

Article

Optimal Consumer Electronics Product Take-Back Time with Consideration of Consumer Value

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Academic Editor: Bhavik Bakshi

Received: 21 September 2016; Accepted: 2 March 2017; Published: 7 March 2017

Abstract: Rapid economic growth in recent years has transformed our lifestyle to massively produce, consume, and dispose of products, especially for consumer electronics. This change has put great threat to our environment and caused natural resource depletion. Moreover, short product life cycles and quick replacements of consumer electronics create enormous electronic wastes (e-wastes). Without proper waste management, immense environmental damage is expected. In this empirical study, we notice that lots of valuable materials that can still be recycled from these used consumer electronics are left unused at home instead of being recycled at the appropriate time, which causes a low collection rate and a decrease in residual value for the used products. Therefore, it is important for the government and the recyclers to handle them efficiently by increasing the used product take-back rate. Our study develops an assessment model for customer value based on the idea of value engineering and the perspective of product life cycle. We also explore the relationship between product value and the total cost of ownership with an evaluation of their time variation, considering different usage modes for various consumer groups and different recycling award schemes (fixed and variable recycling awards). Proper take-back management is likely to create a win-win situation both for consumers and environmental protection. This study regards the notebook computer as an example to determine the optimal time for recycling laptops based on usage patterns and provides consumers a reference for when to replace their used product. The results from our modeling firstly clearly indicate that consumers with higher frequency of usage have shorter take back times and higher maximum consumer value. Secondly, a variable recycling award scheme with higher maximum consumer value is more practical than a fixed recycling award scheme.

Keywords: product take-back time; consumer value; total cost of ownership; recycling award

1. Introduction

The rapid development of technology has brought consumer electronics into our daily life in the past decades. This has changed the way we communicate, entertain, and obtain information. Innovative technology continuously pushes out the old model and brings in the new one to meet consumer's demands. This has shortened the life cycle of consumer electronics and resulted in greater replacement and disposal compared to other products. Without proper recycling processes, these accumulated electronic wastes (e-waste) will not only pose threats to the ecological environment but also cause valuable resources to be destroyed or unused. According to the research of Balde et al. [1], the estimated amount of e-waste generated in 2014 was 41.8 million metric tonnes (Mt), and this was forecasted to increase to 50 Mt of e-waste in 2018. In Europe [2], e-waste is increasing at an annual rate of 3% to 5%, which is almost three times faster than the total waste stream. Developed countries are not the only ones that generate e-waste; developing countries are also expected to triple their e-waste production. United Nations Environment Program (UNEP) [3] estimated that 50 million tons of

e-wastes are produced each year globally, but only 15%–30% of e-waste is recycled; the rest go directly to landfills and incinerators. In addition, US government researchers [4] investigated the quantity of electronic products ready for end-of-life between 1990 and 2010; the result implies that 5 million short tons of electronic products are in storage, remain stockpiled, and are waiting for disposal.

Today's computer industry innovates at a rapid pace and brings new technologies with upgrades to market on average of every 18 months. According to data provided by the Statista website [5], the average life of PCs and tablets is expected to drop in the next four years. While the average life for these devices was almost 3.1 years in 2013, that number is expected to drop to a little over 2.8 years by 2017. It shows that computer replacement has increased and caused a huge disposal problem. Kwak et al. [6] presented the results of an analysis of data collected from an e-waste collection center in Chicago, showing that the mean age of collected laptop computers is 11 years old, which is very different from its typical wear-out lifespan. United States Environmental Protection Agency (U.S. EPA) [7] discovered that many consumers did not recycle their consumer electronic products when they first became defunct or obsolete and more than 70% of retired products were kept in storage, typically for as many as 3–5 years.

In order to resolve these serious waste problems caused by consumer electronics, the European Union proposed an Integrated Product Policy (IPP) [8] that aims to take a life cycle perspective instead of the end-of-pipe treatment. Integrated environmental awareness is blended into the processes from design, extraction of natural resources, manufacturing, assembly, distribution, and use to the eventual disposal as waste to reduce damage and pressure on the environment. It also needs to include all relevant stakeholder viewpoints for the whole product development process from idea generation to product management and reverse logistics. End-of-life management (EOLM) has become an important global issue in electronic consumer products, home appliances, and industrial equipment products recently. Many enterprises have successfully applied this management method as a feasible solution to solve the E-waste problem. Ramani et al. [9] define EOLM as the process of converting end-of-life products into remarkable products, components, or materials. It enables manufacturers to comply with environmental legislation while gaining economic advantages.

EOLM can be divided into two parts: (1) product take-back, which is the process of acquainting the end of life products from the consumer; and (2) EOL recovery options, which take the products after the acquisition to elect product reuse, component reuse, and material recovery options [10–12]. Guide et al. [13] considered the uncertainty of quality and quantity, as well as the timing of end-of-life products that made EOLM difficult. In line with that dilemma, Rayet al. [14] proposed the concept of an active product recovery system. They believe that, through economic incentives, there is an opportunity to enhance consumer product recycling to achieve an economy of scale. While others addressed the issue as a problem of scheduling take-back, a problem in the demand for parts or recovered products with the objective to fulfill the demand at a minimum cost. White et al. [15] presented an overview of the EOLM problems existing in each stage of the product recovery process and showed that better information about product design, product quality, and timing can improve the product EOL opportunities. Zhao et al. [16] developed a model to help the manufacturers determine optimal take-back time and the number of lifecycles for warranty purposes. In addition, some literature explored recycling facility locations and the number of resource allocations for the optimal recycling solutions [17–19].

As summarized above, most of the product manufacturers (recyclers) explore an end of life product recycling strategy, with the goal either to identify product recovery process to obtain maximum profits at minimum cost or to reduce the impact on the environment. Conversely, only a few papers considered the value of the consumer, but none uses consumer value to study take-back time for consumer electronics, based on our best knowledge. This motivates our study. However, if we want to reduce the environmental impacts throughout the life cycle of a product, all the different actors and stakeholders, such as designers, manufacturers, consumers, and recyclers, should participate. In this study, in order to help consumers understand the perfect timing for the take-back of a laptop computer,

we have developed an assessment model from the consumer's position and taken the point of view of a product life cycle to construct the consumer value over time. We have also considered the usage patterns of various consumer groups to obtain their different optimal take-back times and to provide different consumers with a reference for their product replacement.

This paper is organized as follows. In addition to this introduction, Section 2 develops a proposed assessment model. Section 3 illustrates the proposed assessment model using real data on laptop computers. Finally, Section 4 gives a conclusion with suggestions for future research.

2. Model Development

Value engineering (VE) is a powerful technique to determine the best relationship between cost and value by analyzing product and process performance. It could be introduced at any point in the life-cycle of products, systems, or procedures [20]. This study proposes a consumer value model that is based on the idea of VE and the perspective of product life cycle. The consumer value is a function of time, and this study uses it to determine the optimal take-back time from the consumer aspect during the product life cycle. The consumer value ($V_C(t)$) can be defined as the ratio of product value ($V_P(t)$) and total cost of ownership ($TCO(t)$). The product value is the value that the consumer obtains in his or her holding time, and the total cost of ownership is the cost that the consumer pays in his or her holding time. They are discussed in detail below and shown in Figure 1.

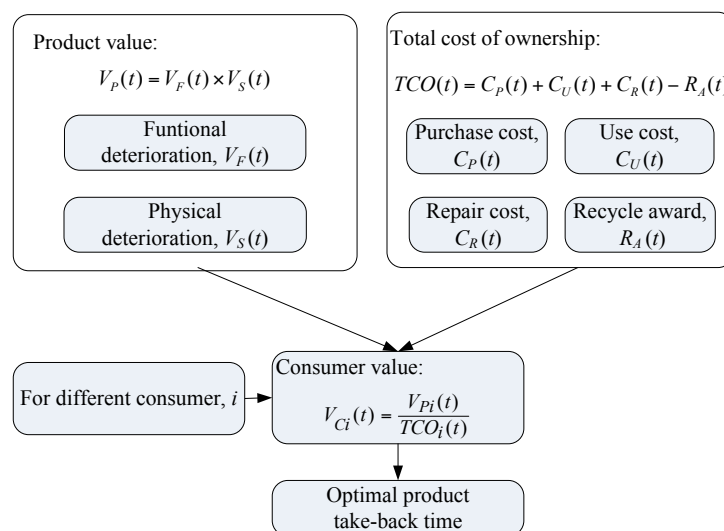


Figure 1. The concept of consumer value.

2.1. Product Value Modeling

According to the work of Kondoh et al. [21], the value of the product deteriorates over time in general. The factors that cause this recession can be classified into functional value deterioration and physical value deterioration. The functional value deteriorates with time due to obsolescence resulting from rapid technological innovation and/or changes in market trends. For example, as hard disk capacity increases, the existing product capacity no longer meets consumers' expectations. The physical value deterioration may also decrease due to the aging and wearing off of product components. For example, LED screen brightness may fade away and even malfunction with the time. This study employs Equation (1) to model product value ($V_P(t)$) that incorporates functional value ($V_F(t)$) deterioration and physical value ($V_S(t)$) deterioration. We use different weightings, w_F and w_S , respectively, to denote different ratios for both the functional value and physical value for different products.

$$V_P(t) = \omega_F \times V_F(t) + \omega_S \times V_S(t) \quad (1)$$

where $\omega_F + \omega_S = 1, \quad 0 \leq \omega_F, \omega_S \leq 1$

Figure 2 below shows that at $t = 0$, $V_F(0)$ and $V_S(0)$ are equal to 1 ideally in the beginning. However all values decrease as time goes by. The solid line represents the product value, when consumers are holding product at time t_h , the product value is $V_P(t_h)$; when holding time t reaches the product's end-of-life, the product value will decrease to $V_P(t_{EoL})$. To note, at the end-of-life point (t_{EoL}), the product value drops. Henceforth, it represents the lower economic benefit of recovery. The conclusion can be ascertained from the diagram that those who store their unused valuable items at home instead of recycling them not only lose the best timing to retrieve residual profits but also leave products to decay. Therefore, consumers should be encouraged to recycle their products in an appropriate time to improve economic efficiency for product recovery and consumer value.

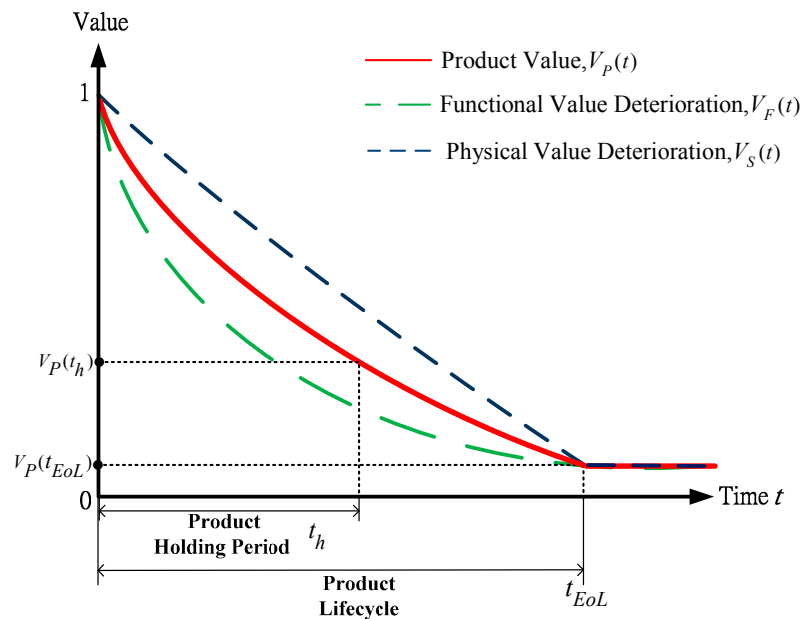


Figure 2. The time variation of product value.

2.1.1. Functional Value and Physical Value Deterioration Model

This study modifies the work of Yeh [22] and considers a more general situation to assume that the functional value deterioration model follows an exponential distribution and the physical value deterioration model follows a linear distribution, as shown in Equations (2) and (3), respectively:

$$V_F(t) = \left(1 - \frac{X}{\omega_F}\right) \times e^{-\alpha \times t} + \frac{X}{\omega_F}, 0 \leq X, 0 \leq t, 0 < \alpha \quad (2)$$

$$V_S(t) = \left(\frac{Y}{\omega_S} - 1\right) \times \beta \times t + 1, 0 \leq Y, 0 \leq t, 0 < \beta \quad (3)$$

where t denotes holding time counting after the product is bought. $V_F(0) = V_S(0) = 1$, $V_F(\infty) = X/\omega_F$ and $V_S(t_{EoL}) = Y/\omega_S$. X/ω_F and Y/ω_S denote the residual value of the functional performance and the physical performance, respectively, when t approaches ∞ or the time longer enough. Actually, when the product reaches its end-of-life ($t_{EoL} < \infty$), its residual value is the material value for recycling. The rate of functional value deterioration is denoted by α , and different products have different α values. When α is greater (such as for a worse performance product, like α_3), the value declination is greater, otherwise it is lesser, as shown in Figure 3. For the physical value, the rate of physical value deterioration is denoted by β , and different groups of users have different β values. For higher frequency use persons, who have greater β values (like β_3), the value declination is greater and products reach their end-of-life earlier. The discussion of α and β in detail is shown later.

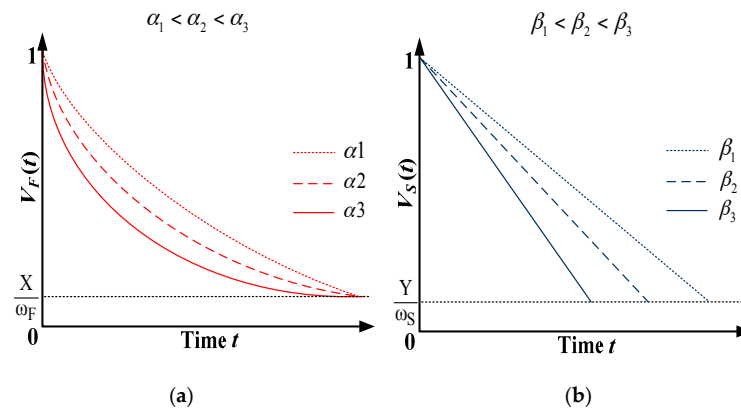


Figure 3. The deterioration rate of functional value and physical value. (a) Functional deterioration, $V_F(t)$; (b) Physical deterioration, $V_S(t)$.

2.1.2. Modeling the Deterioration Rate of Functional Value

Many companies (Fujitsu, Mitsubishi, Hitachi, and Toshiba from Japan) have already adopted the Factor X method to assess the degree or rate of progress of a new product. Although the calculations of the rate are different, the concept is similar and is used in evaluating product specifications to compare the reference product specifications and to obtain the total function progress rate of the evaluated product.

Fujitsu's Factor X method [23] used the root mean square (RMS) concept to calculate the product overall progress ratio; Mitsubishi's Factor X [24] used the arithmetic mean (average) to calculate the product overall progress ratio; and Toshiba's Factor T [25] used the quality function deployment (QFD) method to obtain the weight of user demand, then multiply it with the specific progress rate, and finally sum up the total value to get the product overall progress ratio. We modify the Factor T method and express the functional deterioration value in Equation (4). The goal of this equation is to obtain the product overall rate of deterioration.

$$\text{Functional deterioration value} = \frac{\text{Evaluated product specifications (old)}}{\text{Reference product specifications (new)}} \quad (4)$$

The calculation steps of functional deterioration value are the following:

- (1) Determine a product to be evaluated (Ep) and a product that is comparable to the reference product (Rp).
- (2) Identify key specifications of the product ($m = 1, 2, \dots, M$).
- (3) Choose the most significant attributes or functions for each key specification, then find their performance (Ep_m is the performance of key specification m of the evaluated product).
- (4) Apply the weighting factor (ω_m) to express the contribution of each key specification.
- (5) Determine the key specifications progress vector, when the progress vector goes up, the better the performance is; and use Equation (5) to find each attribute's performance. When the progress vector goes down, use Equation (6) for the calculation, where Rp_m is the performance of key component m of the reference product.

Multiply the attribute's performance by the weighting factor and sum the value of the total specifications to obtain the total deterioration value of product (Dp), as shown in Equation (7). Substituting Dp into Equation (2), we can obtain α :

$$Dp_m = \frac{Ep_m}{Rp_m} \text{ for the case of larger the better} \quad (5)$$

$$Dp_m = \frac{1/Ep_m}{1/Rp_m} \text{ for the case of smaller the better} \quad (6)$$

$$Dp = \sum_{m=1}^M Dp_m \times w_m \quad (7)$$

2.2. Total Cost of Ownership Model

The HP Corporation [26] defined TCO to provide the consumer with the direct and indirect cost of IT product evaluation. Ellram [27] indicated that, in general, the TCO of products should include acquisition cost, use cost, maintenance cost, and other relevant costs. This study assumes that the consumer is required to pay the total cost of product, including the product purchase cost, C_P , product use cost, C_U , product repair cost, C_R , and the recycling award, A_R . Equation (8) shows the time function of TCO, and each cost will be discussed in the following sub-sections.

$$TCO(t) = C_P(t) + C_U(t) + C_R(t) - A_R(t) \quad (8)$$

2.2.1. Purchase Cost Modeling

The time function of product purchase cost, $C_P(t)$, is the product market value with respect to time. The market value will decrease as the use time of product increases, as shown in Equation (9).

$$C_P(t) = P \times e^{-\gamma \times t} \quad (9)$$

where P is the sale price of the product and γ represents the deterioration rate of product price.

2.2.2. Use Cost Modeling

We define the time function of product use cost to be the total cost of electricity consumption under different user scenarios. According to the report of the EuP Lot3 final report [28], the consumer use model can be divided into three modes; off ($j = 1$), sleep ($j = 2$), and active ($j = 3$). The off mode is the wattage consumed (kw_1) in soft off. The sleep mode is the wattage consumed (kw_2) in several low energy consumption states, none of them permitting interactive usage. The active mode is the wattage consumed (kw_3) in all power states between idle and high (maximum power usage). The cost of kilowatt hour (kWh) consumption required for mode j at time t , $U_j(t)$, is shown in Equation (10).

$$U_j(t) = h(t) \times r_j \times kw_j \times c, \text{ for } j \in \{1, 2, 3\}, t \geq 0 \quad (10)$$

where $h(t)$ is the number of hours in t years, r_j is the percentage of each mode per year, and c is electricity cost per kWh. The use cost of the consumer is the sum of the cost spent at the three modes, as shown in Equation (11).

$$C_U(t) = \sum_{j=1}^3 U_j(t), \quad t \geq 0 \quad (11)$$

2.2.3. Repair Cost Modeling

The product repair cost is defined as the cost it takes to repair the product as time passes. We do not consider the product warranty, as shown in Equation (12).

$$C_R(t) = R \times f(t) \quad (12)$$

where R is denoted as the total repair cost of the product during the holding time and f is the cumulative failure rate of the product in holding time, and we use a quadratic function of time to simulate it, as shown in Equation (13).

$$f(t) = g \times t^2 + h \times t + v \quad (13)$$

where g and h are coefficients and v is a constant value that we obtain from a curve fitting method.

2.2.4. Recycling Awards

The product recycling award, which is a function of time, is defined as an award given by the recycler for the used product recycled from the consumer due to the residual value of the used product. Based on the recovery option of the EOL product [29–31], the recovery option can be divided into three recovery types; product reuse, part reuse, and material recycling. Each recovery type could be applied to the Gazelle model on the website [32], where both the length of time used and the current product conditions are considered to estimate the amount of recycling awards, and the result is used as an important reference in this study.

2.3. Consumer Value Assessment Model

Zheithaml [33] defined the value of consumer (V_C) as the consumer's overall assessment of product utility based on the perceptions of what is received and what is given, as shown in Equation (14). The receipts (R_C) cover functionality, quality, or personal value obtained by the customer and positive feelings sensed by the customer; whereas the contributions (C_C) cover the money, time, or effort given by the customer and negative feelings sensed by the customer.

$$V_C = \frac{R_C}{C_C} \quad (14)$$

In this study, a consumer value assessment model is developed and we define the product value (V_P) obtained by the customer, as shown in Equation (1), as the receipts of the customer, R_C . TCO is used to represent customer contribution, C_C , as shown in Equation (8). Then the customer value for different consumer use patterns i is a function of time t and can be defined as Equation (15).

$$V_{Ci}(t) = \frac{V_{Pi}(t)}{TCO_i(t)} \quad (15)$$

where $V_{Pi}(t)$ represents the value of the product receipt with a different consumer pattern of usage i in holding time t , while $TCO_i(t)$ is the total cost of the product contributed. This study explores the value of $V_{Ci}(t)$ from the time of the product purchased to determine when is the best time to recycle the product for different use pattern consumers, which can benefit both the customer and the environment.

3. Numerical Illustration

To recap from Kwak et al. [6], the typical laptop wear-out lifespan is around 3–5 years, but people tend to keep their laptops for an average storing time of 11 years without using them. The main reason is because notebooks are smaller in size and easier to store. When new replacements are purchased, consumers usually keep the old ones at home instead of recycling them right away. Notebooks have a higher replacement rate, and most of the replaced products are still functional and have high residual values. If the consumer does not recycle her or his product at the right time, then its value will decline over time. It will have negative effects on the economy and the environment. To illustrate the applicability of the proposed model, a simplified numerical study has been conducted. This study aims to develop a model to help users determine the optimal take-back time. We take notebooks as our research target. The following will explicate the illustration process.

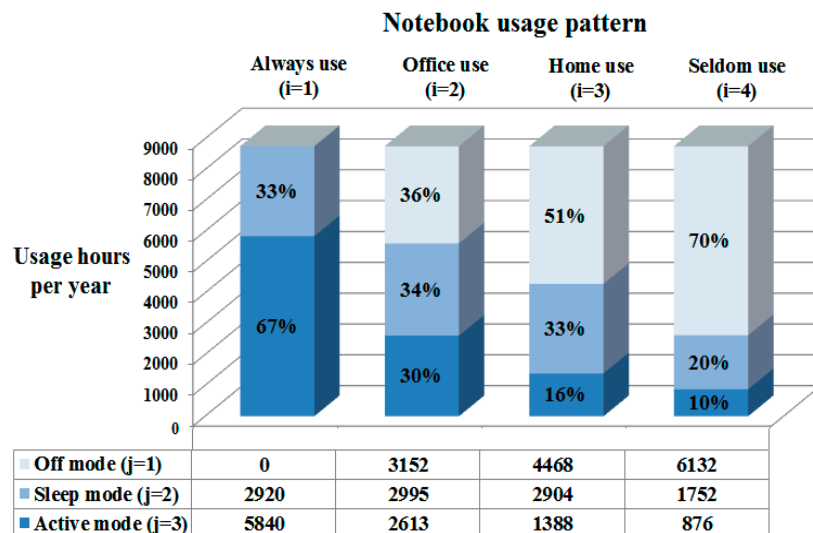
3.1. Description of Evaluated Product and Consumer Groups

In this study, the oldest 13.3-inch MacBook Air is used as the evaluated product, and two reference products with the same size are selected as reference products. Table 1 indicates the specification data of the evaluated product and reference products.

Table 1. Product specification of evaluated product and reference product [34].

	Evaluated Product (E_p)	Reference Product (R_p)	Reference Product (R_p)
Introduction date	8 June 2009	11 June 2012	9 March 2015
Processor Type (Speed)	Intel Core 2 Duo SL9400 (1.86 GHz)	Intel Core i5-3427U (1.8 GHz)	Intel Core i5-5250U (1.6 GHz)
RAM Type (Speed)	DDR3 SDRAM 2 GB (1066 MHz)	DDR3L SDRAM 4 GB (1600 MHz)	DDR3L SDRAM 8 GB (1600 MHz)
Video Card	NVIDIA GeForce 9400 M	Intel HD 4000	HD Graphics 6000
Display (Resolution)	13.3" (1280 × 800)	13.3" (1440 × 900)	13.3" (1440 × 900)
Hard Drive	120 GB (4200 RPM)	256 GB SSD	256 GB SSD
USB Ports	1 (USB 2.0)	2 (USB 3.0)	2 (USB 3.0)
Battery life	5 h	7 h	12 h
Dimensions (H × W × D)	1.94 × 32.5 × 22.7 (cm)	1.7 × 32.5 × 22.7 (cm)	0.68 × 12.8 × 8.94 (cm)
System Weight	1.36 kg	1.35 kg	1.35 kg
Original Price	US\$1299	US\$1299	US\$1199

According to the EuP Lot3 investigation report, there are two types of consumer product usage patterns; an office use pattern and a home use pattern [28]. In this study, we add two more usage patterns an always use pattern as the upper bound and a ‘seldom use’ pattern as the lower bound of the usage patterns. We explore the consumer value and optimal product take-back time for four different consumer groups and show each usage pattern as a percentage of the number of hours per year in Figure 4. The ‘always use’ customers spend 5840 h (67%) in the active mode and 2920 h (33%) in the sleep mode, and these two modes totally cover the hours in a year (8760 h); namely, they leave the computer powered on all the time. The ‘seldom use’ customers spend 876 h (10%) in the active mode, 1752 h (20%) in the sleep mode, and 6132 h (70%) in the off mode; namely, they let the computer power off most of time and only use the computer 10% of the whole time.

**Figure 4.** Product usage patterns of the notebook computer.

3.2. Calculation of Product Value

Base on the data shown in Figure 4, in this example, the use frequency percentages of the product for the always use (F_1), use in the office (F_2), use at home (F_3), and seldom use (F_4) patterns are set to 100%, 64%, 49%, and 30%, respectively.

The functional deterioration value over time is obtained by the Factor T that we modified, as shown in Table 2; here the key specification items are based on a consumer survey report from the Market Intelligence and Consulting Institute [35]. Nine elements to which consumers pay more attention in terms of product specifications were identified as the key specifications of notebooks; they are Processor/RAM, Video Card, Display, Hard drive, USB ports, Battery, Dimensions, and Weight. The last two specifications are smaller for having better performance; the others are the opposite. Using Equations (5)–(7), we can obtain that the functional deterioration value of the evaluated product declines from 1 to 0.508 after 3 years and to 0.262 after 6 years. Use Equation (2) to obtain the functional deterioration value rate, α , which is 0.225. Figure 5 shows the curve of the product functional deterioration.

Table 2. Value of overall functional deterioration.

Specifications	Performance	Unit	Ep_m	Rp_m	Dp_m	W_m
CPU/RAM	Geekbench Performance ¹	Score↑	2701	6757	0.40	0.34
Graphic Card	PassMark G3D Rating ²	Score↑	124	474	0.26	0.13
Display	Resolution	Pixel↑	1,024,000	1,296,000	0.79	0.17
Hard Drive	PassMark Disk Rating ³	GB↑	181	3887	0.05	0.09
USB Ports	Date Transfer Speed	Gbps↑	0.96	10	0.10	0.01
Battery	Max. Battery Life	Hours↑	5	7	0.71	0.15
Dimensions	Max. High	Cm↓	1.94	1.7	0.88	0.03
Weight	Avg. Weight	Kg↓	1.36	1.35	0.99	0.09

¹ Geekbench uses a number of different benchmarks to measure performance, which included Integer Performance, Loathing Point Performance, Memory Performance, and Stream Performance [36]; ² G3D Rating conducts three different tests and then averages the results together to determine the PassMark 3D Mark for a system [37]; ³ Disk rating conducts three different tests, Disk Sequential Read, Disk Sequential Write, and Disk Random Seek RW, and finally averages the results together to determine the PassMark Disk Mark for a system.

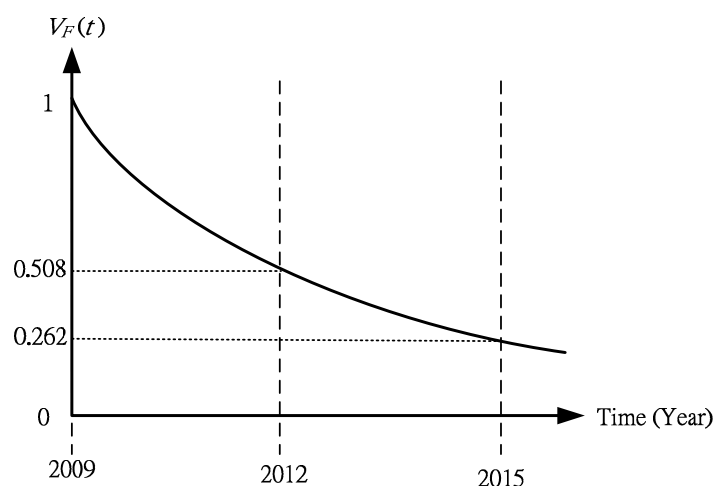


Figure 5. Functional deterioration value rate, α .

According to are port from Apple [38], the average physical life of a notebook computer is 7 years, and we take this data to project other consumer groups' average physical life; always use (N_1), use in the office (N_2), use at home(N_3), and seldom use (N_4) are set to 4.5, 6.3, 8, and 12 years, respectively. The rates of physical value deterioration, β , discussed in Equation (3) can be calculated from Equation (16), which are 0.222, 0.101, 0.061, and 0.025, respectively, for the different consumer groups. The notebook computer product value of different consumer groups with holding time is shown in Figure 6. With an increase in the frequency of use, the value of the product decreases over time. When the holding time reaches the products maximum physical life (lifespan), the value of the product will become stagnant.

$$\beta = \frac{F}{N} \quad (16)$$

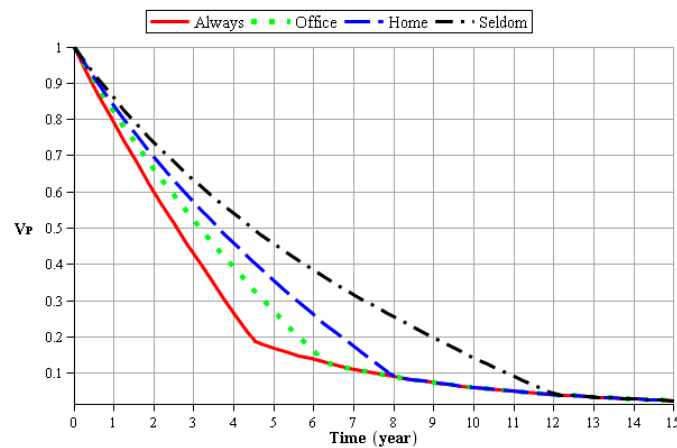


Figure 6. The product value for various consumer groups.

3.3. Calculation of TCO

3.3.1. Purchase, Use, and Repair Cost

The product purchase cost of a notebook, P , is the price as shown on Apple's official website [34] and is assumed to be $P = \text{US\$}1299$. Figure 7 shows the holding value of different consumer groups over time. When the frequency of use increases, the amortization cost increases with time and the market value decreases with time.

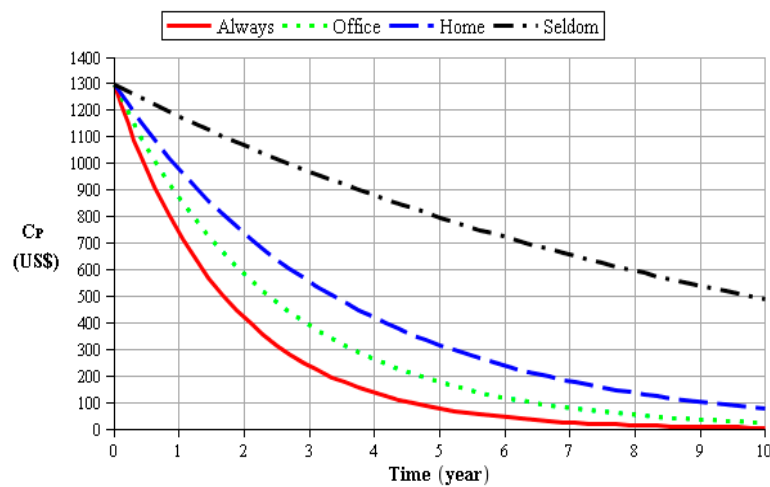


Figure 7. The purchase cost varies over time for various consumer groups.

Based on the data from the International Energy Agency (IEA) [39], in Equation (11) we use $c = \text{US\$}0.125 / \text{kWh}$ for the price of electricity in USA. The average power consumption for each operation mode and the annual power consumption cost of different consumer groups are shown in Table 3.

Table 3. Power consumption for the evaluated product.

Operational Modes	Electricity Used (kW) *	Annual Power Consumption Cost (US\$)			
		Always Use	Office Use	Home Use	Seldom Use
Off (kW1)	0.00056	0	0.176	0.250	0.441
Sleep (kW2)	0.00102	0.327	0.335	0.325	0.049
Active (kW3)	0.0131	7.708	3.449	1.832	0.576
Total	-----	8.035	3.961	2.407	1.068

Moreover, assume that the average maintenance fee, R , of a notebook computer is US\$175 within the product's cycle life. On the other hand, the survey by the notebook computer warranty provider Square Trade [40] in America indicates that the malfunction rate of the evaluated product in the first year is 5.8%, and this goes up to 25.1% after using the computer for 3 years. The components like keyboards, pointer devices, media drives, and hard drives are all mechanical components that wear out when subjected to heavy use. As a result, we determine the malfunction rate curve, $f(t)$, by curve fitting. In the case of the home use model, the accumulative malfunction rate will be 100% when the product used for 7 years, as shown in Figure 8.

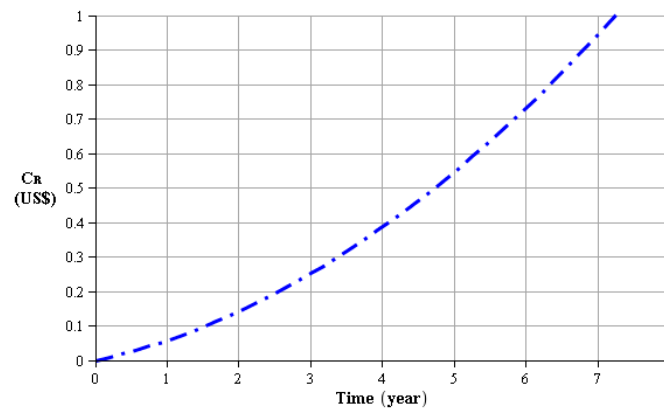


Figure 8. Accumulative malfunction rate over time.

Figure 9 presents the time variation value for the purchase cost ($C_P(t)$), use cost ($C_U(t)$) and repair cost ($C_R(t)$) for the different consumer groups. $C_P(t)$ is a decreasing function with respect to time, while $C_U(t)$ is a horizontal straight line and $C_R(t)$ is an increasing function. The aggregate effects of these three costs form a concave function. As the frequency of usage increases, the amortization for the $C_P(t)$ will increase relatively, and the declining rate of the $C_P(t)$ is faster than the increasing rate of the $C_R(t)$. As a result, the lowest point of the curve of $C_P(t) + C_U(t) + C_R(t)$ (concave function) will be reached earlier as the frequency of usage increases more.

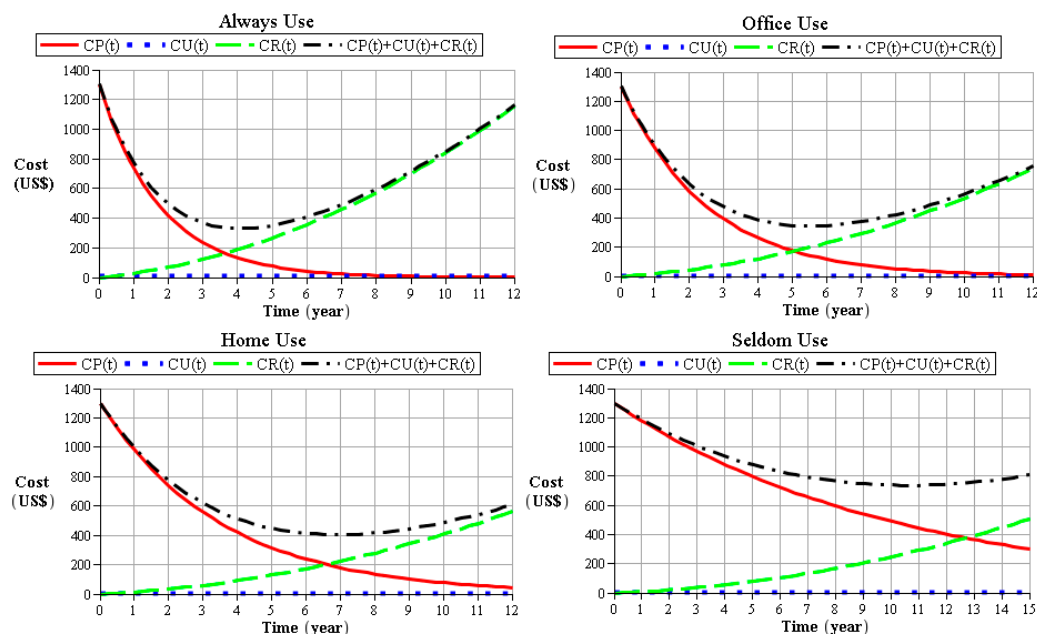


Figure 9. The purchase, use, and repair costs change over time for various consumer groups.

3.3.2. Recycling Award

Different countries may have different recycling award regulations for returned products (cores). Consumers could negotiate the award money with the recyclers through market mechanisms. Basically, there are two kinds of recycling award scenarios; Scenario 1 assumes that the recycling award is fixed no matter how good the product condition is or whether its age is young or old, whereas Scenario 2 assumes variable recycling awards, namely, different awards for products with different conditions and ages. For the fixed recycling award scenario, it reduces recycling incentives and leads to the result that the consumers tend to store their products, even if they no longer use them. Figure 10 shows a recycling award, A_R , for two recycling award scenarios, and the data are adopted from the Gazelle website [32]. We will investigate the relationship between the recycling awards and the consumer values by comparing the results of these two scenarios in the following section.

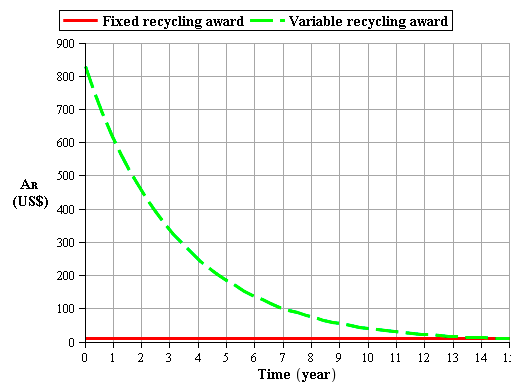


Figure 10. Recycling award, A_R , for two recycling award scenarios.

In the fixed recycling award scenario, TCO behaves similarly to $C_P(t) + C_U(t) + C_R(t)$ in Figure 9, and the lowest point of the curve of TCO is reached earlier as the frequency of usage increases more, as shown in Figure 11. In the variable recycling award scenario, the product groups of always used, used in the office, used at home, and seldom used have their lowest TCO at the holding time of 2.55, 3.47, 4.36, and 5.46 years, respectively. With a higher frequency of use, the greater is the decline of TCO compared with the fixed recycling awards scenario. This is because the variable recycling award is a decreasing function over time; the earlier the consumer recycles her or his product, the higher is the award.

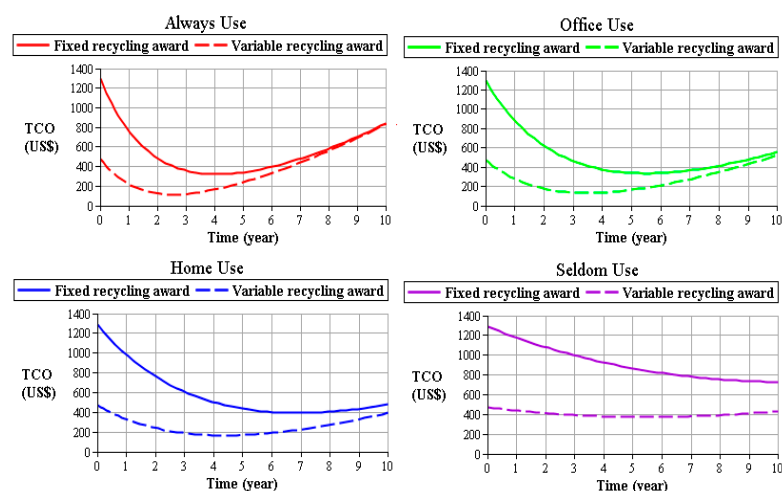


Figure 11. Total cost of ownership (TCO) for various consumer groups with two recycling award scenarios.

3.4. Optimal Take-Back Time of Product

In this study, the Maple 13 software is used for optimization. Figure 12 shows the consumer value of four consumer groups with fixed and variable recycling award scenarios. With a higher frequency of use, the highest point of the $V_C(t)$ occurs earlier for both scenarios. In the variable scenario, each consumer group also attains a higher consumer value in advance compared with the fixed scenario, and this scenario will motivate the customers to recycle their unused products as soon as possible.

In order to understand consumer value better, this study defines relative consumer value, $V_{Ci}'(t)$, for use group i , as shown in Equation (17), which uses the initial consumer value ($V_{Ci}(0)$) as a reference to calculate the ratio of $V_{Ci}(t)$ to $V_{Ci}(0)$.

$$V_{Ci}'(t) = \frac{V_{Ci}(t)}{V_{Ci}(0)} \text{ for group } i \quad (17)$$

where $V_{Ci}'(0) = 1$. When $V_{Ci}'(t)$ is greater than 1, it represents how much the consumer value increases compared with the initial consumer value.

Figure 13 shows that $V_{Ci}'(t)$ increases from $V_{Ci}'(0)$ then reaches its maximum value at T_1 . After it reaches the maximum value, it starts to go down to reach $V_{Ci}'(0)$ again at T_2 , then its value will keep going down and the value becomes less than 1. Except for the seldom use group, all other groups behave similarly, as described above, for both recycling award scenarios. For the variable recycling award scenario, all use groups have higher maximum relative consumer value and shorter T_1 and T_2 compared with the fixed recycling award scenario, as shown in Figure 13 and Table 4. Since at T_1 , the customer has maximum consumer value and at T_2 the customer value goes back to its initial consumer value, this study suggests that the customer can take T_1 and T_2 as important factors to determine the optimal take-back time. For the customer that likes to use new (or like new) products all the time, she or he can choose T_1 to recycle his product; the ordinary customer can choose T_2 (or an approximate time) to recycle their product. Table 4 demonstrates $V_{Ci}'(T_1)$ and $V_{Ci}'(T_2)$ for various usage patterns in two recycling award scenarios and illustrates that those use groups with a higher frequency of use have shorter value for T_1 and T_2 and a higher value for maximum consumer value. Under fixed recycle awards scenarios, the take-back times for always users, office users, and home users are 4.11, 5.08, and 5.25 years, respectively. On the other hand, under variable recycle awards scenarios, we offer higher awards to those who recycle their products earlier. Therefore, there is a significant change on the optimal take-back time; 3.72 years, 4.59 years, and 4.93 years, respectively. The results imply that the variable recycling award scenario is a better strategy than the fixed recycling award scenario. Moreover, it encourages the consumers to recycle their products in advance when they no longer use them. Different usage frequency groups have different best timing to recycle their products. For the customers in the seldom use group, the results suggest that it is better for them to recycle their product right after they have bought the product; namely, they do not need to buy the product or they can rent the product.

Table 4. Relative customer value and take-back time for various consumer groups with two recycling award scenarios. (Unit of T_1 and T_2 : Year).

		Fixed Scenario	Variable Scenario	Difference
Always Use	$T_1(V_{Ci}')$	2.37 (1.63)	2.04 (2.32)	−0.33 (+42%)
	T_2	4.11	3.72	−0.39
Office Use	$T_1(V_{Ci}')$	2.96 (1.45)	2.57 (1.86)	−0.39 (+28%)
	T_2	5.08	4.59	−0.49
Home Use	$T_1(V_{Ci}')$	3.04 (1.21)	2.80 (1.42)	−0.24 (+17%)
	T_2	5.25	4.93	−0.32
Seldom Use	$T_1(V_{Ci}')$	0 (1)	0 (1)	0 (+0%)
	T_2	0	0	0

Maximum consumer value occurs at T_1 , consumer value goes back to $V_{Ci}'(0)$ at T_2 .

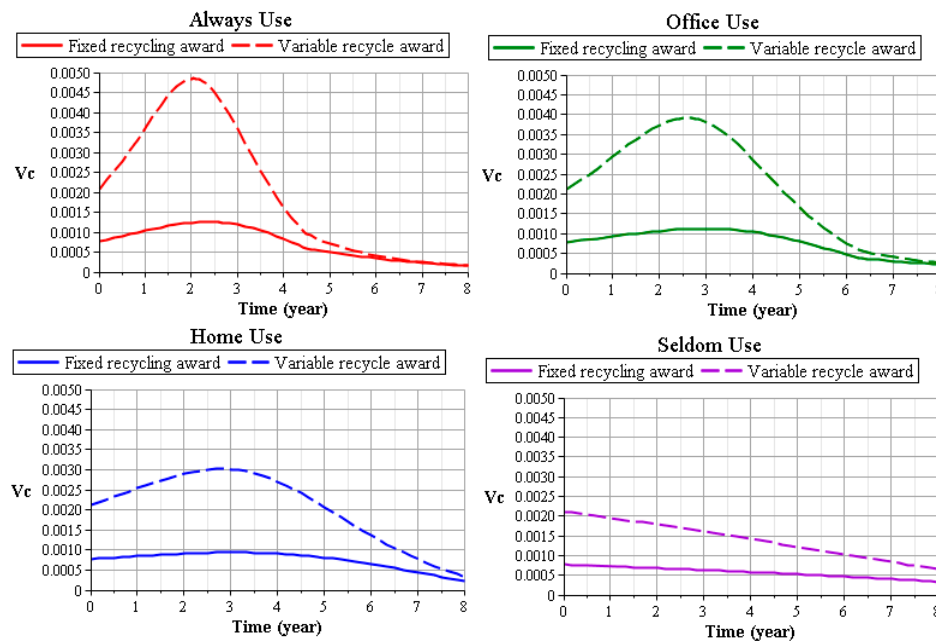


Figure 12. The consumer value for various consumer groups with two recycling award scenarios.

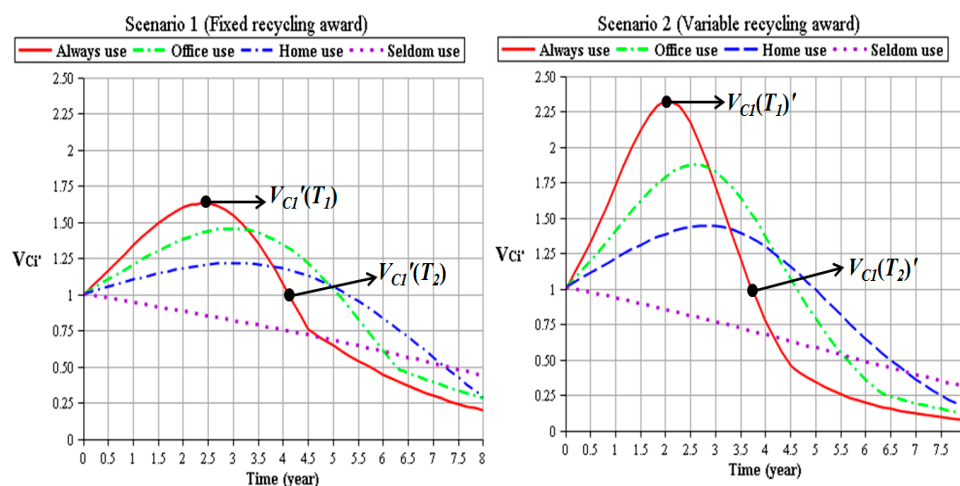


Figure 13. Optimal take-back time of the product for different consumer groups with two recycling award scenarios.

4. Conclusions

The study proposed a consumer value assessment model, which is a function of time, and could help consumers to understand how value changes during the holding period and to determine whether the product is worth keeping or should be recycled. The optimal product take-back time with consideration of consumer value can be determined when the consumer value decreases below its original value and when the cost of consumers keeping the product exceeds the value received and it is no longer worth keeping for economic benefit.

The study found that there are two main factors affecting the optimal take-back time; namely, the usage hours of laptop and the recycling award of used products. There are two different recycling award schemes, fixed and variable recycling awards. A fixed recycling award, executed in most countries, only gives a fixed amount of award for recycling, which does not consider the quality and life of the used products. This award offers an insufficient amount of incentive and cannot induce consumers to recycle laptops that are no longer in use, whereas, with a variable recycling award,

consumers could become more willing to recycle the used product at an earlier time to receive a better award. This variable award scheme can promote higher product residual values as social resource use and can reduce the negative impact on the environment. It is highly suggested to governments for their policy making in future.

We believe that the result of this study can help consumers to calculate the optimal take-back time for their product as well as the consumer value when they input their product specifications and conditions. In addition, the result enables consumers to compare different products in the same category for a reference of future purchase. Upon data mining with the offered information, we expect that manufacturers may exploit environmentally friendly products that possess higher consumer value.

Although this study has taken care of many issues, there is still more research needed. For example, an extension of our model can be applied to different brands or types of laptop or even different products. Moreover, the effects of government subsidy on different recycling award schemes are also interesting to study.

Acknowledgments: This work is supported in part by the Ministry of Science and Technology of Republic of China under the grant MOST 105-2221-E-033-044.

Author Contributions: Both authors designed the research and wrote the paper. Yi-Tse Fang collected and analyzed the data. Hsin Rau controlled the quality assurance.

Conflicts of Interest: The authors declare no conflict of interest.

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