THE ECONOMICS OF PC REMANUFACTURING

by

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Abstract

Personal computers are among the durable goods of shortest life cycle. Given the increased population of PCs, and their quick turnover, their disposal represent a considerable environmental concern. However, many users do not require the latest technology for running their applications. This opens an opportunity for renovated or remanufactured machines. This paper addresses the complexity of PC manufacturing and the difficulties in developing adequate recovery processes. A recovery process is proposed and evaluated. It allows the coexistence of two markets: one for remanufactured PCs and another for all-new PCs.

Keywords: product recovery, remanufacturing, recycling, waste reduction, personal computer, product obsolescence, design for the environment, regression

1. Introduction

Legislators in many countries have drafted laws requiring computer manufacturers, among others, to take back their used products at the end of their useful lives. At the time of this writing, none such laws have been approved yet, but many manufacturers have taken positive steps toward the development of a material recovery technology that is compatible with their product lines. Large product variety, product designs not suitable for disassembly and an erratic reverse logistics are some of the difficulties that have been addressed by other researchers. Aside these issues, I would like to identify the product recovery method that is best suited for personal computers.

The simplest material recovery method is to shred the entire computer for recycling the ferrous and non-ferrous metals, and eventually recover approximately 400g of precious metal per ton of machine shredded. In this case, all machine types are treated the same way. The process is relatively simple, with low labor requirement -- both in quantity and quality. On the other extreme, one may remanufacture the computer, reusing most or all of its original parts. This process would require the development of specific disassembly and repair routines for each type of machine treated in the plant, and trained labor to deal with the potentially large variety of repair decisions.

Both processes have inconveniences. Shredding whole computers would destroy any value still remaining in the components, except the value of secondary recovery of raw materials. On the other hand, complete remanufacturing is not always desirable, because of the speed of technological change which limits the market for remanufactured computers. Faced with this trade-off, the material recovery decision should be based on the cost of recovering the value that was added in the product during the final manufacturing stages. The paper concludes analyzing this procedure.

2. From silicon to IC: the production of semiconductor devices

In any electronic product, silicon represents just a minor fraction of the raw materials used in its manufacture. Ferrous and non-ferrous metals, plastic and glass account for most of a computer's weight. However, the special semiconductive properties of the silicon have made it the main raw material of this industry. Silicon in itself is the most common metal in the earth's crust, in the form of oxides (various qualities of sand and gravel), but the recovery of electronic grade silicon requires a complex and low-yield process. Hence, if the raw mineral is practically costless, after incorporating the cost of several refining stages, the ultra-pure electronic grade silicon becomes a very expensive product. The process to obtain silicon wafers follows[i]:

2.1 Reduction of silicon oxide

Silicon oxides (sand, usually SiO_2) are reduced with coke in an electric furnace to obtain metallurgical grade silicon (MGS). The production of MGS generates waste in the form of slag, as well as CO_2 . Usually not all silicon is reduced, and some silicon oxide is also wasted.

This is a well understood process, similar to the production of pig iron from iron ore. Process yield is 90% and the resulting MGS presents at least 98% silicon content. The metallurgical grade silicon is largely produced for the steel production, but 4% of the world production of MGS is directed to the purification process to obtain electronic grade silicon.

2.2 Hydrochlorination of the metallurgical grade silicon.

The metallurgical grade silicon contain a number of metal impurities which are removed in this step. The process consists of the hydrochlorination of the metallurgical grade silicon and decomposition of the resulting molecule, obtaining electronic grade silicon (EGS) rods. First, MGS reacts with hydrochloric acid producing silicon chlorides as well as other metal chlorides. This reaction allows the separation of these metals from the MGS. This leaves a mixture of silicon chloride, silicon hydrochloride, other silanes and other metal chlorides. A process of multi-distillation and gas cleaning with hydrogen (H_2) separates the silicon hydrochloride from the other compounds – these become the chemical waste in the process.

Further reaction with hydrogen separates the chlorine from the silicon obtaining ultra-pure polycrystalline electronic grade silicon, the EGS rods. This final reaction generates waste in the form of hydrochloric acid (HCl), MGS, hydrogen gas and silicon chloride, all of them suitable for recycling in the same process. This process is rather inefficient. World consumption of MGS for EGS production was 32,000 tons in 1990. World production of polycrystalline EGS rods was approximately 6,500 tons in 1989. Hence, this process has a yield of roughly 20%. Other reports[ii,iii] say that the yield ranges from 18% to 23%.

2.3 Breaking and etching the polycrystalline EGS. Production of Mono-Si wafers.

Now that impurities have been removed, the silicon rods have to converted to mono-crystals and sliced in wafers. Polycrystalline silicon has many electronically active defects which affect the devise speed. This is why electronic devises require monocrystalline silicon for optimal operation.

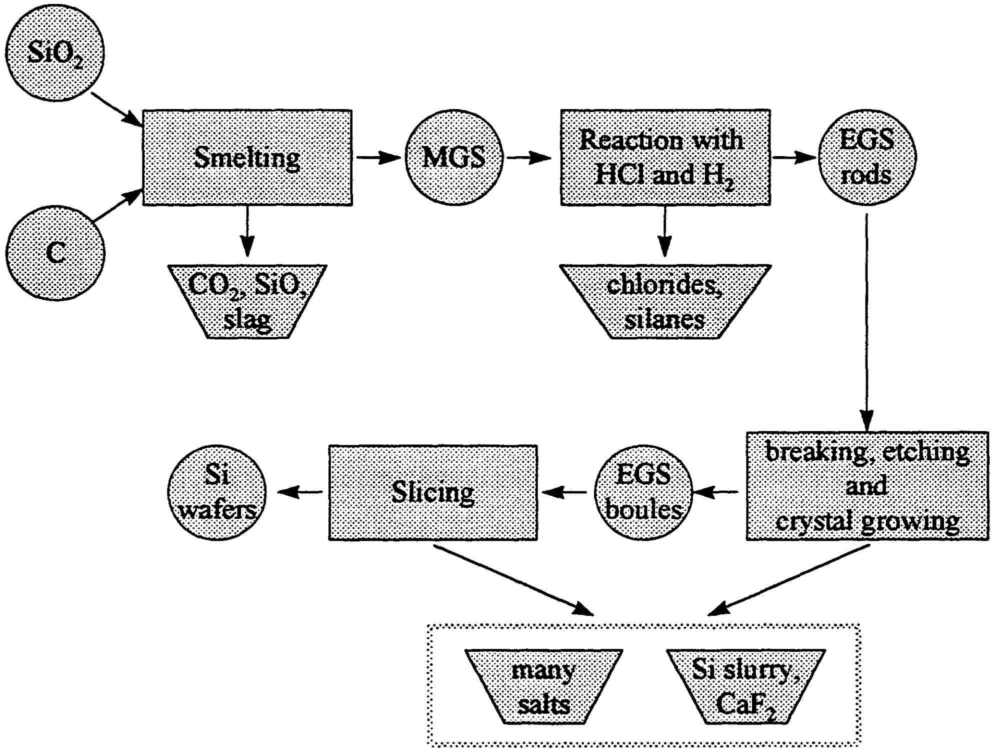

Figure 1: Material flow in silicon wafer production

The EGS rods go through an etching process in an acid bath. Several organic and inorganic acids are used in this process. The etching bath generates a large amount of chemical waste in the form of acids, which are neutralized with sodium and calcium bases forming a variety of salts that is wasted. Both the etching bath and the final cleansing generate special waste, in the form of silicon slurry and calcium fluoride (CaF_2). After etching, the EGS rods are is melt and re-crystallized into monocrystalline silicon ingots or boules. The result is inspected, generating a large amount of defective EGS boules that may reenter the etching bath and recycle. The monocrystalline EGS boules that pass inspection are sliced into wafers and cleaned. The silicon is ready to be used in the fabrication of integrated circuits.

Most of the losses in this step occur at the cutting stage. World consumption of mono-Si wafers in 1989 was 2,189 tons. Since the production of EGS rods was about 6,500 tons in the same year, it follows that the process of breaking, etching and slicing the EGS rods has an yield of 34%. The aggregate yield for the production of monocrystalline silicon wafers from metallurgical grade silicon is estimated as 7%. At the time of this writing, there was not a visible trend towards the improvement of this yield. It appears that the rejects could be recycled with some economic benefit, specially in the early stages in the purification process. However, production remains a small scale batch process, and the cost of inputs is relatively low, reducing the incentives to develop and implement an efficient recycling process. Figure 1 shows the material flow in the process of obtaining silicon wafers, the raw material used in the production of integrated circuits.

2.4 Integrated circuit fabrication

Monocrystalline silicon wafer is the 'raw material' in the production of integrated circuits. Ayres et al. (1995) have estimated the silicon embedded in the semiconductor devices produced in Japan in 1988 to be 428 tons, from an input of 1200 tons of silicon wafers. Assuming the same efficiency in the production process of other countries, this implies that the world production of integrated circuits in the same year was around 750 tons.

Several steps are necessary to fabricate the integrated circuits. This fabrication is not a linear process. Each step may occur many times in a distinct order, depending on the design of the final IC. The major steps are[iv]:

- **Oxidation**: A thin layer of non-conducive silicon dioxide is deposited on the wafer surface in the presence of distilled water or oxygen.
- **Photolithography**: The circuit design is transferred from a master pattern to the wafer. A number of acids, solvents and bases are sequentially used until the desired pattern is left on the wafer surface.
- **Etching**: This process removes excess silicon oxide left by the photolithography with the help of strong acids.
- **Doping**: It is the process of adding impurities, altering the resistivity in specific sites on the semiconductor. Two processes exist: *diffusion*, where the wafer is baked in

controlled atmosphere for impurity removal, and *ion implantation*, where a precision electron beam shoots ions to change the resistivity of a specific site.

- **Metalization**: Individual circuit elements on a chip are interconnected by thin metal, such as gold, which is deposited on the pattern. Alternatively, semiconductor films can be used, insulated from the rest of the circuit by thin dielectric layers.
- **Packaging**: The integrated circuit is assembled into packages containing external electrical leads to facilitate insertion into printed circuit boards for interconnection with other circuits or components.

The production of a specific electronic devise may go through each of these steps several times, before going through metalization. This process achieves a yield of roughly 35%, with many chips being actually wasted.

Several hundred identical integrated circuits (ICs) are made at a time on a thin wafer of several centimeters in diameter. The wafer is subsequently sliced into individual ICs or chips. In large-scale integration (LSI), as many as 5000 circuit elements, such as resistors and transistors, are combined in a square of silicon measuring about 1.3 cm on a side. Hundreds of these integrated circuits can be arrayed on a silicon wafer 8 to 15 cm in diameter. Larger-scale integration can produce a silicon chip with millions of circuit elements. During recent years, the integrated circuits have observed increased functional capability and reliability combined with great reductions in size, physical complexity, and power consumption, greatly benefiting computer technology. The complete logic, arithmetic, and memory functions of a small computer can be packaged on a single printed circuit board, or even on a single chip.

3. Components in the Personal Computer

A personal computer is an aggregation of assemblies that may take several configurations. Each assembly contains complex subassemblies designed and manufactured by specialized firms, given the low verticalization in this industry. The industrial organization is similar to what is observed in the automobile industry. However, the computer market differs from the automobile market in that all elements in an automobile are in the same body, while many connections in the computer are flexible, which increases the variety of possible configurations. This flexibility facilitates the technological progress of individual components because the constraints in their interconnections are relatively low. Hence, new developments can be immediately integrated in the computer design as long as it respects a general compatibility. There are five kinds of assemblies:

- **Central processing unit (CPU):** the microprocessor
- **Input devices:** keyboard, mouse, scanner, modem.
- **Output devices:** video monitor, printer, modem.
- **Memory storage devices:** RAM chips, floppy disk drive, hard disk drive, CD-ROM drive.
- **Communication network:** the *bus*.

Some of these devices are installed internally others as peripherals. The microprocessor has the ability to fetch, decode, and execute instructions and to transfer information to and from other resources over the computer's main data-transfer path, the bus.

3.1 Main console

The main console contains many subassemblies, aggregating a large variety of functions. In 1997, a standard desktop computer is an assembly including at least the following subassemblies:

- motherboard with microprocessor and bus
- memory board with memory chips or cards
- power source
- hard disk drive
- floppy disk drive
- CD-ROM drive
- external casing

The technological development of most or all of these components has been very significant. A new microprocessor with faster clock speed is introduced every five or six months. The standard size of a memory chip for personal computer, 1 MB in 1990, has doubled every year. The standard size of a hard disk drive, 40 MB in 1990, has seen even faster growth. CD-ROM, a rarity in 1990, has become standard equipment in all PCs. These changes reduce the opportunities for computer reuse, and even for components reuse.

3.2 Video monitor

The video monitor is an assembly of four components:

- cathode ray tube (CRT)

- power source
- control card
- external casing

The technological change in video monitor has been quite dramatic, with increased resolution, reduced emissions and improved energy consumption. For the consumer, these changes have secondary impact on the performance of the computer, but a major ergonomic effect. Moreover, the performance of the video monitor degrades with wear, and repair cost is relatively high, even on large scale operations. The challenge is in the development of a process that reuses most of the material and circuits in the used monitor to manufacture a new one.

4. Material Recovery of Used Computers

Most of the large computer manufacturers in Europe have started their recycling programs. Generally, the recycling effort is driven by the need to be prepared in the event that regulation requires them to take back their used products. Drafts of such laws have been under scrutiny in Germany, Holland and other European countries; they could become a Europe-wide law within a few years. Some companies had the vision to accept this challenge as an opportunity to gain a stronger foothold in these markets, by establishing disassembling units that can generate profits while minimizing waste. Others went even further, starting take-back schemes long before the regulation were discussed. All of these operations have in common the need to learn how to build products that are easy to disassemble and that can be recovered with minimal generation of waste.

In addition to material recovery units organized by OEMs, a number of small firms have identified this niche with to the purpose to reclaim raw materials (precious and nonferrous metals), as well as integrated circuits. European regulation against the export of waste, and the difficulty in classifying used equipment in anything other than waste, have discouraged some firms of centralizing the materials recovery operation, to avoid the transportation of used equipment across the borders. Often, the used machines return to the original equipment manufacturer as a result of the competitive environment, as the following examples show.

- A large computer manufacturer won a bid to substitute the computers operating in a certain network in Germany. One of the conditions imposed by the customer was the collection and disposal of the used machines in an environmentally friendly way.

- In order to win a competitive bid in Italy, another manufacturer offered to buy the used machines already installed in the firm, increasing the competitiveness of their bid. This offer made their bid more affordable, and eliminated the advantage held in that bid by the manufacturer of the machines being removed. The used machines were disassembled and the components were recycled or sold.

Value recovery operations may reduce the cost associated with take back schemes and environmentally friendly disposal, providing the recovery of valuable raw materials and components to be reused. Hewlett-Packard and DSL Logistica, IBM logistic arm in Italy, have similar recycling centers where the operating objective is to maximize the weight fraction of the recycled materials from the used computers. These operation are discussed below.

4.1 Components and subassembly reuse and materials recycling

Often times, a used computer is technologically outdated for the customer, but some of the electronic components within are suitable for reuse in different application. This opportunity is addressed by some computer manufacturers in Europe.

In 1989, Hewlett-Packard started its recycling center in Grenoble (France). Since than, the center has expanded to recondition, refurbish and upgrade used products for reuse. Products and components that cannot be reused are recycled, totaling more than 100 tons of returned printer cartridges, computers or peripherals processed per month. The center deals with the following recovery opportunities:

- Recovery of boards, hard discs and power source
- Remarketing of floppy disc drives and microchips.
- Remanufacturing of printer toner and ink-jet cartridges
- Safe disposal of toxic materials (batteries, CRTs).
- Recycling of precious metals, copper cables, metal casings.
- Recycling or incineration of plastic materials.

Only 3% of all materials received by the recycling center in Grenoble is landfilled. Consequently, 10% of all parts used by HP maintenance unit in Europe come from the take back scheme. Now, the operation is being decentralized, with the opening of two new centers, one in the UK and the other in Germany, supplied by take-back operations in several European countries.[v]

In the IBM organization, when a computer model has its production discontinued, maintenance parts can be obtained from the materials recovery centers such as the one manage by DST Logistica. Parts disassembled from a used machine but not repaired and inspected are called *raw parts*. Once these parts are repaired and inspected, they are ready to ship to the central maintenance stock, located in Holland.

The Busnago (Italy) facility has the capability of certifying parts for the medium range IBM machines. IBM has a similar operation in Holland which certifies parts for personal computers. A new refurbishing and certifying capability is now added to the German plant to treat end-of-lease machines and a small material recovery facility operates at the French IBM manufacturing plant.

DST supplies circuit boards to the maintenance stock of medium size IBM machines. The boards are extracted from the original machines, cleaned, inspected, certified, packaged, shipped and sold to the maintenance stock for a price equivalent to 70% of the price of a new part. Periodically, DST receives the demand forecast for these parts. The firm manages this demand attempting to have raw parts inventory of the size of one-year of forecast demand and repairing the raw parts to order. The rationale for this inventory policy is that, since storage space is limited, the firm would like to restrict the number of computers that is not disassembled. Warehouse capacity is managed by disassembling earlier computers containing reusable parts. However, since the demand for these parts is very uncertain – and may never confirm – it is not worthy to repair them before a firm order arrives. Moreover, maintenance part orders come with a very long lead time, up to one month, while the repair lead time is less than a week. Hence the high value-adding operation, part recovery, only takes place when the demand is confirmed.

Another demand stream for recovered parts comes from external customers. Each medium size computer may contain 10 memory boards or more, each of them holding several memory chips ranging from 256 Kbytes to 16 Mbytes, depending on the generation. As long as the part *is not* an IBM brand product, DST may negotiate it as a commodity: the circuit structure is destroyed – precluding unauthorized reuse of IBM technology – and the board is sold to memory chip customers, which may reuse them after extraction of the parts from the board remains. Altogether, DST markets 5000 parts or maintenance boards. Once all reusable parts and boards are extracted from a used computer, the remains follows a complete disassembly route for secondary raw material recovery. Combined, the internal market for circuit boards and the external market for memory chips and other electronic parts amount to the reclaim of 5% in weight of all computers received at DST. Nonetheless, this operation is responsible for most of the firm's revenue, financing the totality of the material recovery process.[vi]

4.2 Secondary raw material recycling

Unfortunately, DST Logistica has not found a market for direct use of the remaining 95% of the computers received, yet. If the computer is too old, none of it can be reused; even the recovery of integrated circuits is not economically feasible. The remains of cannibalized machines and the old computers are disassembled for secondary materials recovery. Parts are separated by their raw material and sold to secondary refiners. Ferrous, non ferrous (copper and aluminum), glass, plastic and precious metals (gold, silver and palladium) amounting to 85% in weight of all machines are sent to specialized recyclers.

After recycling parts and secondary raw material, DST still recycles 2.5% of packaging material, leaving just 7.5% of material to the solid waste (an additional 5% should be added from the material disposed by the recyclers). The solid waste includes some plastic, paper and hazardous materials.

The keyboard and the video monitor have a raw material composition different from that in the main console. One important component following this stream is the cathode ray tube (CRT), the main piece in the video monitor. A number of companies is interested in the recycling of CRTs, such as Corning (in association with Digital), and other recycling specialists, such as Valme, in France and Wemex in Germany. The relatively small variety of raw materials involved renders the video monitor attractive for secondary raw materials recovery. Furthermore, if a video monitor recycling technology is dully developed, it could easily be transferred to television sets and other CRTs.

The technology for the remanufacture of CRTs is still under development. For the moment, the CRT recycling procedures remain proprietary knowledge of those developing it. Generally, the metallic parts are removed and the two shells are separated in a continuous process. The metallic coating on the glass are extracted with sand blast or with a chemical process. The rest of the monitor is shredded, separating the ferrous, the nonferrous and the different qualities of plastics. Once separated, each of the raw materials – glass, copper, plastics, etc. – is ready to follow the secondary refining stream.

The hard disk drive (HDD) is another subassembly for which it would be desirable to develop a value recovery process. These components are very complex with very low material value, but extremely high value added during the manufacturing process. The size of an HDD is given by the expression

$$size = 2\,D\,S\,C\,,$$

where D is the number of disks, S the number of sectors per disks and C the number of cylinders, i.e. radii that the drive head can distinguish. The increased capacity of these devices using the same physical space in the PC has required continual miniaturization and precision of movements. See Figure 2.

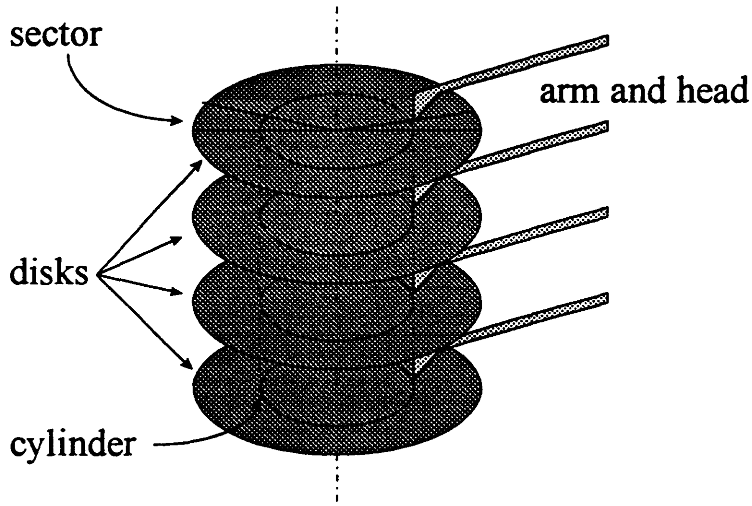

Figure 2: Schematic drawing of a hard disk drive.

Typically, they represent 10% of the direct cost in a PC. The production of HDD requires a white room with controlled atmosphere. Some would say that considering the weight of the driver head and the speed and small distance that it keeps from the disk surface (without ever touching it), it would be equivalent to a jumbo jet traveling 1 meter above the land surface! This dramatic analogy emphasizes the difficulty in recovering these products. It would require the development of a disassembly and recovery line to provide parts that can be reused with the same precision as a virgin part. For the moment, this operation does not seem to be technically feasible.

5. The Computer Market

The computer market is quite fragmented, both in the number and type of OEMs, in the number of suppliers and on the type of buyers. There are several suppliers of hardware in the US, in Asia as well as in Europe. Likewise, there are several suppliers of semiconductors, printed wiring boards (PWB) and computer components from all economic regions.

5.1 Buyers

In the demand side, the PC market is segmented between the large volume buyers, including business, universities and government, and the low volume buyers, which include home users and small business. The typical business market is characterized by large purchases of a single brand machine, with a small variety of machine types in each purchase. An interesting aspect of this market is the block replacement. Some firms may choose to substitute a large number of similar machines at the same time. The replaced machines may cascade successively to less sophisticated users within the firm, and only the oldest machines of the entire network are retired.

The educational market is quite diverse. It includes undergraduate students, very price sensitive, and advanced researchers, very performance sensitive. The main need of the former are to maintain compatibility with the network to which s/he belongs. Basically, the computer is treated as a *course requirement*. As long as it remains compatible with the network, the undergraduate student will not take the initiative to upgrade to a newer or more powerful machine. In the other extreme of the educational market lie the scholars performing computer-based research. These researchers are always pushing their machines *to the limit*. Hence, upgrades and replacements occur frequently. When replacement occurs, their used machines are still powerful enough to satisfy most users.

Another important market is that of the home user. The operating systems have become more user-friendly, minimizing the need for training or prior experience. Hence, the home computer market has become the fastest growing market in recent years. It is hard to predict what impact this will have on remanufacturing PCs. Apparently, the home user does not demand as many upgrades as the business or academic user. Hence, s/he tends to delay replacement for longer periods until a new demand is created. A recent example is the growth of Internet who generated several new users *and* prompted old users to replace their machines for the first time. However, until a new motivating event takes place, it is unlikely that home users will replace their machines in a regular pace, as they do with the family car.

5.2 Suppliers

The market for personal computers includes a large number of suppliers. There are giants such as IBM or DEC, operating worldwide, and small firms operating in specific niches. For the purpose of product recovery, its is useful to classify computers as standard or branded. Descriptions follow.

5.2.1 Standard Computer

Several firms supply personal computers for which virtually none of the design is performed in-house. The same modular design that makes PC assembly so inexpensive is responsible for the development of a flexible industry requiring little capital investment, with low barriers to entry. The standard computer manufacturer use standard-design motherboards as the basis for the final product. The design of the console follows physical specifications that match the size and position of all standard components, such as the power source, the hard disk and the floppy disk drives.

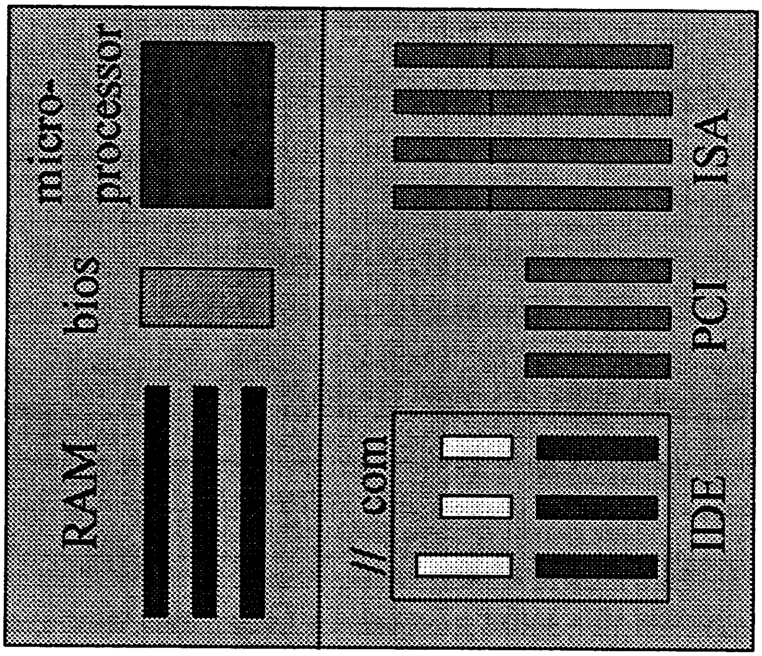

Figure 3: Schematic layout of a motherboard in a standard PC.

Figure 3 shows the schematic drawing of the motherboard used in a standard computer. There is a standard design motherboard for each processor speed. It contains connectors of several types (ISA, IDE, parallel, etc.) for the standard drives as well as for the network, video and sound cards. Consequently, the standard computer may have as many features as there are connectors for the installation of the respective card. This could be regarded as a limitation, but allows easy upgrade of a given feature through the substitution of the respective card. In addition to card and drive connectors, the motherboard contains connections for the microprocessor, the BIOS and the RAM memory. Thus they can be easily accessed and upgraded or substituted, up to the limits imposed by the motherboard design.

The standard computer presents some inconveniences, by-products of the flexible design. It allows the assembler to maintain multiple suppliers of key components, such as drives, memory, processors and cards. If the purchase decisions are driven by cost only, this flexibility reduces the system's reliability and increases the variance of component lives. Managers of large networks have realized this weakness, steering away from standard computers although, presumably, it should be less expensive and simpler to maintain and upgrade them.

5.2.2 Branded Computer

Most manufacturers of branded computers have a long tradition in the industry, with a reputation for quality and technology prowess. This quality assurance, made concrete through long warranty contracts, is one of the key ingredients sought by business customers. In terms of product recovery, branded computers carry great advantages. The stability of design and the regular availability of spare parts make branded computers particularly attractive to large customers. Consequently, these customers award the branded computer manufacturer with a continual flow of repeat business.

Branded computers are characterized by the proprietary architecture, developed to optimize a set of performance measures established by the manufacturer. In extreme cases, the design of a branded computer may be completely original. For example, the motherboard may be designed "from scratch" including features such as the video and sound circuitry. At times, some manufacturers have designed proprietary memory banks, instead of the standardized memory chips adopted in most of the industry.

Because branded computers have stable designs, it is easier to determine a recovery routine that is applicable to a lot of identical machines. That stability translates into easier identification of required upgrades and lower inventory levels.

Moreover, computer networks are generally made of a homogeneous set of machines. This homogeneity is reached with the purchase of computers of a given brand. Similarly, renovated branded machines can be used when such a network is expanded.

Regarding product recovery, branded computers present considerable disadvantages as well. The proprietary design reduces the flexibility which is required for performing low-cost upgrades. Often, the OEM is the only source for a given component, and the cost premium required for upgrading or renovating a branded computer is very high.

5.3 Price evolution

The viability of remanufactured computers depends on the market dynamics. It is quite impressive how difficult it is to follow up on all changes taking place in this market. Prices and specifications change almost daily. For a fixed specification, the price of a given computer decreases every week. However, close observation indicates that the low, average and high price for the computers marketed at any given time is stable.

A system specification[1] stays in the market 12-18 months, from the launch date when it is among the most powerful models available, until its retirement from the new product market. Given this scenario, it is useful to identify the relation between price of a PC and its specification at a given date. The relation would have the form

price of computer = function (price of components, date)

One such function would allow predicting the market value of a remanufactured PC (whose equivalent new-model is not available anymore) and its remanufacturing cost.

5.3.1 The value of PC components

Section 3 offered an overview of the components in the PC. Using price lists in the specialized press, one can identify some of the components that a typical customer would use in order to evaluate a standard PC. They are:

- Microprocessor (CPU), measured according to its operating frequency (Pentium 75 MHz, ..., 200 MHz)
- Working memory (RAM), measured by its size (8 Mbytes, ... 32 Mbytes)
- Storage memory (HDD), measured by the hard disk size (525 Mbytes, ..., 2600 Mbytes)
- CD-ROM, measured by its speed (2x, 4x, 6x, 8x, 10x)
- Image quality, measured by the monitor size (14inches, 15 inches, 17 inches)

The market for these components is very dynamic. As the technology progresses, more performing components are introduced, less performing components are retired, just as it happens with the whole PC. Hence, it is important to find the relationship between the price of each component, its performance (size, speed, etc.) and the date when it is marketed. These relationships were obtained by regressing the prices published in a specialized magazine in the period August 95 - January 97. In this 18-month period, prices of 8 types of CPU, 4 sizes of RAM, 8 sizes of hard disk, 4 speeds of CD-ROM and 3 monitor sizes were collected[2]. Using the ordinary-least-square regression method for each component, I obtained the following price expressions:

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1 In this section, a "system" means a complete multimedia computer, including CPU console, monitor, keyboard, mouse, CD-ROM, speakers and basic software bundle.

2 Certain restrictions were adopted, in order to assure data consistency. See Appendix 1.

$$PCPU = e^{-4.6}\ CPUFREQ^{2.35}\ DATE^{-0.6} \tag{1}$$

$$PRAM = e^{3.9}\ RAMSIZE^{0.98}\ DATE^{-0.7} \tag{2}$$

$$PHDD = e^{1.57}\ HDDSIZE^{0.55}\ DATE^{-0.18} \tag{3}$$

$$PCDROM = e^{4.13}\ CDSPEED^{0.89}\ DATE^{-0.6} \tag{4}$$

$$PMONITOR = e^{-7.13}\ MONSIZE^{4.75}\ DATE^{-0.03} \tag{5}$$

Equation (1) gives an expression for the retail price in sterling pounds (£) of the CPU (left side) as a function of the CPU frequency and date, where date 1 corresponds to August 1995. Equations (2)-(5) give corresponding expressions for the prices of RAM chips, hard disk drives, CD-ROM drives and monitors. Each of these equations fits the data quite well[3]. The equation with lowest fit, $R_a^2 = 0.743$, corresponding to price evolution of CD-ROM drives as a function of the date and drive speed, still fits the data quite well. It is important to notice the difference in the date coefficients of each equation. In the period observed, the prices of RAM, CD-ROM and microprocessors decreased very rapidly. The prices of hard disk drives changed slowly and the prices of monitors was quite stable. Moreover, for all four components, the time coefficient is significant with a 95% confidence level.

5.3.2 The value of complete systems

In order to evaluate the cost of remanufacturing processes, it is important to analyze over time the impact of each component in the price of the PC. This time, it is assumed that a linear model is a better representative of the price behavior than the exponential model used above. The OLS regression generated the following relation:

$$\begin{aligned} PCPRICE = {} & 409 + 1.24\ PCPU + 0.303\ PRAM + 2.01\ PHDD \\ & - 1.59\ PCDROM + 2.43\ PMONITOR - 22.8\ DATE \end{aligned} \tag{6}$$

This expression fits the data quite well, $R_a^2 = 0.92$. Notice that the independent variables *are not* the actual market prices for the component used but the estimated prices resulting from the relations found in equations (1)-(5). One could have developed an expression for the price of the PC as a function of its specifications. However, I chose to use the indirect form to allow the price of each component to behave independently. The coefficients in this regression correspond to the marginal value of each component upgrade.

The coefficients show that the value of each component impacts the total price in a very different way. Equation (6) says that each additional £1 that the manufacturer spends on adding a more powerful microprocessor adds £1.24 to the perceived value of the total system.

The hard disk drive and the monitor exhibit the same value-adding behavior, meaning that it pays off putting together a system with more powerful CPUs, larger storage space and larger monitors. However, the working memory (RAM) and CD-ROM speed does not provide the same returns. Each additional £1 spent on adding RAM increases the perceived value of the system by just £ 0.303. Moreover, the market does not perceive faster CD-ROM drives as adding value to the system. These findings are consistent with the most current PC profiles in the market in the period observed. Those systems include relatively large storage memory, relatively powerful microprocessors, relatively low working memory and demand large premiums to upgrade monitors. Moreover, most manufacturers do not allow the customers to choose the speed of the CD-ROM drive. Equation (6) also indicates that the base value of the additional components in date 0 is £ 409. Now, we incorporate the estimated component values, given by equations (1)-(5) into the value of the PC given by equation (6):

$$\begin{aligned} \text{PCPRICE} &= 408.5 + 0.0123\frac{\text{CPUFREQ}^{2.35}}{\text{DATE}^{0.603}} + 15.24\frac{\text{RAMSIZE}^{0.98}}{\text{DATE}^{0.7076}} + 9.707\frac{\text{HDDSIZE}^{0.547}}{\text{DATE}^{0.1805}} \\ &\quad - 99.03\frac{\text{CDSPEED}^{0.8998}}{\text{DATE}^{0.604}} + 0.001943\frac{\text{MONSIZE}^{4.754}}{\text{DATE}^{0.0323}} - 22.77\,\text{DATE} \end{aligned} \tag{7}$$

Next section, this expression is used to evaluate the remanufactured computer as a function of its specification and of the date when it is released to the market.

6. Remanufacturing Used Computers

The reclaim processes in section 4 uses just a small fraction of the value in the used computer. The functionality still remaining in the used computer is explored by remanufacturing only. All other recovery procedures waste some of this value remaining, but the market limitations can be very large. Owners dispose of their computers, not because of breakdown or excessive wear, but because of technological changes that push the market to another performance level. This has three consequences:

1. The majority of computers arrive at the end of their first life fully operational. Some defects might occur, like virus infection, power source failure and monitor degradation. Nonetheless, the occurrence of major failures is relatively uncommon, and most problems can be solved with the replacement of the failed module.

2. The mainstream market for computers is not interested in a machine developed and built more than two or three years ago. Hence, the computer remanufacturer has to identify an alternative market for its product, and such market is sometimes difficult to find.

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3 See regression statistics in Appendix 2.

3. Computers cannot be remanufactured into a product with the same performance as the new ones in the market. Although the design allows some upgrading and refurbishing, the product cannot evolve into a model comparable to the ones launched a few years after its own introduction.

A computer may last many years beyond the time when the first user decides to substitute it. Let's compare it with the automobile. A new car usually remains with the first owner 2-5 years before it is replaced. Given the relatively low impact of the technological changes in the car industry today, a used car can safely and economically operate for many years after the first owner decides to replace it. This has led to the existence of a healthy second-hand market. The same does not occur with computers. The technological changes in the computer industry have a very broad impact in the market. The most affected users are those operating in an open environment, bound by compatibility constraints (network externalities). In order to remain in the network, the user must follow the software upgrades that are imposed by the community of users to which s/he belongs. Software upgrades generally consume more of the computer resources, requiring hardware upgrade or substitution.

However, users willing to operate in a closed environment have realized that they may forego frequent software upgrades and use their machines longer. Many exploit the extended lives of remanufactured computers, marketed with a considerable discount. Remanufactured computers are in great demand from those that cannot afford or do not need to invest in the newest technology. These include schools and small businesses, who have resorted to suppliers of remanufactured computers to satisfy their needs for affordable machines[4]. Here are some examples:

- A medium size firm has developed a proprietary software to manage customer orders and inventory. The system has been operating for four years with 10 networked machines. The firm's growth has created the need to expand the system. The manager realizes that an expansion with five identical machines would satisfy, but the computer manufacturer does not offer that model anymore. Hence, the firm chooses to buy remanufactured machines of the same type, avoiding the cost of developing new software and retraining.
- A primary school has received a seemingly large budget to install computers in the classrooms. The principal realizes that the budget allows for the acquisition of just 5

new computers with the respective software. Alternatively, she chooses to buy 12 remanufactured computers using DOS-based educational tools.

Suppliers of remanufactured machines have emerged in many countries, including the United States, Canada, UK and France. The first remanufacturers of personal computers appeared because of the absence of a second-hand market. Often, used PCs are donated to less advantaged schools, who then have the opportunity to offer computer education to their students. It so happened that these machines were not ready to operate and the recipients of these donations were not qualified to repair them. For some schools, the cost of repairing donated equipment was so high that they have started to refuse them. This situation created the new business opportunity: it created the need for computers in these schools and an outlet for discarding a machine that eventually could be reused.

6.1 The remanufacturing process

Compared to the recovery of other durable goods, remanufacturing personal computers is a less complex process. Usually, computers are not subject to physical shocks. So, first level disassembly is fully determined by the original design. If the company adopted design for assembly, it is usually true that the computer is easy to disassemble, and material recovery is considerably simpler than it would be otherwise. Even if design for environment is not explicitly embedded in the computer, the market expects that it is designed for easy upgradability.

The remanufacturing procedure is relatively simple. It includes partial disassembly, cleaning, inspection of the electronic modules, elimination of eventual viruses and software installation. The whole process lasts no more than 40 minutes per machine. In some cases, the hardware may be upgraded with larger hard disks, increased working memory (RAM) and, eventually, substitution of the BIOS for a more recent version. This type of remanufacturing is characterized by the preservation of the machine's identity. For any given machine leaving the system, all of its components were once part of the same unit, except for the upgrades and substitutions due to defects. Some, call them *renovated computers*[5].

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[4] Some charitable associations have sponsored the donation of used computers to schools that cannot afford them at any price.

[5] Making another analogy with the automobile market, renovated computers are equivalent to used cars sold with warranty. The dealer inspects the used car eliminating minor defects. If the car passes inspection, the body, interior and engine are cleaned and the car is placed for sale with warranty.

One of the advantages of this type of remanufacturing is that the firm can buy a machine similar to the ones already installed in the firm's network. This simplifies the maintenance procedure and reduces the variability in the performance of the installed base.

The cost of remanufacturing a used computer is much lower than the cost of manufacturing it the first time. The main challenge in remanufacturing computers is not on the repair process but on the identification of the market demanding the reconditioned product. In order to maintain the niche profitable, the computer remanufacturer has to develop the incoming stream of used machines and the demand for remanufactured units.

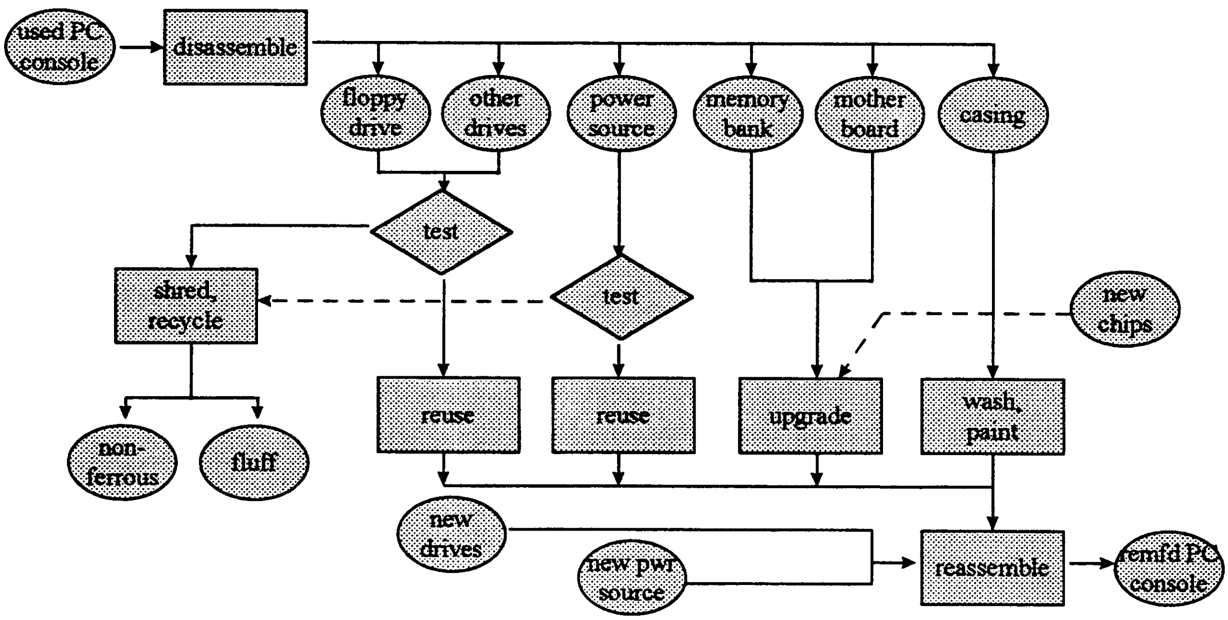

Figure 4: PC console recovery process.

Figure 4 shows the material flow for personal computer remanufacturing as it is performed today. Each subassembly must follow its specific recovery path (not detailed). These paths will vary with the technology developed by the firm and with the type of demand that the final product will have. In any case, the remanufacturer must be knowledgeable about environmental and ergonomic developments, such as low consumption circuitry and low radiation monitors which have become increasingly important for business and private customers. At this point, the remanufacturer will have to perform a trade-off analysis to identify which subassemblies are worth remanufacturing with the repair processes currently available. Moreover, the remanufacturer must develop new processes to remanufacture subassemblies that contain high value-added components that cannot be remanufactured with the current technology.

6.2 The economics of remanufacturing with limited upgrading

The cost of remanufacturing a particular machine is dictated by its state. In the case of computers, it is described as follows:

$$RemanCost = TranspCost + DisassCost + InspCost + \sum_i (1 - P_i) ComponentPrice_i$$

where P_i is the probability that component i will pass inspection (here, cost variables are intuitively defined). Hence, the remanufacturing cost equals to the sum of transportation, disassembly and inspection costs, in addition to the expected cost of replacing some key components. The components most likely to need replacement are the mouse, monitor, keyboard, hard disk, and power source, in that order. In a network of approximately 150 machines, following two years of trouble-free usage, approximately 1/5 of all monitors and keyboards had to be substituted, as well as 5% of all hard disks. Less than 2% of all systems had power source failure. The expected life of mice (pointing devices) is less than three years. (Usually the failures are due to careless usage.) These percentages are not necessarily the same faced during remanufacturing. Other factors play a role: the remanufactured computer may have had some components substituted in the past. In this case, it is unlikely that the component needs to be replaced. On the other hand, the inspection process may identify components that are below specification, inducing their substitution before failure. In practice, the power source always pass the inspection. The interfaces, keyboard and mouse, are substituted based on their physical appearance.

Now, we examine the case of renovating a 2-year old computer network composed of several machines. Suppose that these machines have the same specification:

CPU: Pentium 75Mhz

RAM: 8Mbytes

HDD: 525Mbytes

Monitor: 14 inches

CD-ROM: 4x

According to equation (6), the marginal value of RAM is less than its marginal cost. However, the marginal value of monitor and HDD is greater than the marginal cost. Hence, all systems needing monitor and hard disk replacement should receive components that are larger than the ones removed (for instance, 1GB HDD and 15 inch monitor). Systems needing CD-

ROM replacement may receive units that are at most as fast as the one removed[6]. RAM level is not increased unless the customer explicitly asks so. Table 1 shows the value of new systems according to equation (6), in each of the competing specifications, in month 24:

Table 1: Estimated value of complete systems, Pentium 75MHz, RAM = 8 MB, in July 1997.

	CD-ROM 2x monitor: 14"	CD-ROM 2x monitor: 15"	CD-ROM 4x monitor: 14"	CD-ROM 4x monitor: 15"
hard disk: 525 MB	£ 554.02	£ 745.16	£ 530.57	£ 721.71
hard disk: 1080 MB	£ 635.25	£ 826.39	£ 611.80	£ 802.94

The choice should lie not on the value of the system but on net payoff, after the expenses are incurred. The transportation, testing and inspection costs are the same, regardless the alternative. Also, the value of the old system, prior to any recovery, has to be covered by the operation. *Assuming that all three components have to be replaced,* the total component cost is given in Table 2.

Table 2: Estimated market value of required components, in July 1997.

	CD-ROM 2x monitor: 14"	CD-ROM 2x monitor: 15"	CD-ROM 4x monitor: 14"	CD-ROM 4x monitor: 15"
hard disk: 525 MB	£ 303.10	£ 381.70	£ 317.90	£ 396.50
hard disk: 1080 MB	£ 343.50	£ 422.00	£ 358.30	£ 436.80

Comparing the two tables, it is clear that the largest payoff occurs when both the hard-disk drive and the monitor are upgraded, but the CD-ROM drive is not. In this case, the component cost amounts to £422.00 but the value of a machine with that specification is £ 826.39. The used system is worth £250.95 (the value of a system that is operational minus the value of the failed components, on date 24). Hence, the contribution amounts to £153.44. It must cover transportation and labor expense, the warranty, fixed costs and the entrepreneur's margin. Whether the operation is profitable or not, it depends on the volume of returned used machines and on the demand for remanufactured PCs with these characteristics.

[6] The regression indicates that the customers would prefer a slower drive. This is unlikely to be exact. Most likely, customers are indifferent regarding CD-ROM speeds, because the applications available in the market cannot take advantage of the increased speed.

6.3 The economics of remanufacturing with broader upgrading

In the previous section, other replacements could have been considered, such as the replacement for even larger hard disk drives or monitors. However, the value of these systems assume that there is a market for each of these configurations. The specifications suggested are quite similar to the entry-level systems offered throughout 1996. It seems that they would not have problems finding a market at the suggested prices. On the other hand, larger monitors are usually associated with very powerful systems. Sometimes they are perceived as luxury. Hence, it is not likely that customers of remanufactured systems would be willing to pay the premium required (despite the regression model!), unless more of the system is upgraded. Finally, there is the compatibility problem: not all hardware upgrade is possible, given limitations in the BIOS and in the microprocessor.

Now, allow BIOS and CPU upgrade. This would allow upgrading a two-year old machine to approximately the same standard as a machine offered today. Consider the renovation of the same network of similar computers in the previous section. According to Equation (6), the CPU speed, the size of HDD and the amount of RAM have marginal values greater than their marginal costs. Table 3 show the market value of new systems in the alternatives considered.

Table 3: Estimated value of complete Pentium systems with 4x CD-ROM, 14" monitor, in July 1997.

	Pentium 120 16 MB RAM	Pentium 120 32 MB RAM	Pentium 166 16 MB RAM	Pentium 166 32 MB RAM
hard disk: 1080 MB	£ 717.21	£ 740.86	£ 877.04	£ 900.69
hard disk: 2160 MB	£ 832.06	£ 855.71	£ 991.89	£ 1015.54

Upgrading to 32 MB of RAM makes 8MB available for installation in another system (perhaps, an upgrade from 8MB to 16 MB). This adds an expected revenue of £40.70 in month 24. Technological limitations prevent reusing the 75MHz microprocessor to upgrade computers prior to the Pentium technology. *Assuming that the original hard disk is damaged and cannot be reused*, Table 4 shows the cost of making the suggested upgrades.

Table 4: Estimated upgrade cost of complete Pentium systems with 4x CD-ROM, 14" monitor, in July 1997.

	Pentium 120 16 MB RAM	Pentium 120 32 MB RAM	Pentium 166 16 MB RAM	Pentium 166 32 MB RAM

hard disk: 1080 MB	£ 277.60	£ 354.50	£ 406.90	£ 483.70
hard disk: 2160 MB	£ 334.70	£ 411.60	£ 464.00	£ 540.90

Based on these tables, one should upgrade the hard disk to 2160MB and the microprocessor to 166 MHz, but the RAM memory should be upgraded just to 16MB. The contribution obtained from this process is £276.94. It is larger than the margin obtained with the limited upgrading process, discussed in section 6.2. Moreover, the extended upgrade increases the flexibility of the system, allowing efficient use of applications that will not run satisfactorily with the limited upgrade. Hence, it becomes a machine that will have a longer expected life, certainly more than 2 additional years.

However, there are other costs that are not accounted here, such as the increased labor required to upgrade the CPU and the BIOS, the cost of the BIOS itself, and the additional treatment necessary to improve the marketability of the remanufactured product to attract and please a more demanding customer base.

7. Discussion

The primary objective of this paper is to show the viability of remanufacturing computers, extending their useful lives several years beyond the typical 2-3 years life-cycle. A secondary objective is to show some of the critical steps in manufacturing computer hardware, emphasizing the value-adding operations and the technological speed. The third objective is to raise the awareness for the existence of a potential outlet for remanufactured computers, namely the less sophisticated user operating on closed networks.

The original manufacturing process consumes an incredible amount of natural resources and human resources. If we consider the material consumed in the first steps in the production process, the production of electronic chips and accessory circuitry has extremely low yields and release unacceptable amount of toxic waste. The industry has made significant efforts to reduce emissions but the increasing demand for computer products counter-effects the waste reduction. Hence, one should try to satisfy some of this demand with remanufactured products.

We should not look for these outlets in the mainstream computer market. Demand for remanufactured PCs and new PCs coexist in the same way that the demand for used cars and new cars do. Hence, it suffices ensuring the profitability of the remanufacturing operation. This was discussed in Section 6. Although the value of computers decay rapidly with the age of its technology, most components remain operational far beyond its typical life-cycle.

Moreover, the cost of components do decay as well. In the case studied in Section 6.2, upgrading a 24-month old system the equivalent to 6 months of technological development generated a contribution of £153.44 to finance the remanufacturing process. In the case studied in Section 6.3, if the system suffers broader upgrade, equivalent to 18 months of technological improvement, the contribution is even higher, £276.94. Entrepreneurs involved in computer renovation have realized this opportunity. Two challenges remain: (1) improving the reverse logistics such that these systems become available to an even broader customer base and (2) developing recovery processes for high value components such as hard disk drives and monitors.

Acknowledgment

I would like to acknowledge the insightful comments about the maintenance and renovation of computers by Jean-Pierre Durand from the EDS/INSEAD team.

Appendix 1: Criteria for data collection

In order to maintain data consistency, all prices were collected from the same source, the *Personal Computer World* edited in the UK. In a typical edition, the last 200 pages are dedicated to the price lists of retailers and manufacturers of computer systems, components and software. For each component, there are 20-30 retailers publishing their price lists every month. Hence, the main question is to define the bounds for the data being collected. Table 5 summarizes the criteria:

Table 5: Bounds for data collection for each component

Component	Brands	Sizes	Technology
microprocessor (CPU)	Intel	66MHz, 75Mhz, 100Mhz, 120Mhz, 133Mhz, 150Mhz, 166Mhz, 200MHz	DX2 and Pentium
random access memory (RAM)	generic brands	4MB, 8MB, 16MB, 32MB	72-pin, non-parity 70ns SIMM
hard disk drive (HDD)	Seagate	545MB, 630MB, 845MB, 1080MB, 1260MB, 1600MB, 2160MB, 2600MB	3.5" (E)IDE control
CD-ROM drive	Mitsumi, Goldstar, Panasonic, Aztech, Hitachi	4x, 6x, 8x, 10x	Internal, IDE control
Video Monitor	Sony, Panasonic, NEC	14", 15", 17"	comparable models from different brands

Regarding CPU, only Intel microprocessors were considered. Although there are several other manufacturers of microprocessors, only Intel products were consistently offered by most component retailer. Hence, it was possible to obtain a large number of prices, each month, for the best selling CPUs at the time. Table 6 shows the average price of microprocessors of different operating frequencies in each month.

Table 6: Retail average price (£) for Intel microprocessors between August 1995 (Date 1) and January 1997 (Date 18).

Date	DX2-66	P75	P100	P120	P133	P150	P166	P200
1	92.33	205.50	343.00	554.00				
2	78.00	165.67	295.50	435.60	612.67			
3	90.60	148.00	294.20	466.17	589.60			
4	74.75	132.33	276.00	414.33	523.50			
5	72.40	129.60	268.50	383.75	494.00			
6	66.67	122.00	241.00	324.00	431.50			
7	58.00	116.00	207.67	286.67	401.50			
8	62.50	116.00	199.00	273.50	394.33	445.00	539.67	
9	45.00	84.33	155.67	193.00	252.33	327.67	477.67	
10	25.00	82.00	154.00	197.00	249.00	324.33	469.00	
11	19.00	75.67	135.00	172.33	229.33	308.00	456.50	
12	22.00	78.00	103.33	143.67	198.33	279.00	366.00	
13	19.00	78.00	99.00	141.00	192.67	271.00	353.75	
14	15.00	74.25	89.50	127.25	177.25	248.00	354.00	389.00
15		75.00	86.00	112.75	160.67	216.33	313.67	406.00
16		72.33	85.75	110.75	156.60	205.50	305.40	399.67
17		71.33	86.00	110.00	151.75	203.00	293.00	390.50
18		77.50	90.00	110.00	151.25	203.00	287.75	391.00

Regarding RAM, only generic SIMM chips were considered. These chips are used by most generic manufacturers of PCs, including all small makers and some of the models by the leading brands. The data collection were limited to the non-parity 72-pin chips used in most computers. Table 7 contains the average price for RAM chips of each size in each month.

Table 7: Retail average price (£) for generic SIMM memory chip, non parity, 72 pins, between August 1995 (Date 1) and January 1997 (Date 18).

Date	4MB	8MB	16MB	32MB
1	97.50	201.75	320.25	612.00
2	102.80	207.20	337.00	744.67
3	99.33	204.33	337.25	652.25
4	95.25	194.67	328.25	642.50
5	94.00	187.25	329.25	642.50
6	92.33	186.00	323.00	642.50
7	86.50	166.50	317.80	680.75
8	78.50	162.00	297.00	559.00
9	66.50	128.50	264.00	549.50
10	48.00	96.00	203.50	348.00
11	44.25	88.75	196.25	468.25
12	34.50	69.00	140.50	249.00
13	29.33	57.33	123.00	242.00
14	19.00	37.50	74.50	163.00
15	19.50	37.00	71.00	158.00
16	16.00	31.00	64.60	135.60
17	17.50	35.50	71.50	157.00
18	14.00	26.67	57.67	135.00

As for hard disk drives, the data collection was more difficult. The variety of models is very large, even within a single manufacturer. The hard disk can be measured according to three parameters: its storage capacity, its access time and its cache memory. For the initiated. each of these parameters has a significant impact. For the general public, only capacity is observed. The data collection was limited to Seagate brand using the well established IDE technology. The access time and the cache memory were not considered. Table 8 gives the average price for HDD of each size in each month.

Table 8: Retail average price (£) for Seagate IDE hard disk drives between August 1995 (Date 1) and January 1997 (Date 18).

Date	545MB	630MB	845MB	1080MB	1260MB	1600MB	2160MB	2600MB
1	115.80		167.00	229.20				
2	114.40		152.33	198.80				
3	114.00		144.75	197.20				
4	106.17		142.00	174.50	195.00			
5	105.25		141.25	174.40	189.75			
6	108.75		141.00	169.67	185.25			
7	112.00		140.00	164.00	183.25			
8	112.25	125.00	138.50	157.00	176.33	215.00	302.50	
9	109.75	130.00	137.00	152.00	169.00	204.00	262.00	
10	107.00	127.00	135.00	147.00	164.00	202.00	242.00	
11	107.00	125.33	124.00	142.75	144.67	187.00	214.00	
12	107.67	115.50	124.00	128.25	141.25	184.00	208.20	
13	104.00	115.00	119.00	128.20	139.00	182.00	202.00	
14	102.00	105.67	115.00	116.00	129.75	177.67	188.75	
15	99.00	104.50	118.00	116.33	126.50	161.50	188.33	
16	95.00	104.67	107.67	114.80	124.00	146.33	179.33	237.00
17	85.00	95.00	99.00	114.50	123.50	146.00	179.00	232.00
18	95.00		98.00	115.33	123.25	146.00	178.67	200.67

The market for CD-ROM drives is quite fragmented. There is not a leading brand such as with hard-disk drives. Yet, the need for continual technology advancement does not allow turning the product into a mere commodity. Hence the need to choose a limited number of innovative brands in the data collection. The manufacturers included were Mitsumi (4x, 6x), Goldstar (4x, 6x, 8x), Panasonic (4x, 6x, 8x), Aztech (all speeds) and Hitachi (4x, 8x). Each month, the price of a given size from each manufacturer was collected from up to six retailers and averaged. Then, the average price from each manufacturer was used to obtain the average price charged for a given size, in a given month, regardless of the brand. Table 9 shows the average price for CD-ROM drives of each speed in each of the 18 months examined.

Table 9: Retail average price (£) for CD-ROM drives from 5 manufacturers between August 1995 (Date 1) and January 1997 (Date 18).

Date	4x	6x	8x	10x
1	114.11			
2	113.25			
3	104.27			
4	101.58			
5	99.25	143.50		
6	96.42	137.50		
7	95.19	132.67		
8	90.56	126.00		
9	70.17	111.00		
10	54.75	92.67		
11	49.73	75.01	104.50	
12	43.00	59.75	100.50	
13	39.81	57.58	89.00	
14	38.67	52.33	80.00	
15	38.00	49.50	77.75	
16	37.89	47.00	67.59	85.00
17	35.25		65.44	85.00
18	33.00		63.86	83.00

The market for computer monitors is similar to that of CD-ROM drives, with an important difference: monitor prices are considerably more stable. Other than that, there are several monitor suppliers, none of them leading the market, all of them competing in the development of superior technology. In the period analyzed, one can notice the fall and rise of Panasonic, the fall of Philips and the rise of two smaller players: Iiyama and Taxan. Other important competitors include Hitachi and ADI, not considered here. The data contains the prices from the basic models offered by 3 important players: Sony (15" and 17"), Panasonic (15" and 17") and NEC (14", 15" and 17"), summarized as follows:

Table 10: Retail average price (£) for computer monitors from 3 manufacturers between August 1995 (Date 1) and January 1997 (Date 18).

Date	14"	15"	17"
1	222.00	279.20	585.50
2	217.67	279.40	581.75
3	217.00	279.33	575.00
4	215.50	276.25	566.87
5	213.50	275.67	540.15
6	213.50	275.33	536.49
7	213.50	273.33	534.93
8	213.50	273.33	528.18
9	213.50	273.33	520.33
10	213.50	273.33	546.00
11	213.50	273.33	531.00
12	213.50	273.25	525.47
13	213.50	273.00	525.47
14	213.50	273.00	520.50
15	213.50	273.00	512.92
16	212.00	273.00	500.42
17	210.00	273.00	498.67
18	210.00	273.00	498.33

Regarding whole systems, the data collected contains PCs offered by 9 manufacturers in the 18-month period. Each month, the price of 9-12 complete systems were collected, representative of the models offered at that time. Considering the variety of components considered, everything else constant, one could assemble up-to 8x6x3x3x4 = 1728 computer configurations each date. In practice, not all configurations were available at all times. The 10-12 systems surveyed each month always included two or three "entry level" systems, four or five "average" systems and one or two "powerful" systems. Moreover, in order to ensure comparability, all systems in the database are considered "typical" multimedia systems without fax/modem or other accessory that would affect the price. If the model already included any such accessory, the price was reduced by the same amount usually charged for that accessory that month. Table 11 gives an account of the data-points collected and their specifications.

Table 11: Profile of the complete systems surveyed.

Make	# data points
Adams	16
Atlantic	35
Brother	1
Dan	63
MJN	23
Opus	32
Panrix	8
PC Science	4
Simply	14
Total	196

CPU	# data points
75 MHz	35
90 MHz	5
100 MHz	39
120 MHz	31
133 MHz	37
150 MHz	14
166 MHz	32
200 MHz	3
Total	196

HDD	# data points
>500 MB	196
<600 MB	20
<1000 MB	35
<1200 MB	54
<1500 MB	30
<2000 MB	38
<3000 MB	19
Total	196

Monitor	# data points
14 in	72
15 in	83
17 in	41
Total	196

RAM	# data points
8 MB	74
16 MB	113
32 MB	9
Total	196

CD-ROM	# data points
2x	12
4x	93
6x	44
8x	47
Total	196

Appendix 2: Regression outputs

Tables 8-13 contain the main statistics for the regressions used to generate equations (1)-(6). In all of them , the expression obtained had an excellent fit, as witnessed by the high value of adjusted R-square. Notice that the ratio between the standard error and the expected value of each coefficient is quite small. In addition, the 95%-confidence intervals, for each variable in every expression, do not contain 0, an indication that the choice of explanatory variables is coherent with the price evolution of these components.

Table 12: Summary output of the OLS regression of the price of Pentium microprocessors:
$\log(PCPU) = k_0 + k_1 \log(CPUFREQ) + k_2 \log(DATE) + \varepsilon$

Regression Statistics	
Multiple R	0.93971
R^2	0.88305
R_a^2	0.88091
Std. Error	0.27638
Observations	112

Analysis of variance	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	2	62.86967	31.43484	411.52496	1.6044E-51
Residual	109	8.32610	0.07639		
Total	111	71.19577			

Term	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
k_0	-4.60710	0.37974	-12.13216	5.9276E-22	-5.35974	-3.85446
k_1	2.35024	0.08449	27.81617	2.5245E-51	2.18278	2.51770
k_2	-0.60324	0.03883	-15.53411	2.1311E-29	-0.68021	-0.52628

Table 13: Summary output of the OLS regression of the price of non-parity 72-pin SIMM chips:
$\log(PRAM) = k_0 + k_1 \log(RAMSIZE) + k_2 \log(DATE) + \varepsilon$

Regression Statistics	
Multiple R	0.9136
R^2	0.8347
R_a^2	0.8299
Std. Error	0.4266
Observations	72

Analysis of variance	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	2	63.4028	31.7014	174.1843	1.0774E-27
Residual	69	12.5579	0.1820		
Total	71	75.9607			

Term	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
k_0	3.9171	0.2105	18.6068	1.3460E-28	3.4971	4.3371
k_1	0.9798	0.0649	15.1023	1.4542E-23	0.8504	1.1092
k_2	-0.7076	0.0645	-10.9676	9.0254E-17	-0.8363	-0.5789

Table 14: Summary output of the OLS regression of the price of Seagate hard disk drives:
$\log(PHDD) = k_0 + k_1 \log(HDDSIZE) + k_2 \log(DATE) + \varepsilon$

Regression Statistics	
Multiple R	0.9309
R^2	0.8665
R_a^2	0.8639
Std. Error	0.0994
Observations	104

Analysis of variance	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	2	6.4758	3.2379	327.8450	6.8056E-45
Residual	101	0.9975	0.0099		
Total	103	7.4733			

Term	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
k_0	1.5741	0.1479	10.6408	3.4875E-18	1.2806	1.8675
k_1	0.5468	0.0219	24.9299	5.9932E-45	0.5033	0.5903

k_2	-0.1805	0.0154	-11.6942	1.7357E-20	-0.2111	-0.1498

Table 15: Summary output of the OLS regression of the prices of CD-ROM drives: log(PCDROM) = k_0 + k_1 log(CDSPEED) + $k_2$log(DATE) + ε

Regression Statistics	
Multiple R	0.8695
R^2	0.7561
R_a^2	0.7432
Std. Error	0.2104
Observations	41

Analysis of variance	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	2	5.2138	2.6069	58.8875	2.2826E-12
Residual	38	1.6822	0.0443		
Total	40	6.8960			

Term	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
k_0	4.1347	0.1859	22.2368	2.1909E-23	3.7583	4.5112
k_1	0.8998	0.1160	7.7556	2.3929E-09	0.6649	1.1347
k_2	-0.6041	0.0589	-10.2587	1.6709E-12	-0.7233	-0.4849

Table 16: Summary output of the OLS regression of the prices of computer monitors: log(PMONITOR) = k_0 + k_1 log(MONSIZE) + $k_2$log(DATE) + ε

Regression Statistics	
Multiple R	0.9974
R^2	0.9949
R_a^2	0.9947
Std. Error	0.0283
Observations	54

Analysis of variance	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	2	7.9149	3.9574	4931.4	4.353E-59
Residual	51	0.0409	0.0008		
Total	53	7.9558			

Term	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
k_0	-7.1322	0.1312	-54.3433	8E-47	-7.3956	-6.8687
k_1	4.7537	0.0480	99.0972	5E-60	4.6574	4.8500
k_2	-0.0323	0.0049	-6.5309	3E-08	-0.0422	-0.0224

Table 17: Summary output of the OLS regression
$$PCPRICE = k_0 + k_1\,PCPU + k_2\,PRAM + k_3\,PHDD + k_4\,PCDROM + k_5\,PMONITOR + k_6\,DATE + \varepsilon$$

Regression Statistics	
Multiple R	0.9610
R^2	0.9236
R_a^2	0.9211
Std. Error	151.6059
Observations	196

Analysis of variance	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	6	52487591	8747931	380.60	1.168E-102
Residual	189	4344042	22984		
Total	195	56831633			

Term	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
k_0	408.5408	68.8795	5.9312	1.4064E-08	272.6695	544.41
k_1	1.2363	0.1067	11.5912	8.1571E-24	1.0259	1.4467
k_2	0.3032	0.1282	2.3654	0.0190	0.0504	0.5561
k_3	2.0113	0.4190	4.8000	3.2156E-06	1.1847	2.8378
k_4	-1.5852	0.4939	-3.2096	0.0016	-2.5594	-0.6110
k_5	2.4324	0.1188	20.4699	7.7382E-50	2.1980	2.6668
k_6	-22.7705	2.7605	-8.2487	2.6664E-14	-28.2159	-17.3252

References

[i] Source: Ayres et al. *Electronic Grade Silicon for Semiconductors*, in Materials-Optimization in the Production of Major Finished Materials, INSEAD-CMER Study Contract BRE2.CT93.0894, January 1995.

[ii] Source: Hagedorn, G. and E. Hellriegel. *Environmentally Relevant Mass Inputs for Solar Cell Production: A Comparative Analysis of Conventional and Selected new Processes, Taking into Account both Input Materials, Process Chains, Decommissioning and Recycling Options*, Forschungsstelle fuer Energiewirtschaft, February 1992 (originally in German, quoted in Ayres et al. 1995)

[iii] Source: O'Mara, W.C., R.B. Herring and L.B. Hunt (eds.): "Handbook of Semiconductor Silicon Technology", Noyes Publications, Park Ridge, NJ, 1990 (quoted in Ayres et al. 1995)

[iv] Source: Ayres et al. (1995)

[v] Source: Hewlett-Packard. "Electronic Product Take-Back", European Public Affairs, Issue Brief - No. 1, May 1994.

[vi] For more details on IBM DST Logistica operations, see also: Ayres, R.U., G. Ferrer, T. Van Leynseele. "Eco-efficiency, Asset Recovery and Remanufacturing", INSEAD-CMER working paper, March 1997.