RECYCLING NOTEBOOK COMPUTERS IN TAIWAN: A PRELIMINARY STUDY

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Key Words: Obsolete computers, notebook computers (NB’s), recycling, life cycle assessment (LCA), cost-benefit analysis

ABSTRACT

Taiwan boasts a booming information industry making it one of the largest information hardware makers in the world. 58.6% of the world’s notebook computers (NB’s) are manufactured in Taiwan. Since the average lifespan for NB’s is only 3-4 years, the large quantities of toxic heavy metal materials in obsolete NB’s will increase Taiwan’s already burdensome waste problem. In order to reduce the e-waste and efficiently recover useful materials from obsolete computers, the Taiwan government began a recycling program in 1998. However, the program lacked a concern for the environmental impact as well as a cost-benefit analysis. Therefore, this study aims to demonstrate how cost-benefit analysis combined with Life Cycle Assessment (LCA) could be used as a tool to analyze the environmental impact of NB’s recovery as stated in Taiwan’s current program. At present, most NB’s motherboards and central processing units (CPU) can not be recycled. The use of LCA software, SIMAPRO, showed that the higher the rate of NB’s flowing to recycling plants the greater the negative environmental impact. It also suggested that if the government can modify the current rate of NB’s flowing to recycling plants, as well as its recycling fee policy, the environmental impact from recycling components of obsolete NB’s would be emphasized in the new program.

INTRODUCTION

Over the past several years, great strides have been made in information technology which have resulted in the widespread use of computers in our daily lives. Due to the striking developments in personal computers (PC’s), new models with greater processing capacity and speed have been introduced to the market [1]. At the same time, vast quantities of obsolete electronics are piled in mountains of waste. Obsolete computers contain significant amounts of recoverable materials including metals from wires and circuit boards, glass from monitors, and plastics from casings. [2]. For example, 1 metric ton of electronic scrap from PC’s contains more gold than that recovered from 17 metric tons of gold ore. In 1998, the amount of gold recovered from electronic scrap in the United States was equivalent to that recovered from more than 2 million metric tons of gold ore and waste [3]. The electronics industry in Taiwan has been impressive in its development in recent years. And since 1995, upstream industries (which include semiconductors and printed circuit boards) as well as those in the downstream industries (such as PC’s, notebook computers (NB’s) and computer peripheral products) have all expanded their production capacities. This has in turn created a comprehensive production system in Taiwan’s electronics industry, making it possible for mass production and integration of upstream and downstream products. For example, all Dell and about 70% of Compaq’s NB’s are produced by Taiwan’s manufacturers. In addition, Taiwan-made computers account for more than 20% of Fujitsu and IBM’s NB’s. To put this in perspective, in 2001 Taiwan’s NB’s production represented 58.6% of the global output; thereby, exceeding Japan as the world’s largest NB’s

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manufacturer [4].

In order to reduce the e-waste to pollute the environment and efficiently recover useful materials from obsolete computers, the preliminary study selected NB’s as the sole item to show and discuss the results of its recycling program. Furthermore, the recycling program was assessed on whether or not the program followed Taiwan’s principles of recycling.

This study aims to demonstrate how cost-benefit analysis combined with Life Cycle Assessment (LCA) could be used as a tool to analyze the environmental impact of NB’s recovery as stated in Taiwan’s current program. The motivation for the early interest in LCA by the industry was primarily to defend its position in demonstrating the environmental superiority of products. Later, interest in LCA was motivated by product differentiation, especially for eco-labeling programs. Today, identifying opportunities to alter a product or process in order to address its environmental impact and improve the manufacturer’s environmental profile has become a driving force behind the use of LCA [5].

**RECYCLING FLOW**

According to IBM, 83.3% of obsolete computers could be recycled, while the remaining nonrecyclable parts (16.7%) are toxic and need to be reprocessed [2]. These parts usually include circuit boards in the mainframe of the computer which contain a lot of heavy metals, color tubes, electric cables and other special materials such as batteries and oil wastes. Computers and other electronic devices represent a large resource of potentially recoverable material [6]. In 1998, about 2.6 million PC’s and NB’s were recycled in the United States, and this number is expected to quadruple by 2003 [7].

In Taiwan, disposal sites that are extremely limited have made “material recycling” almost the only choice to really ease its environmental loads. In 1997, the amended Waste Disposal Act began to promote recycling projects in which the government mandated what was to be recycled and the fees associated with those items. The mandatory items to be recycled not only include computers, but covered many other electronic devices.

Taiwan’s local recovery plants disassembled the collected e-waste. The retrievable parts such as large pieces of plastics and metals were resold. The IC boards and the materials containing precious metals were sent to foreign experts for further processing, while the remaining waste was transferred to local landfills. Figure 1 illustrates the material flow of e-waste in Taiwan. Figure 2 illustrates the material flow and study area of NB’s in Taiwan.

**METHODOLOGY**

This study assessed whether the recycling program in Taiwan followed recycling principles to prevent it from serving as a dump site for computers. Economic efficiency of the program was analyzed by integrating the Life Cycle Assessment (LCA) and the cost-benefit analysis [8]. Figure 3 represents the objective, decision variables, and constraints in the simulation scenario of this study.

The LCA software package, SIMAPRO [9] was used to analyze the environmental impact in order to gain the overall value of each scenario. In its analysis, this study identified a NB’s components into seven parts: hard disk (HD), floppy disk (FD), central processing unit (CPU), battery, liquid crystal display (LCD), case, and keyboard. The weight of each part was used to evaluate its environmental impact.

The concept of the simulation model can be expressed as follows:
Decision Variables

<table>
<thead>
<tr>
<th>The rate of obsolete NB flow to recycle plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
</tr>
<tr>
<td>10%</td>
</tr>
<tr>
<td>40%</td>
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<tr>
<td>70%</td>
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<tr>
<td>80%</td>
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<tr>
<td>90%</td>
</tr>
<tr>
<td>100%</td>
</tr>
</tbody>
</table>

Objective: Environmental Impact Evaluation

Constraints:
- Cost-Benefit Analysis
- Environmental Impact Evaluation

Objective: Environmental Impact Evaluation

Minimizing Environmental Impacts.

Environmental Impact Evaluation of LCA (3 eco-indicators: human health, ecosystem quality and resources consumption)

B/C is greater than 1.

Cost (C): transportation and disposal costs.

Benefit (B): profits from recycling material sales and second-hand market.

Fig. 3. Three components in the scenario simulation model in this study.

Minimize (environmental impact value) (1) subject to

Constraint on the mass balance (2a)

Constraint on the maximize benefit/cost ratio (2b)

Constraint on the current recycling program (2c)

MODEL FORMULATION

1. Objective Function

The objective function (1) can be quantified as

Min(Iw) = \sum_{ij} \sum_{i} E_{ij} X_{ij} \quad (3)

where Iw is the total environmental impact value; E_{ij} is the environmental impact value of environmental impact indicator i at what happens to obsolete NB’s j in; X_{ij} is the rate at which happens to obsolete NB’s where X_1 means the rate of obsolete NB’s flow to second-hand market, X_2 means the rate of obsolete NB’s flow to recycle plant, X_3 means the rate of obsolete NB’s flow to incineration, X_4 means the rate of obsolete NB’s flow to landfill; i=1 means the first environmental impact indicator of human health, i=2 means the second environmental impact indicator of ecosystem quality, i=3 means the third environmental impact indicator of resources consumption.

2. Decision Variables

Based on practical considerations, the considered decision variables were defined as the ratios between “recycling plants”, “second-hand markets”, “landfills” and “incineration”. Different rates of obsolete NB’s to recycling plants, 0%, 10%, 40%, 70%, 80%, 90% and 100% were considered to combine with two different ratios as follows:

Obsolete NB’s flow to incineration: obsolete NB’s flow to landfills: obsolete NB’s flow to second-hand markets=3:0:1 (4a)

Obsolete NB’s flow to incineration: obsolete NB’s flow to landfills: obsolete NB’s flow to second-hand markets=2:1:1 (4b)

A total of 13 scenarios were yielded.

3. Constraints

The mass balance of obsolete NB’s can be described (2a) as follows:

\[ \sum_{j=1}^{4} X_{ji} = 1 \quad (5) \]

where X_{ji} is defined in equation (3).

The benefit over cost per unit obsolete NB’s must be greater than or equal to 1(2b) as follows:

\[ \frac{B}{C} \geq 1 \quad (6) \]

Where B is the benefit per unit obsolete NB’s, C is the cost per unit obsolete NB’s.

B is the sum of recycle benefit and the selling price of a NB’s in the second-hand market.

\[ B = \sum_{j=1}^{2} (BF_{ji}) X_{ji} \quad (7) \]

where (BF_{ji}) is the sum of recycle benefit and the selling price of a NB’s in the second-hand market at j condition; j=1 means the selling price for a second-hand NB’s, j=2 means the final selling price for recycling materials from NB’s.

C is the sum of transportation cost and treatment cost.

\[ C = TS \times X_{ji} + \sum_{j=1}^{4} TT_{ji} \times X_{ji} \quad (8) \]

where TS is the average transportation cost for NB’s going to recycling plants, incineration, landfills and second-hand markets (assuming that the transporting distances are the same and the disposal fee per unit is equal); X_{ji} is defined and mentioned in equation(3); TT is the average treatment cost (including incineration, landfills and recycling plants) for obsolete NB’s.

Restriction of the current recycling program(X_1, X_3 and X_4) and scenario assumptions (X_2) of NB’s in Taiwan’s EPA as follows:

\[ X_1 \leq 25\% \quad (9a) \]

\[ X_2 = 0\% \text{ or } 10\% \text{ or } 40\% \text{ or } 70\% \text{ or } 80\% \text{ or } 90\% \text{ or } 100\% \quad (9b) \]

\[ X_3 \leq 75\% \quad (9c) \]

\[ X_4 \leq 25\% \quad (9d) \]
Fig. 4. The B/C value and environmental impact value at different recycle rate of obsolete NB’s flow to recycle plant under Obsolete NB’s flow to incineration: obsolete NB’s flow to landfill: obsolete NB’s flow to second-hand market is 3:0:1 and 2:1:1.

Fig. 5. The general inputs of the template datasets in SIMAPRO.

Restriction of all variables in this study was shown as follows:

\[ \text{All variables} \geq 0 \quad (10) \]

**RESULTS AND DISCUSSION**

To compare the model results under various assumptions, a base case is defined using the SIMAPRO forecast of the environmental impact value. Figure 4 shows the general inputs of the template datasets. Based on the model outputs, the environmental impact value could be calculated according to 13 scenarios with emphasis on different recycling rates of obsolete NB’s going to recycling plants. As a result, the B/C value for each scenario and the related magnitude of the environmental impact value assessed are shown in Fig. 5. Table 1 represents the LCA results for 13 NB’s scenarios.

When seeking the optimum objective function (see in Table 1) under the main boundary condition of economic benefit, this study observed that scenarios 1-8 are feasible solutions within the boundaries set.

Note worthy are the decision choices with recycling rates of NB’s going to recycling plants that were below 70% yielded benefits which were greater than cost, making them economically feasible solutions.

As far as the smallest environmental impact value was concerned, the best solutions would be scenario 1 and 2. A further analysis shows that the CPU, the major contributor, takes up over 80% of the total environment impact value, as shown in Fig. 6. On the other hand, the CPU also contains heavy metals such as copper, tin, iron, lead, cadmium, chromium, gold, silver, nickel, zinc, etc. As such, the concentration of these metals flowing to the environment is constant and cannot be ameliorated.

Therefore, the result shows that increasing the recycling rate of obsolete NB’s going to recycling plants implies an increase in the environmental impact value, but a decrease in the B/C value. If the environmental impact value is at its lowest, the model dictates that the recycling rate of obsolete NB’s going to recycling plants would be zero. It means that nothing should be recycled at recycling plants from obsolete NB’s. Since most NB’s motherboards and CPU can not be recycled at present, the higher the recycling rate of obsolete NB’s going to recycling plants the more serious the environmental impact will be. Therefore, the study suggests the recycling rate of obsolete NB’s going to recycling plants rather than recovery rate alone should be emphasized in the coming new program. In addition, an assessment of B/C shows that when B/C is at 1, the marginal recycling rate of obsolete NB’s going to recycling plants is 70%-80%.

![Fig. 5](image-url)  
 ![Fig. 6](image-url)
CONCLUSIONS

Taiwan is a new industrial country that is mak-
Table 1. LCA and B/C analysis results for model scenarios of NB’s.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycle rate(^a) (%)</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>40</td>
<td>40</td>
<td>70</td>
<td>70</td>
<td>80</td>
<td>80</td>
<td>90</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>The rest rate(^b) (%)</td>
<td>100</td>
<td>100</td>
<td>90</td>
<td>90</td>
<td>60</td>
<td>60</td>
<td>30</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Incineration(^c) (%)</td>
<td>75</td>
<td>50</td>
<td>67.5</td>
<td>45</td>
<td>45</td>
<td>30</td>
<td>22.5</td>
<td>15</td>
<td>15</td>
<td>10</td>
<td>7.5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Landfill (%)</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>22.5</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>7.5</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
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<tr>
<td>Second-hand (%)</td>
<td>25</td>
<td>25</td>
<td>22.5</td>
<td>22.5</td>
<td>15</td>
<td>15</td>
<td>7.5</td>
<td>7.5</td>
<td>5</td>
<td>5</td>
<td>2.5</td>
<td>2.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Environmental impact value

- **Human Health**: 100, 100, 103.1, 103.1, 113.2, 113.2, 122.9, 122, 126, 126, 129.5, 129.5, 132.6
- **Ecosystem Quality**: 100, 100, 103.2, 103.2, 113.2, 113.2, 123.1, 122.3, 126.3, 126.3, 129.5, 129.5, 132.8
- **Resources consumption**: 100, 100, 103.2, 103.2, 112.9, 112.9, 122.6, 121.6, 126.0, 126.0, 129.1, 129.1, 132.3

The average value

- **Human Health**: 100, 100, 103.2, 103.2, 113.1, 113.1, 122.8, 121.9, 126.1, 126.1, 129.3, 129.3, 132.5

The ratio of benefit and cost \((B/C)\)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{ij}) &amp; 1.944</td>
<td>1.945</td>
<td>1.862</td>
<td>1.863</td>
<td>1.541</td>
<td>1.542</td>
<td>1.028</td>
<td>1.028</td>
<td>0.781</td>
<td>0.782</td>
<td>0.473</td>
<td>0.473</td>
<td></td>
</tr>
<tr>
<td>(X_j) &amp; 0.781</td>
<td>0.782</td>
<td>0.473</td>
<td>0.473</td>
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</tbody>
</table>

\(^a\) represents recycle rate of obsolete NB’s flow to recycle plant.

\(^b\) represents (1-recycle rate).

\(^c\) represents the rest rate was divided into incineration, landfill and second-hand by the ratio of 3:0:1 and 2:1:1.

**NOMENCLATURE**

- \(E_{ij}\): Environmental impact value at what happens to obsolete NB’s \(j\) in environmental impact indicator \(i\);
- \(X_j\): Rate at what happens \((j)\) for obsolete NB’s;
- \(B\): Benefit per unit obsolete NB’s;
- \(C\): Cost per unit obsolete NB’s;
- \(BF_j\): Sum of recycle benefit and the selling price of a NB’s in the second-hand market at \(j\) condition;
- \(TS\): Average transportation cost for a obsolete NB’s flow to recycle plant, incineration, landfill and second-hand market; and
- \(TT\): Average treatment cost (including incineration, landfill and recycle plant) for a obsolete NB’s.

**REFERENCES**


Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-chief within six months.

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台灣地區筆記型電腦回收再利用初探

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關鍵詞: 廢棄電腦、筆記型電腦、回收、生命週期評估、成本效益分析

摘   要

台灣的電子業自上游的半導體、印刷電路板，到下游的筆記型電腦、筆記型電腦以及生產週邊產品，近年來蓬勃發展，已經成為世界最重要資訊產品製造生產地區之一。以筆記型電腦為例，2001年台灣已超越日本成全球筆記型電腦最大製造中心，全球有 58.6%的筆記型電腦在台灣生產。由於台灣地區筆記型電腦的高生產量，亦伴隨著民眾之高擁有率，但當筆記型電腦遭淘汰，約 3-4 年即可能被淘汰。而被棄置時，若無適當處置資源，便會對環境品質造成負面影響。台灣環保署自 1998 年開始執行包括廢棄型電子等廢棄資訊商品之強制回收工作，但皆未考慮資源耗費、對生態的影響、對人體健康的影響及其經濟效益。爰此，本研究在不同回收率(指廢棄型電子流向資源回收場之比例)與廢棄型電子直接流向焚化爐、掩埋場、二手市場不同比例之情景假設下，結合成本效益分析，以生命週期評估軟體 SIMAPRO 進行環境衝擊評估量化模式模擬之比較。研究結果發現，未被筆記型電腦之控制單元，如主機板、中央處理系統等，對環境的衝擊影響最大(約占總值之 80.6%)，且這些物質經回收後，並未有效處理，導致回收愈多反而造成環境衝擊愈大；依本研究模式模擬所提出之最佳方案為“暫不回收廢棄型電子”，其所代表的意義是，為了回收與再處理廢棄型電子之內涵物，所投入的人力、物力與消耗的資源，對生態環境的影響與對人體健康的影響，皆未達其經濟效益。因此，本研究建議唯有提高廢棄型電子中主機板、中央處理系統等物質之再利用率，而非一味追求物質回收率數字的提升，才能對環境的衝擊減至最小，也才能真正達到物質循環再利用的目的。