities. It reports empirical research based on two field based activities. The first is an operational analysis of eighteen players in the Eastern Canada reverse logistics network. To provide a global perspective of the computer recycling supply chain, players which have different roles in this supply chain have been visited, including suppliers, non-profit organizations and players in the international computer secondary markets. This research tackled questions such as why are computers (and other electronic equipment) recycled, does it come from people awareness of pollution problems or by law enforcement? How and where are computers collected? Who recycles them: the original manufacturers, a government, profit based businesses or non-profitable organizations? Are they repaired, do they have parts reused, or are they recycled?

The second research activity underlying the paper is a set of two in depth case studies of representative recycling facilities. This involved modeling their operating process with its numerous decision points associated with sorting and evaluating the quality of the computers and the parts received. The nature of typical operations was analyzed, allowing notably the characterization of the flow of computers, parts and materials through such facilities. The specific nature of the uncertainties that such recycling facilities have to deal with was documented, as well as how they cope with such uncertainties.

The remainder of the paper is structured as follows. In Section 2 we present the motivations for refurbishing and recycling computer hardware. Then in Section 3 we describe and analyse the computer hardware reverse logistics industry and network. In Section 4 we describe typical refurbishing and recycling facilities through two in-depth case studies. Section 5 pinpoints the exact nature of the uncertainties that such recycling facilities have to deal with and documents how the facilities cope with these uncertainties. Finally, we present conclusion and research avenues in Section 6.

2 Motivations for refurbishing and recycling computer hardware

Physical waste generated by information and telecommunication technologies is getting ever more attention since each technological progress increases the obsolescence rate of previous technologies and results in disuse of material embedded in these previous technologies. The average life time of a computer is currently between two and three years. It is more likely to diminish exponentially over the next few years [24] Thus, it results in a currently large and expected-to-increase quantity of material going in the waste flow. The computer related wastes is the only type of waste which has been increasing recently in Canada [4]. This flow is likely to increase since new product sales keep growing. As evidence, consider that between 1997 and 2002 the quantity of computers owned by Canadian households has increased from 1.8 to 3.2 millions, which represents an increase of more than 75% [4]. The sale increase is explained by the fact that, contrary to what is generally believed, many homes still do not have a computer. Moreover, the technology is developing at such a rate that it requires frequent material upgrade. Environment Canada evaluates that most of the technological obsolete products still end up in a landfill or in an incinerator. In 2004, the ratios were as follows in the province of Québec: 59% ended up in landfill, 28% have been reused, 7% have been stored and only 6% have been recycled [19]. In 2005, the quantity of waste coming from computer hardware in Canada has reached 170 491 tons. From this quantity, nearly 40% has been taken to a landfill [5].

The millions of computers that end up in a landfill represent a high risk for the environment and the population health. Indeed, those materials contain toxic wastes which are dangerous for environment if they are not adequately managed. The computer and monitor composition illustrated in Figure 2 reveals a variety of materials such as copper, lead, zinc, ferrous metal, glass and plastics. It also includes a precious metals category englobing material such as nickel, manganese, cobalt, barium, tin, silver, mercury and arsenic. The toxicity of the constituents of a computer is a cause of: stream and natural environment pollution, leading to shortages in drinking water as well as agricultural problems [9]. Furthermore, while being used, a computer pollutes by its power consumption. But this is not the end of its ecological impact. Even before being used for the first time, a computer has already left a trace in the environment, so that every non-reused computer generates its share of negative impact. According to a study from the United Nations University, producing a computer and a 17-inch monitor requires 240 kg of fossil fuel, 22 kg of chemical and 1500 litres of water [18].

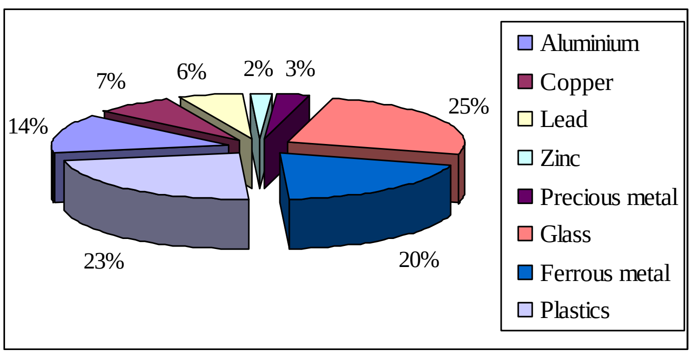

Figure 1. Computer and screen components
Source : Silicon Valley Toxics Coalition [23]

In Europe, the decree n°2005-829 of July 2005 [16] relating to the composition of electrical and electronic equipment and to the elimination of waste from this equipment gives the manufacturers entire responsibility of their waste, including post product life waste. They must put in place infrastructure so that consumers can bring back their equipment without charges. It is the manufacturers responsibility to insure that their equipments are reused or disposed properly. Europe has gone even farther by restricting the use of toxic material in the electrical and electronic equipments, in accordance with "RoHS" directive.

On June 21, 2007 the Canadian government announced its intent to introduce a regulation project based on the notion of extended producer responsibilities (ERP) [20]. This regulation will oblige producers of electronic products, battery and fluorescent lamp to recover and salvage those products at end of life and to reach the goal set by the government. According to Environment Canada, the regulation is applicable if the recycled materials are considered dangerous since they have a dangerous characteristic or that they correspond to some risk criteria. The recyclable materials can also be regulated if they are composed of parts or elements cited in specific lists. The dangerous materials are liable to the "Export and import of Hazardous Waste and Hazardous Recyclable Material Regulation" if there are flows between frontiers [6].

Dangers of technological product waste for the environment are thus more and more known and many pressure groups make it there battle horse from now on. Thus, sensitive and aware to the risks that represent electronic wastes, many actors of the electronic industry and of the recycling industry put in place a network to insure an ecological processing of the material.

Overall, this portrait reveals that the basic motivations of the industry actors for refurbishing and recycling computer hardware are twofold. First it aims to decrease the negative effects that computer hardware can have on environment and public health. Second, it aims to insure that their public image is not stained, which would negatively impact their revenue and profit potentials.

3 Computer hardware reverse logistic industry and network

Reverse logistics is "*the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal, while providing an efficient and environmental utilisation of the resources made use of*" as defined by Lambert and Riopel [14] from an extension of the early definition of Rogers and Tibben-Lembke [21].

Reverse logistics differs from forward logistics in many ways beyond the fact that flow is reversed. Indeed the roles of players are less clearly defined in reverse logistics and its operations are more complex due to inherent multifaceted uncertainty. Key differentiators are forecasting, distribution network, routes and destination, distribution costs, product quality, product packaging, disposal options, price, importance of the speed of disposal, inventory management and production planning, product life cycle, negotiation, marketing techniques and process visibility, according to Rogers et Tibben-Lembke [22] and Lambert and Riopel [14].

Figure 2 details the key constituents of reverse logistics, as proposed by Lambert and Riopel [14]. Central in Figure 2 are such activities as recycling, remanufacturing and refurbishing which are keys to recapturing value from merchandise returned due to such reasons as damages, returns of unsold seasonal inventory by retail clients, returns from consumers for underperformance or misfit, quality and safety related recalls, overstock clearance, obsolete equipment disposition, hazardous materials protection, end-of-useful-life salvage and asset recovery (e.g. Rogers et Tibben-Lembke, [21]. These key activities and the facilities at which they are performed for recapturing value from returned products are the focus of this paper, especially for computer hardware.

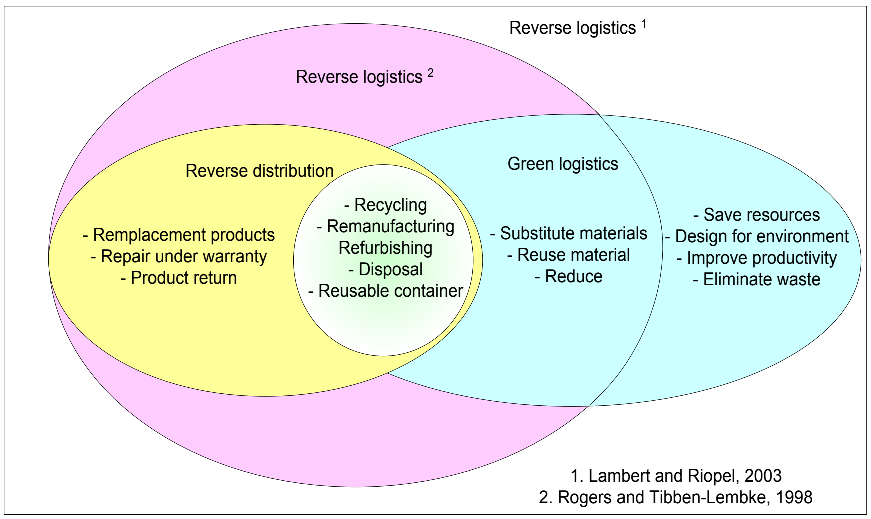

Figure 2. Constituents of reverse logistics
(source: Lambert and Riopel, [14])

Figure 3 illustrates those key types of actors and the relationships between these actors. Many relationships are usual customer-supplier relationships, yet creating chains bringing back to market the disposed computers. For example, some user facilities keep their technological park up-to-date. When they dispose of their computers, they sell them to a refurbishing facility. These refurbish the disposed computers and sell them to other organizations or businesses that do not need an up-to-date technological park. Sometimes, a relationship involves actors that each are both suppliers and clients of each others. An example is the relationship between a computer part recycling facility and a refurbished equipment retailer. The recycler may sell parts to the retailer which in turn will use those parts to repair equipment. The retailer might get stocked with computers that are getting obsolete, and decide to send it to the recycler. Another special link is between a broker, computer users and refurbishing facilities. Indeed, a broker gets a computer from a computer user; subcontract the refurbishing, then sell it to another computer user.

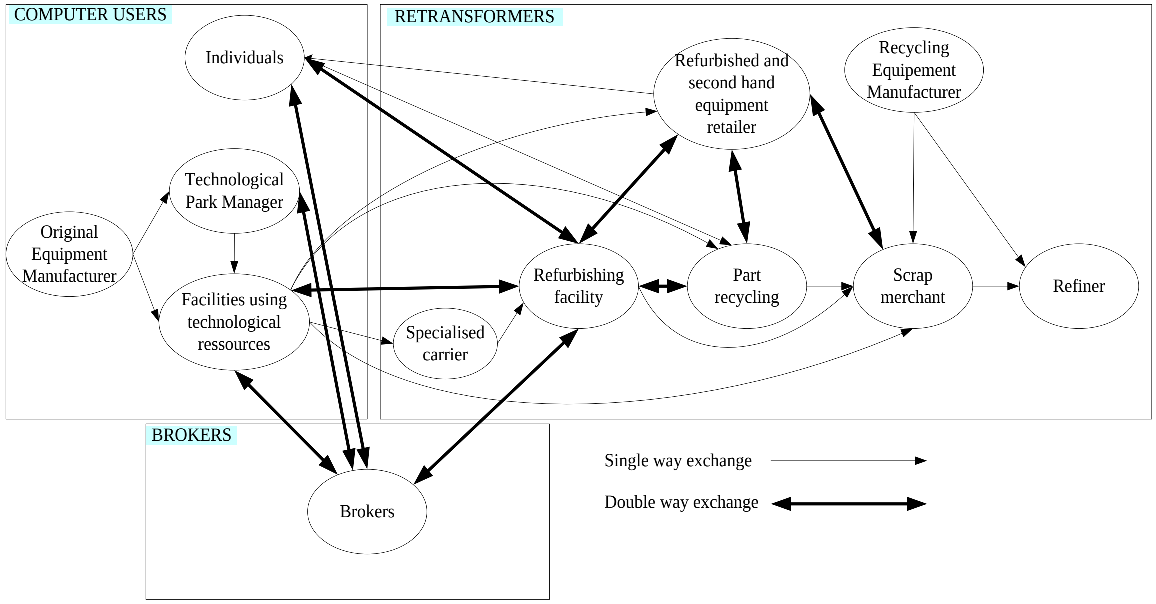

Figure 3 Computer Hardware Reverse Logistics Value Network

The network described in Figure 3 shows the multiple relationships between the computer users, the retransformers and the brokers. To study the Québec's computer hardware reverse logistics network, eighteen businesses have been visited and studied. Figure 4 distinguishes profit making from non-profit businesses. It depicts the roles performed by each business. Some roles are performed by multiple businesses and some businesses perform multiple roles. The many relationships between the retransformers render more complex the overall set of supplier-costumers relationships. For example, in Figure 4, business PD is concurrently playing roles as a refurbisher, a scrap merchant, and a retailer of refurbished products and parts, it has a significant number of relationships with other businesses, as depicted in Figure 3. As will be analysed in section 5, a business like PD faces a large number of decision steps in the operation process and thus faces high facility flow complexity.

Table 1 provides more information on the businesses introduced in Figure 4. It specifies their type of facility and their motivation for recycling. Those motivations vary hugely from businesses to businesses, closely related to their profit vs. non-profit making mission. The non-profit making businesses are focused on social inclusion as the profit-making ones are focused on sales. In the interviews, only one manager of a profit making business mentioned a significant worry for environment.

Table 1 also shows their main input and output categories of computer hardware. There are strong distinctions among types of actors. For example, refurbishers focus on generating value from refurbished computers and parts while the scrap merchants focus on maximizing value from recycled materials

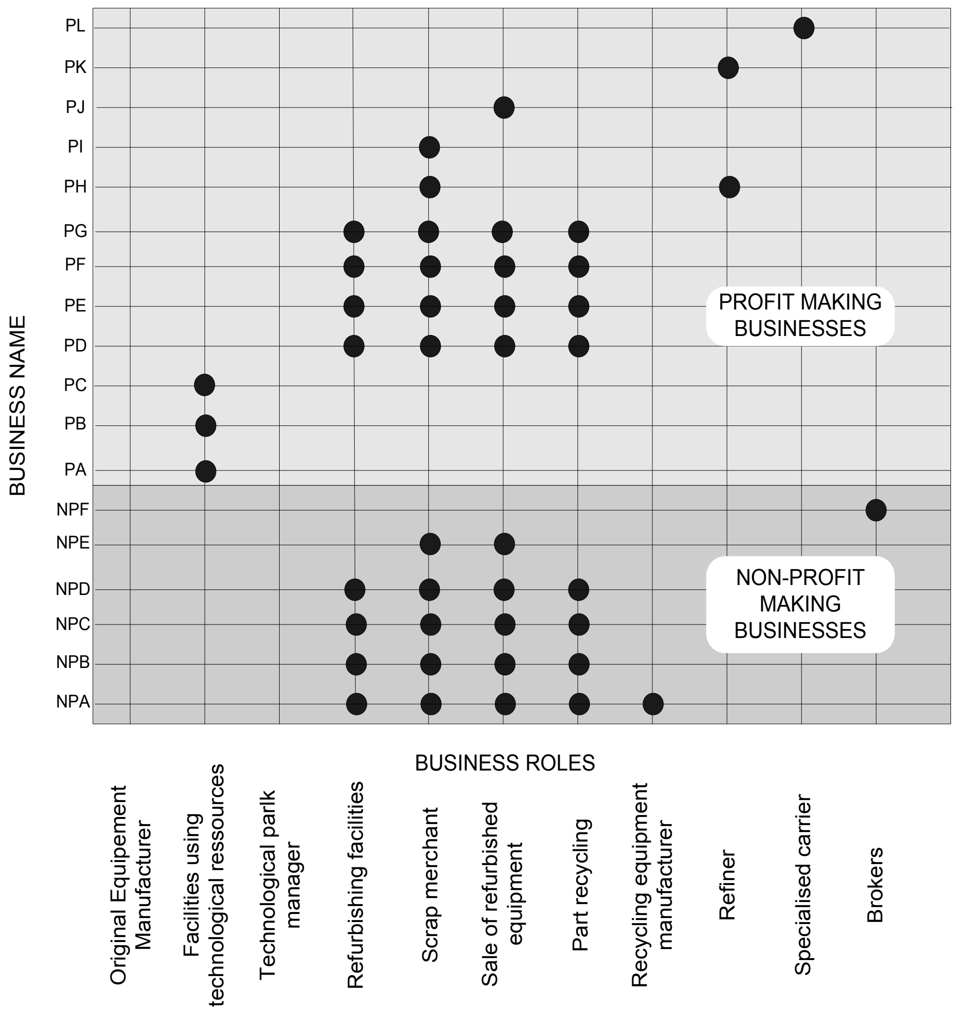

Figure 4. Multiplicity of business roles in sampled Quebec's computer hardware reverse logistic industry (source: Hallé, [10])

Most of those businesses have a single facility except NPD, NPE, PD, PE and PI. NPD is affiliated with a Canadian business. NPE is a group of collecting and recycling centers where individuals dispose of goods that are not collected in the regular weekly trash and recycling collections. One of the profit-making facilities (PI) is vertically integrated with NPE which is his one of his suppliers. Business PE is part of a large business that has several facilities across North America and one facility in Europe. Finally, the head office of PD is located in Toronto.

Table 1 Description of the 18 facilities analysed in this study (source: Hallé, [10])

Business	Type of facility	Motivation	Input processed	Output
NPA	Refurbishing facility	Social inclusion of young dropouts Work-school alternation	Obsolete computers and input/ouput devices	Valorisation Equipments and parts resale Waste disposal
NPB	Refurbishing facility	Social inclusion to labor market	Obsolete computers	Valorisation Equipments and parts resale Waste disposal
NPC	Refurbishing facility	Offer technology to Africa emerging economies countries	Obsolete computers and input/ouput devices	Valorisation Equipments and parts resale Waste disposal
NPD	Refurbishing facility	Social inclusion of mentally challenged	Obsolete computers and input/ouput devices	Valorisation Equipments and parts resale Waste disposal
NPE	Scrap merchant	Warehouse – to reroute from landfills	Salvagable material	Waste disposal Material resale
NPF	Broker	Offer computer to Québec schools	Computers	Link between suppliers and refurbishing facilities
PA	Businesses using technologies	n/a	Utilization of high technology	Purchase of the technology Resale of this technology
PB	Businesses using technologies	n/a	Utilization of low technology	Computer purchase Storage of obsolete computers
PC	Businesses using technologies	n/a	Utilization of medium technology	Computer purchase Resale of computers
PD	Refurbishing facility	Resale of refurbished material	Obsolete computers and input/ouput devices	Valorisation Equipments and parts resale Waste disposal
PE	Refurbishing facility	Revalorisation and resale of material	Obsolete computers and input/ouput	Valorisation Equipments and parts resale

4 Computer hardware refurbishing and recycling facilities

This section describes typical refurbishing and recycling facilities through two in-depth case studies revealing their layout and the numerous decision points for sorting and evaluating the quality of the computers and the parts received. This uncovers the nature of typical operations and allows characterizing the flow of computers, parts and materials through such facilities. Subsequently, Section 5 pinpoints the exact nature of the uncertainties that such recycling facilities have to deal with and documents how the facilities cope with these uncertainties.

Figure 5 shows the generic process of refurbishing and recycling facilities. The operations are identified by letters. After the equipments are collected (A) from their suppliers, a visual sort (B) must be done to eliminate equipments that cannot be reused. The criteria are: color, model, hardware type, obsolescence and quality of the device. They are then sorted according to their type (computers, screen, keyboard, etc.) and stored (C) until a sufficient amount of equipment is available to process a batch of it. Since computers constitute the bulk of the hardware being refurbished, the process is hereafter described for computers, although it is very similar for other types.

The process begins with a visual inspection (D) of the computer to identify the model (for example Pentium II, III or IV) and to check whether the computer is obsolete. If the computer has a potential marketability as a computer, its functionality is tested (E). If it is functional as is, it is cleaned and its memory is erased (F) otherwise it is tested to see if repairable (J). If the computer is functional, it is reconfigured (G) and other devices are added to the computer, such as a keyboard and a mouse, and finally packaged (H). It is then stored with the equipment to be sold (X). If it is not repairable, it is disassembled (I) to salvage the parts. If it is repairable, it is stored (K) until the required parts are available (L) from disassembled computers or from new parts bought. When the repair (M) is completed, the computer is cleaned (F), reconfigured (G) and packaged (H). The parts that are disassembled to be replaced by new ones in the repair step (M) are disassembled (R). If the computer waits for too long, its marketability is verified. If it is still marketable, it is kept in storage (K), otherwise it is disassembled (I).

When a computer is disassembled, the parts are tested to check whether they are functional (O) or not. If they are functional, the inventory level and their usefulness for repair are checked (P). If positive, they are put in the storage as parts for sale (Q), otherwise their marketability is checked (S). If the parts are marketable, they are stored to be sold (T), otherwise they are disassembled (R). Periodically, the usefulness (P) and the marketability (S) of parts in storage (Q and T) must be checked. If they are not reusable or not expected to be sold, they are disassembled (R) to salvage the raw materials. The remaining materials are sorted (U) between recyclable (V) and non recyclable materials (W). Before shipment, the latter are stored until the minimal quantity required by the refiner is reached.

Recycled parts require continuous inventory control. Indeed, even if a part is expected to be used in a future repair, if the time spent by the part in the storage is too long, the demand for that part might change and the part might become obsolete.

To repair computers, new parts are sometimes required. Indeed, some components, such as keyboards, mice, DVD drives and memory are often bought new since in a used state their technology is too old, hard to repair, discoloured, or too few of them are reusable. Also, to facilitate packaging, transport and selling, boxes and other packaging materials are required. Finally, upgraded or new software are required, thus facilities must buy the software or get rights to install basic software.

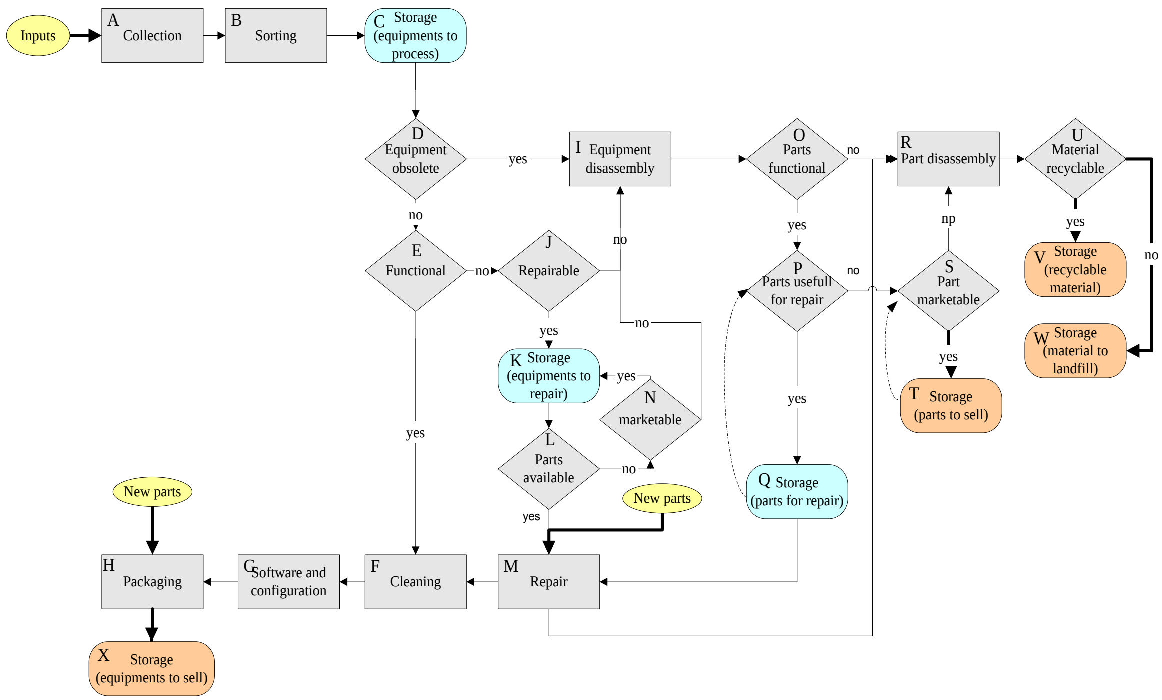

Figure 5. Refurbishing/recycling facility process

The layout of both studied facilities PE and NPB, as well as the flow of products and parts, are respectively provided in Figure 6 and 7. The layouts differ widely, as do the flows since facility PE is organised as a linear layout while facility NPB is organised as a job shop.

As many of the other refurbishing facilities, facility PE has many inputs, mainly used computer hardware and more specifically computers. These inputs come mostly from facilities having a technological park of computers. The inputs are thus somehow homogeneous and information about the components of a computer is provided with it. This simplifies the operations and the flow of products since a batch of computers from the same supplier requires about the same process and generates a continuous flow, mostly with a single piece between workstations. When the equipments are received, they are identified by a bar code and then stacked on pallets (C). After the pallets are verified and routed to the staging area, the computers are codified and a bill of materials is created. Along the process, the bar coded units are scanned and monitored, enabling traceability of all units. This codification system also enables an excellent inventory management. The facility knows the detailed inventory in real-time and can issue requests to find specific components. The system releases a work order and then the refurbishing process starts. At the control step (E), another work order is released according to the next operations required. About three fourth of the computers only require minor repairs, cleaning and packaging. The cleaning step (F) includes hard drive erasing and the packaging step (H) includes adding new keyboard, mouse and wiring. If a major repair is required, which corresponds to about 10% of the computers, the work order also specifies the required parts list.

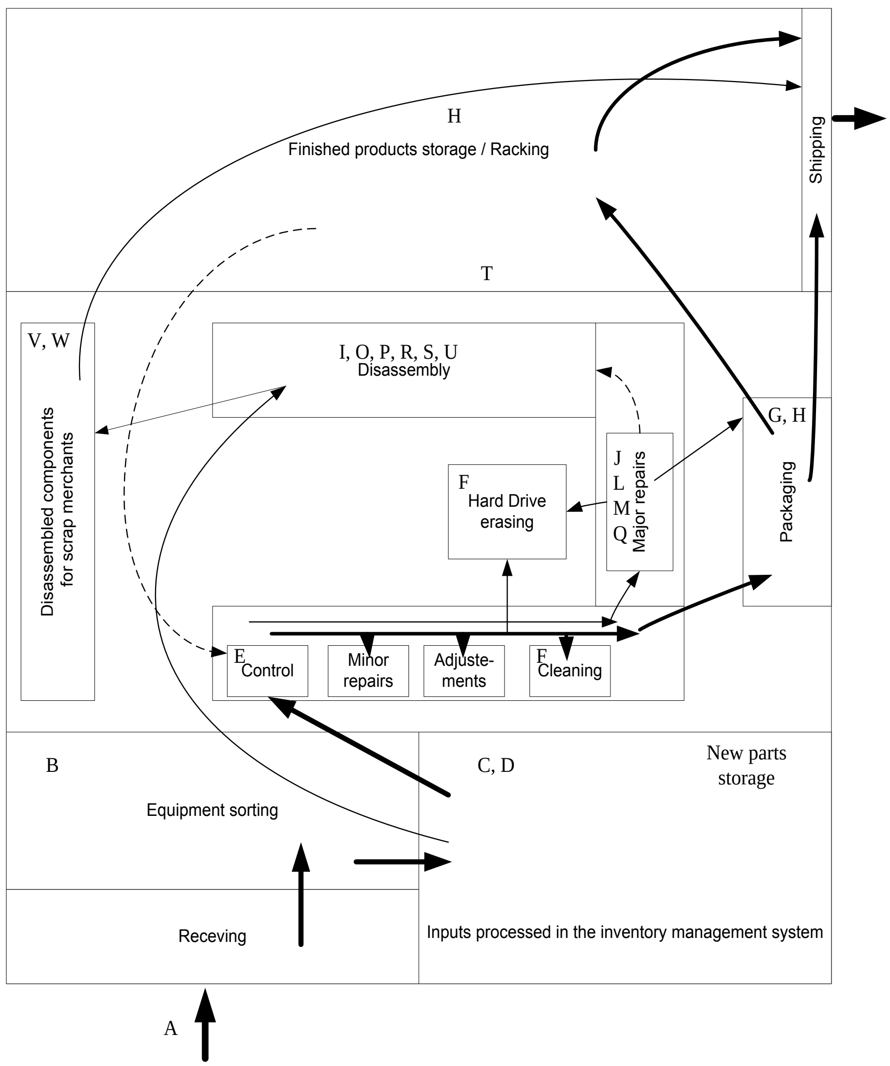

Figure 6. Facility PE layout and flows
(source: Hallé, [10])

About 15% of the computers cannot be refurbished. Those are partially or totally disassembled to maximize their salvage value. Materials and parts are sorted in boxes to be either sent to refiners or to be used for repair. If the finished products spend significant time in the warehouse, their marketability is routinely evaluated. If it becomes too low, the products are disassembled for the parts or the raw materials.

The job-shop oriented layout of facility NPB, shown in Figure 7, has been designed to promote learning and not to optimize flows. Facility NPB has two types of supplies: equipments that will be processed for the Computer For School of Québec organisation (CFS) and those coming from various sources of supplies. The forthcoming needs for the equipment refurbished for the CFS are known with minimal uncertainty, which eases operations planning. However, the configuration of the equipments from other sources is not known so that each must be analysed prior to any sorting decision. The equipments are processed trough the shop and one person is responsible to decide the salvage operations to be done on each one. He bases his decisions on the analysis of inventory levels and the requests from the retailing store.

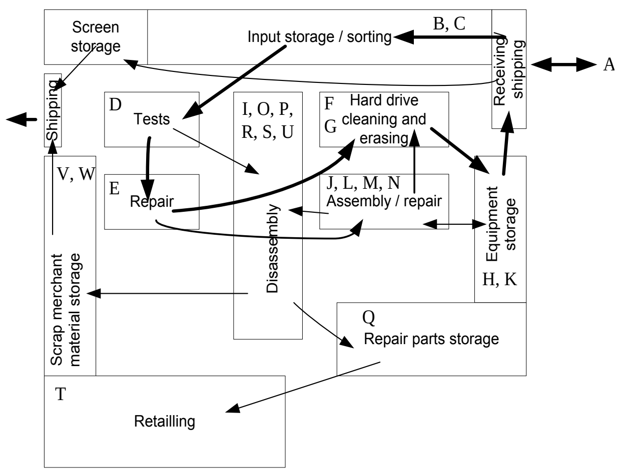

Figure 7. Facility NPB layout and flows
(source: Hallé, [10])

5 Dealing with complexity in refurbishing and recycling facilities

The complexity of computer hardware reverse logistics stems from a variety of factors. Among these, two complexity factors are particularly important.

The first key complexity factor is high uncertainty of both demand and offer. Both the arrival times and the quantities of returned computers are usually unknown ahead of time and generally hard to predict. Computers are returned from a variety of heterogeneous scattered sources such as individual computer owners as well as large or small businesses and organizations owning significant computer parks. Some of the sources dispose of computers when a new generation is put on the market and return them as the new computers are installed. Others pile discarded computers until they have enough to justify the handling and transport costs. Timing uncertainty is also caused by the wide variety of computer brands with wildly distinct obsolescence rates. Overall the disposal and return rates are hard to predict. They are irregular trough the year, although there are known high points such as the back-to-school period. The demand rates for computer hardware, from brand new to refurbished and recycled, are also hard to predict. Thus both demand and offer forecasting are challenging tasks, resulting in frequent shortages and excesses through the year.

The second key complexity factor is the hard-to-assess and fast-decaying value of returned hardware. Quality of a returned product or part is hard to assess and varies significantly, directly impacting potential market value. Various sources of returns with distinct yet generally fast obsolescence rates imply various quality and value levels. Some hardware are particularly prone to fast obsolescence, such as input/output devices like mice and printers. Also, users do not upgrade or take care of computer hardware in the same way. This makes it hard to evaluate the salvage value of incoming hardware, both products and parts. It also means that the effort necessary to bring back value from returns varies and can be quite significant. This involves an endless struggle related to how much cost to incur so as to bring value from every returned hardware. Furthermore this value decays fast. The younger the returns is and the faster they are processed and put for sale, either as a product or a set of components, the higher the probability that returns will indeed get sold at a good price to such clients as end users and repair shops.

Linking with the findings of Fleischman [7, 8], these two key factors instil complexity in terms of time, quality, cost, network, inventory management and production planning, and network.

To have a better understanding of how those two key factors have impact on the flow management complexity of the process shown in Figure 5, the sources of uncertainty and variability of each operation are shown in Figure 8. These sources can be generically summarized as the quantity, date and location of the sources of supplies, quantity, homogeneity and marketability.

At several steps of the process, the quality and the marketability of the equipments influence the specific process that each item will follow. Among the factors that make flow management complex, quality of the incoming equipment can be hard to assess depending of the type of suppliers. Quality also influences the operating time to clean computers, to repair them, etc. It thus creates both uncertainty and variability. As synthesized in Figure 8, the decision to keep a reusable part or a functional computer depends on a sequence of interrelated factors. For example, the inventory level impacts on the decision since if the inventory level is too high, the equipment or parts will not be kept. The inventory threshold value itself depends on the product marketability. Yet marketability depends heavily on current and forthcoming market needs, which are characterized by a high level of uncertainty and variability. Looping back, this creates uncertainty and variability on both the operations to be performed on an incoming product and the associated operating times.

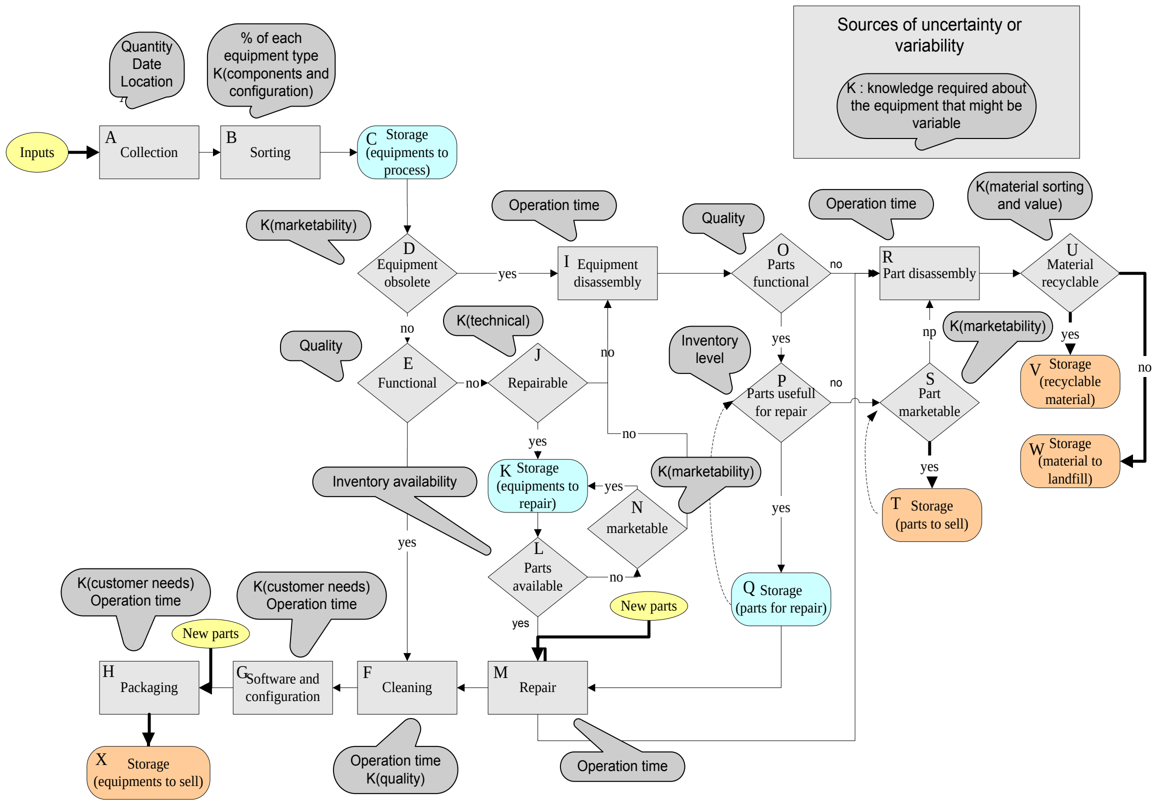

Figure 8. Uncertainties related to refurbishing/recycling facility process

Businesses and their facilities vary widely in the way they cope with the key complexity factors to reduce to flow management complexity, and how they succeed in doing so. In the sampled facilities, three have stood out by the way they cope with uncertainty.

First, profit-making facility PE signs long-term contracts with large facilities that have technological park. Such contracts define most of their clientele, reducing uncertainty about the sources of incoming products. Through negotiated contract agreements, they are entitled to get advance knowledge about when they will get equipment and what will be their configuration. Also, the equipments received from a given supplier are homogeneous so that it lowers the uncertainty on many steps of the refurbishing process by a great deal. Overall, their contracting strategy thus lowers significantly their inbound process uncertainty. It enables them to implement efficiently a linear layout.

On the outbound side, PE is part of an international business. It has the advantage to be able to sell off some of its excess inventory to others facilities of the same business across North America whenever some computers are requested by a customer of another facility while the inventory is low at that facility. This helps to cope with demand uncertainty. It also helps to maximise equipment salvage value because the increase overall market accessibility allows more computers to be sold as a whole rather than as disassembled parts and materials. It thus avoids a bane suffered by most other sampled facilities. Finally, the combination of its contract strategy and its North American network availability allows PE to provide an overall better offer to customers in terms of variety and availability of equipment for sale.

Second, non profit-making refurbisher NPB, described earlier in section 4, has taken a different twist on the contract strategy to minimize its exposed complexity. NPB does a very significant share of its business with a broker. In fact, this broker provides NPB with 60% of its supplies. So for the majority of its incoming computer hardware, NPB does not have to take care about matching offer and demand. All computers incoming from the broker are aimed to be refurbished and returned to the broker who then sends them to the customers who ordered them.

Third, profit making recycling facility PI applies its own distinctive drastic way to cope with complexity. As mentioned in the previous section, there is a lot of uncertainty related to the marketability of computer hardware and it implies many decision steps in the process. Consequently, this uncertainty increases flow management complexity. Facility PI aims to minimize the amount of computer hardware ending up in landfills. Their strategy is quite simple. They make no attempt to check whether the computer is functional or repairable, they aim to regain value mostly through recycling materials. Most computer hardware is torn apart, with the key mission of efficiently retrieving and sorting the embedded materials, as well as a few key pre specified high value parts. The strategy of PI is such that it is not affected by the quality, functionality or marketability of the equipment it receives, avoiding great sources of uncertainty at the price of lower potential value regeneration and lower environmental efficiency.

So by strategically putting in place specific business relationships or focusing on specific potential supplies, the facilities find a way to decrease their sources of complexity and consequently to simplify the required operating processes and ease flow management. This is applicable to both profit-making and non-profit-making facilities.

6 Conclusion and research avenues

This paper has reported Canadian field based evidence and insights on computer hardware refurbishing and recycling facilities. The key findings lie at multiple levels.

First, the motivation for refurbishing and recycling computer hardware is double sided. On one side, there is pressure for solving the crying environmental problem associated with dumping ever more computer hardware in landfills. On the other side, there is business opportunity in doing so. In fact, when you talk with many managers in the reverse logistic industry, the sense transpiring from their discourse is that the environmental problem is in fact the business opportunity generator and that they are really in there for the business itself.

Second, the computer hardware reverse logistic industry involves four types of players: the manufacturers, the computer user people and organizations, the brokers and the retransformers. These are entangled in a complex overall reverse logistic value network. This network has many players, with a mix of profit-making businesses and non-profit-making businesses. Each player often plays multiple roles and is in relationships with many other players. These relationships are usually more subtle and complex than traditional customer-supplier relationships, with many bidirectional relations and many relational loops.

Third, computer hardware reverse logistic facilities all have a lot in common. They differ widely in terms of their size, intent, capabilities, operations scope, product mix, and technologies. Yet they all focus on activities such as receiving products, testing and sorting products, parts and materials, disassembling products and parts, cleaning and repairing products and parts, storing and shipping items, matching offer and demand, managing flow and operations.

Fourth, there are two key complexity factors for computer hardware reverse logistic facilities: the high uncertainty of both demand and offer, and the hard-to-assess and fast-decaying value of returned hardware. The amplitude of these factors is driving the complexity of designing these facilities, as well as the complexity of managing and operating them. Dealing with these complexity factors is highly strategic. Some facilities do not try to attenuate them and therefore have to learn to thrive through complexity. Others are taking strategic approaches to attenuate complexity, mostly by prioritizing stabilizing and risk reducing business relationships or by focusing on specific potential supplies.

The field study was realized in the province of Québec in Canada and is thus influenced by the provincial and national regulations, cultures and industry maturity. For example, there is currently no European-like legislation enforcing manufacturers' responsibility for their products at the end of useful life. This results in computer hardware not being revalorized as much and as best as theoretically possible.

A lot of research still needs to be done. One avenue along the lines of the current research is extending the field investigation to the whole world, developing a more holistic picture and enabling a richer characterization, understanding and benchmarking of such facilities, networks and industries. Another is extending to more types of products, beyond computer hardware.

Even though the evidence is still limited, two promising research avenues emerge relative to reverse logistic facilities design and management. The first is to exploit the similarities among the various facilities to develop protomodels of centers and relationships within reverse logistic facilities and networks, along the lines generically proposed by Montreuil [17]. The aim would be to elevate the facilities design capabilities within the reverse logistic industry by avoiding reinventing the wheel every time and by offering design guidelines to optimize expected performance from the designed facilities. The second avenue revolves around developing integrated operational strategies for reverse logistics, well conceived to cope with the inherent complexity factors described in the paper. What to dynamically accept and seek as input? How much to stock of inbounds, in-process computers and parts, and outbounds? What to launch into treatment through the facilities, overall and in each center composing them? How many people to have working daily, and what to assign them to? How to dynamically price both inbound and outbound items? All these questions dynamically need answering, yet the science base and the instrumental base are not yet there.

The paper also uncovers potential research avenues of wide scope such as reverse logistics business models and reverse logistics value network design, as well as complementary avenues such as inbound product collection network design which has significant impact on the accessibility of inbounds and economics of getting them to reverse logistic facilities.

Through the next decades, the computer hardware industry may well live a significant transformation catalyzed by the green and sustainable development awareness raising and prioritizing by the people, the governments, and the industry. On one side regulations are to impose more responsible, intense and complex reverse logistics. On the other side, ecological design of computer hardware is bound to simplify reverse logistic and minimize its need in terms of both scope and scale.

Acknowlegdements

The authors thank the Creation and Research Financial Support Program (PAFARC) from Université du Québec à Montréal.

References

[1] Andriesse, F. G. (1999). Successful implementation of reverse logistics at Philip Morris. In Van Goor, A. R., Flapper, S. D. P., and Clement, C., editors, Handbook Reverse Logistics. Kluwer, B.V., Deventer, The Netherlands.

[2] Coca-Cola “Corporate Responsibility” retrieved from http://www.cocacola.ca/fr/corporate_responsibility.htm on March 2008.

[3] De Brito, M. P. (2004), Managing Reverse Logistics or Reversing Logistics Management?, ERIM PhD Series Research in Management, N. 35, Erasmus University Rotterdam, Rotterdam, The Netherlands, 2004.

[4] Environment Canada, "Information Technology (IT) and Telecommunications (Telecom) Waste in Canada", (2000). 104 p. retrieved from: http://www.rpec.ca/pdfs/IT_Telecom_Waste_Canada_Fr.pdf.

[5] Environment Canada, "Information technology and telecommunication waste in Canada" retrieved from http://www.ec.gc.ca/nopp/docs/rpt/itwaste/EN/summary.cfm.

[6] Environment Canada, (2006), retrieved from http://www.ec.gc.ca/wmd-dgd/default.asp?lang=En&n=FB2EC4CD-1, last update on July 8, 2007.

[7] Fleischmann, M. (2001). Reverse logistics network structures and design. ERIM Report series research in management ERS-2001-52-LIS, Erasmus University Rotterdam, The Netherlands

[8] Fleischmann, M. (2001). Quantitative Models for Reverse Logistics. PhD thesis, Erasmus University Rotterdam, Rotterdam, the Netherlands.

[9] Groupe Nord, "Rapport sur la fin de vie des ordinateurs" retrieved from http://isf.etu.inpg.fr/archive/rapport/rapport_ordi.pdf (december 2002 - March 2003).

[10] Hallé, Marie-Eve, (2008), "Logistique inverse d'ordinateurs : une étude de la complexité des flux et des stratégies dans le réseau québécois de revalorisation", Master thesis (to be published), Université du Québec à Montréal, Montréal, Canada

[11] HP "Record Number of HP LaserJet Print Cartridges Recycled in 2002" (2002) News Release retrieved from http://www.hp.com/hpinfo/newsroom/press/2003/030422c.html.

[12] Infrastructure Canada, "Solid Waste, Recycling and Diversion" retrieved from http://www.infrastructure.gc.ca/research-recherche/result/studies-rapports/rs16-figure6-2-3_e.shtml, in December 2007.

[13] Kodak "Corporate Citizenship" retrieved from http://www.kodak.com/eknec/PageQuerier.jhtml?pq-locale=en_CA&pq-path=4198&_requestid=9373 on March 2008.

[14] Lambert, Serge, Riopel, Diane (2003). Logistique inverse : revue de littérature, Les Cahiers du GERAD G-2003-61, 45 pages.

[15] L'Oréal, "Sustainable Development" retrieved from http://www.loreal-finance.com/eng/sustainable-development, March 2008.

[16] Ministère de l'Écologie, de l'Énergie, du Développement durable et de l'Aménagement du territoire, Decret DEEE, retrieved from http://www.ecologie.gouv.fr/IMG/pdf/Decret_050720_DEEE_EN.pdf, July 22, 2005.

[17] Montreuil, B. (2006). *Facilities Network Design: A Recursive Modular Protomodel Based Approach*, **Progress in Material Handling Research: 2006**, ed. by R. Meller & al., Material Handling Industry of America (MHIA), Charlotte, North-Carolina, U.S.A., p. 287-315.

[18] Ranger, Steve, (2007) “UN digs into 'e-scrap' mountain: There's gold, palladium and indium in them there hills...” retrieved from http://hardware.silicon.com/desktops/0,39024645,39166238,00.htm, March 7, 2007.

[19] Recyc-Québec, retrieved from http://www.recyc-quebec.gouv.qc.ca/Upload/Publications/Fiche-tic.pdf on December 2004.

[20] Recyc-Québec, Communiqué retrieved from http://www.recyc-quebec.gouv.qc.ca/client/fr/rubriques/Nouvelles.asp?id=476.

[21] Rogers, D., Tibben-Lembke, R. (1998), Going Backwards: Reverse Logistics Trends and Practices, RLEC Press, Pittsburgh, PA.

[22] Rogers, D. S. and Tibben-Lembke, R. S. (2001). An examination of reverse logistics practices. Journal of Business Logistics, 22(2):129–248.

[23] Silicon Valley Toxics Coalition, (2004),” Poison PCs and Toxic TVs: E-waste Tsunami to Roll Across the US: Are We Prepared?” retrieved from http://svtc.igc.org/cleancc/pubs/ppcttv2004.pdf.

[24] Un PC pour mon prochain: retrieved from http://pcprochain.com/TIC-et-implications-energetiques.html.