Reducing Component Time to Dispose through Gained Life

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Abstract

At the end of the useful life of a component, it becomes liable to being disposed by its owner or the servicing engineer of the system to which the component belongs. Although recycling agencies exist, not all components are currently recyclable. More so, some of those rated as eco-friendly may have been self-rated and user-verification of such claim may be difficult. One way to extending the useful life of a component is through the act of maintenance. In accordance with the age reduction model, component age is rejuvenated, implying age gained at each maintenance stage. Thus, the estimation of component extended life becomes possible; suggesting that component time to dispose can be delayed. Consequently, this reduces e-waste where the rate of concentration of greenhouse gases into the food chain and atmosphere is reduced.

Keywords: *Green computing, green IT, preventive maintenance, eco-friendly*

1. Introduction

Anything that has a beginning surely has an end. This is true for both natural and artificial objects. The beginning can be termed as beginning of life (BoL) and the end as end of life (EoL). What occurs at the end of life is limited to the activities that took place before the beginning of life or in simple terms the make up of the object. Hence, the field of computing and engineering can learn from nature. One of many practical examples is how nature recycles water [1]. Basically, as sunlight falls on the rivers, lakes, seas, ocean, etc, the water particles become high in energy and individually evaporate into the air. The higher they ascend into air, the cooler they become and therefore their energy levels drop. This increases the force of cohesion existing among them and thereby making it possible for the formation of clouds. The clouds in-turn falls to the earth as rain, snow or hail. The process is repeated and goes on and on.

Although some IT products are rated as eco-friendly, some of these ratings are self acclaimed by their manufacturers and not by an independent third party organisation [2]. Also, there is no suggestion in literature that indicates any product being 100% recyclable. A 100% recyclable product is one for which all its parts can be recycled without creating dangerous waste to the environment. Over the years, there has been increase of up to 70% - 89% in recycling rate [3]. However, the metric used focused on the societal compliance to recycling regulations or programmes and not on the products themselves. Though, the regulations and programmes are themselves very essential in promoting environmental friendly society and to mount pressure on manufacturers in producing eco-friendly products. As such, manufacturers are under increasing pressure from both governments and environmentally focused groups to ‘reduce’, ‘recycle’ and ‘reuse’ their industrial waste. These regulations make the Original Equipment Manufacturer (OEM) responsible for the end-of-life treatment of their products [4].

With no suggestion that IT products are 100% (if any) recyclable, it therefore becomes of interest to focus on the products by investigating ways through which their eco-friendliness could be improved. One of such focus is on the end of life of an IT product. The longer the end of life, the longer it takes for the product to be disposed, and this is what this paper precisely addresses through imperfect preventive maintenance (IPM) policy.

In section 2, green computing is introduced, where associated challenges and solutions are discussed. In section 3, the effect of maintenance is discussed, where component extended useful life and total cost per unit time are modelled. Section 4 presents the evaluation of the established models on a given component of IT product. In section 5, conclusions are drawn with proposed further work.

2. Green Computing

Green computing is an emerging field that is concerned with how IT products are used and disposed to reducing the concentration of greenhouse gases entering the food chain and the atmosphere. This could be made easier if IT products are designed with environmental friendliness in mind.

Greenhouse gases are gases in the Earth's atmosphere which allow sunlight to pass freely through the atmosphere and to eventually hit the Earth [5]. As it hits the Earth's surface, some of the sunlight is reflected back towards space as infrared radiation or simply as heat. Over time, the amount of energy striking the Earth's surface should be about the same as the amount reflected back into space, leaving the temperature of the Earth's surface roughly constant. However, the presence of greenhouse gases affects this balance by absorbing the infrared radiation and thereby trapping the heat in the atmosphere. The more the concentration of greenhouse gases in the atmosphere, the more the Earth's temperature rises; this is the concept of global warming.

Some of the greenhouse gases which enter the atmosphere partly or fully due to human activities are Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O) and Fluorinated gases [5][6]. These are further described as follows.

Carbon Dioxide: This gas enters the atmosphere through the burning of fossil fuels (oil, natural gas and coal), solid waste, and also as a result of other chemical reactions (such as those in manufacturing industries). Although the amount of carbon dioxide is reduced in the atmosphere when it is absorbed by plants during photosynthesis, about 3.2 billion metric tons is added to the Earth's atmosphere annually and this imbalance between emissions and absorption results in the continuing growth in greenhouse gases in the atmosphere [5].

Methane: This enters the atmosphere during the production and transport of coal, natural gas, oil and also from the decay of organic waste in solid waste landfills.

Nitrous Oxide: This is emitted through agricultural and industrial activities, and also through combustion of fossil fuels and solid waste.

Fluorinated Gases: These gases are created and emitted solely through human activities. This includes variety of industrial processes. Some of these gases are hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride.

2.1. Challenges

The challenges of green computing refer to addressing those issues or activities which are computer related and have negative effects on the ecosystem (human, animal, plant and environment). This implies that any activity involving computing or its product in any form which increases the amount of greenhouse gases or a threat on human, animal or plant life should be seen as a challenge. These challenges are discussed next.

2.1.1. Disposal of IT products: The disposal of IT products refers to the discarding of such product. A user may dispose of an IT product due to one of the following.

- The product reached its end of useful life
- The reliability or functional performance of the product has degraded to a level below its user's acceptance
- The user looses interest in the product, likely due to prolonged use or the desire for a newer version

IT products are electronic devices, and so the effects of their disposal are same as other electronic products and constitute what is termed as e-waste (electronic waste). The specific dangers of e-waste are the effects of toxic chemicals such as lead, cadmium, mercury, hexavalent chromium IV, PVC plastics, and brominated flame retardants have on human health and the environment [9][10]. Lead, mercury, chromium and brominated flame retardants are the greatest toxins in quantity and are likely to cause the most adverse health effects in humans [10]. These toxic wastes are further discussed as follows.

Lead: Lead is found in the soldering of printed circuit boards, batteries and cathode ray tubes (CRT) [11]. It is known to affect the central and peripheral nervous system. It also has a serious negative effect on the brain development in children [9] and can also cause slowed growth, hearing problems, and behaviour and learning problems [10].

Mercury: Mercury is found in position sensors, relays and switches on printed circuit boards. It is also found in medical equipment, data transmission devices, telecommunications devices, mobile phones and batteries [9]. Mercury is also found in fluorescent lamps that provide backlighting in LCDs and some alkaline batteries [11]. The health hazards of mercury are decrease in cognitive abilities, memory, attention, language and respiratory failure [10].

Hexavalent Chromium IV: Hexavalent chromium IV is used as corrosion protection of untreated and galvanized steel plates in electronic products. It is known to damage DNA and has also been linked to asthmatic bronchitis [9]. Other health effects associated with hexavalent chromium IV exposure include skin irritation and ulceration, asthma and respiratory irritation, perforated eardrums, kidney damage, liver damage, discoloration of the teeth etc, a long-term effect of hexavalent chromium IV in body tissues is possibility of cancerous growth [10]. Examples of IT products where hexavalent chromium IV is found are Data tapes and floppy-disks [11].

Brominated Flame Retardants: Brominated flame retardants are used for reducing flammability in electronic products. They are used in four areas of application in IT products; printed circuit boards, components such as connectors, plastic covers and cables [9]. Brominated flame retardant such as *Polybrominated biphenyls* may increase cancer risk to the digestive and lymph systems [10].

Unwanted IT products are usually disposed as municipal solid waste in landfills and garbage dumps. The toxic chemicals contained in e-waste are capable of leaching into the soil which then enters into the food chain. Another form of leach is ash into space through incineration. Hence disposal of IT products is of challenge to its stakeholders.

2.1.2. The use of IT products: The challenge in the use of IT products lies in the manner in which an individual or group of individuals uses computer systems. The use of IT products is primarily concerned with the consumption of electricity. Contemporary PCs are by far more powerful and smaller in size compared to those of yesteryears such as the mainframes. Also in terms of electricity consumption, PCs consume about 110W - 300W as opposed to the roughly 150,000W consumed by earlier general purpose computers [12]. However, owing to the use of computer systems in achieving simple tasks such as word processing to more complex ones such as banking applications, there is perpetual increase in the numbers of computer users. According to current existing statistics, there are about 850 million PCs in use and these consume an immense amount of electricity, most of which is provided by burning fossil fuels [12]. This process releases greenhouse gases such as sulfur and carbon dioxide into the atmosphere, and hence it contributes to the concentration of greenhouse gases in the atmosphere. These emissions have the risk of causing respiratory disease, smog, acid rain, and of course global climate change.

2.1.3. Handling of IT products: The handling of IT products refers to the way in which such products are stored (or kept), carried around if necessary and generally cared for. The major concern here is that the poor the handling, the more likely it is for the product to sooner depreciate in its form, reliability and performance, and therefore instigate disposal.

2.2. Advances

Although challenges do exist in green computing, there have been advances in the field. Some of these advances are discussed.

2.2.1. Recycling of IT products: Recycling of IT products is the process by which such products (particularly used ones) are either utilised in the production of new products (related or non related to the old) or disposed in such a way that is useful to the food chain. Recycling is aimed at (i) reducing the amount of greenhouse gases caused by incineration of IT products, (ii) reducing the amount of disposal, and (iii) reducing the need to using virgin raw materials in the production of new products. The emergence of biodegradable computer peripherals has made it possible to dispose such devices by burying them [13], after which they decompose into useful plant nutrients.

The act of recycling has drawn government interest where some nations have passed regulations. In the United Kingdom for instance, the WEEE (Waste Electrical and Electronic Equipment) Directive was introduced in 2007 which aims to reduce the amount of electrical and electronic equipment disposal into landfills and to promote recycling of such products [14].

In the United States of America, the State of California passed e-waste legislation in 2003, and since then 24 other states have followed the suit. Among the 24 states is the State of Utah in 2011, more States are expected to follow [7]. Also, information on the recycling of electronic products and listing of links to organisations that are involved in disposing computers is made available on the U.S. Environmental Protection Agency website (http://www.epa.gov/epawaste/conserve/materials/ecycling/index.htm).

2.2.2. Power saving approaches: The power (electricity) saving is an approach that provides support for reducing the amount of power consumed by computers, especially personal computers (PCs). The benefit of this approach is a double saving; it saves (i) cost on electricity bills, and (ii) the environment by reducing the amount of fossil oil needed in producing the required power. Computer systems provide several ways to achieving energy efficiency. There exist power-saving standard that applies to PCs and operating systems describing how a computer can be put into a power-saving mode [8]. This standard has what is called the *advanced configuration and power interface* (ACPI). The ACPI hands the control of power management to the operating system. A computer that complies with ACPI can exist in one of several power modes referred to as G0, G1, G2 and G3. A description of the power-saving modes is here briefly presented.

G0: In this mode, the computer operates in full working state. However some devices may be placed into low-power mode if they are not actively in use. In laptops this tends to occur when running on battery and usually for noise reduction in desktops.

G1: This is referred to as sleep mode and is activated when the computer is idle. This mode can save a significant amount of power. G1 is subdivided into four levels S1 - S4, ranging from the least power saving but quickest to return to full working mode, to the most power saving but slower to return to full working mode.

G1 is obviously the power-saving mode which a computer user can make changes within the operating system. In the S1 sleep mode, the execution of any instruction in the processor is stopped. However, power still flows to the RAM and CPU, and therefore less energy is conserved but it is very quick to awaken from sleep. Few modern PCs support S1. In S2 the processor is powered down, and it is slightly a deeper sleep than in S1. S1 is pretty uncommon.

In S3, the computer can return to the previous state it was in before it went into sleep. This is achieved by allowing the flow of power to the RAM while the processor, display, hard drives and other unnecessary components are powered down. In Microsoft Windows terms, S3 is known as standby. S3 is useful in scenario where a computer will be inactive for a short period of time. In S4, the content of the RAM is transferred to the hard disk so that the memory can be powered down. If a power cut occurs while in S4, contents of opened files remain intact. S4 is also referred to as hibernation.

G2: is referred to as the soft off mode and it is active when a computer is turned off using the operating system while the computer remains unplugged. Computers in this power-saving mode still draw power from the mains. For instance keyboard, USB ports, power supply, motherboard and all expansion cards are still powered in this mode. An average computer is known to consume about 22W of energy in G2.

G3: This is the power-saving mode in which the power has been completely detached or removed from the computer. The computer enters this mode at about 20 seconds after the power is unplugged. This mode is very helpful especially when the computer will not be used for an extended period of time.

In addition to the power-saving modes discussed, it is also possible with I*ntel vPro Technology* to control the time of day to shut down or power on computers [15]. One of several areas where this is useful is setting a time of the day at which to connect to an office or school network for an update during a time that is considered to be of less network traffic.

2.2.3. Desktop virtualization – reviving the past: Virtualisation is a technique for sharing the resource of a computer using a variety of hardware and software abstraction techniques. Its concept has existed in the past, dating back in the 1960s [16]. In desktop virtualisation, resources e.g. operating system, application programs, etc are featured on one physical machine where users have access to through the use of other hardware. For instance each user's monitor, keyboard, and mouse are connected to the shared machine through a small and durable access device [12]. In the past, virtualisation was inspired by the high cost of machines and relatively scarce resources. Soon after, virtualisation went into silence following the emergence of PCs which are cheaper, and so are the application programs. Virtualisation has re-erupted following the need to harnessing the increasing computing power of PCs [12]. Virtualisation is also seen as an approach to reducing energy consumption, most especially in an environment consisting of multi-users. The concept of desktop virtualisation is illustrated in Figure 1.

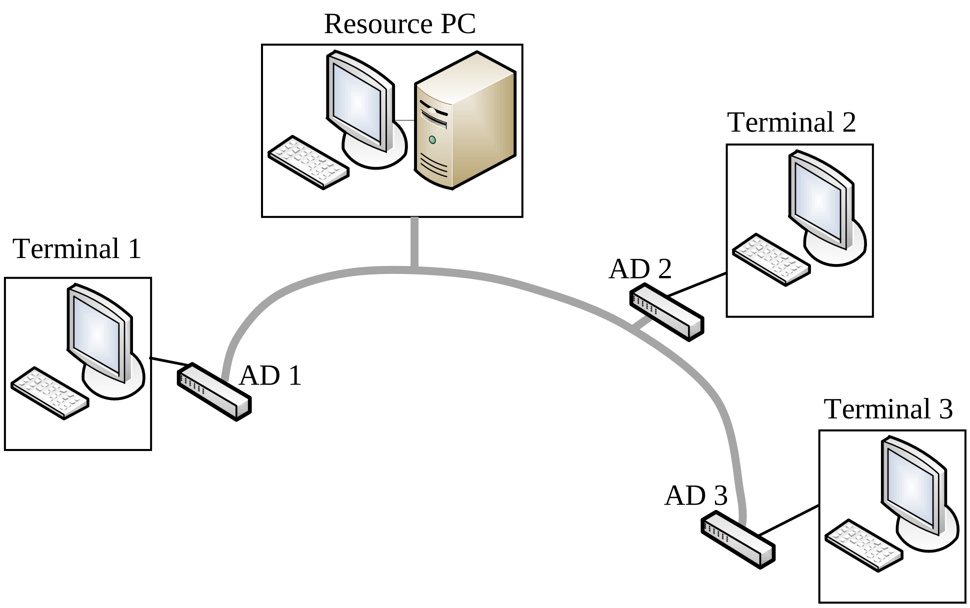

Figure 1. Concept of Desktop Virtualisation

In Figure 1, each user terminal (i.e. Terminal 1, Terminal 2 and Terminal 3) is connected to the shared PC (i.e. Resource PC) through an access device (i.e. AD 1, AD 2 and AD 3). Such access device could be for instance the NComputing access device, where the device itself has no CPU, memory, or moving parts and so it is easy to deploy and maintain [12].

3. Maintenance as a Factor in Green Computing

In the advances of green computing discussed in this paper, there appears to be reasonable level of progress in addressing the identified challenges of green computing with the exception of *handling of IT products*. The handling of IT products includes the manner in which they are used and whether in accordance with manufacturer instructions, and how the product is cared for especially through maintenance. Two of the three reasons identified for component disposal are that the product reached its end of useful life or that the reliability or functional performance of the product has degraded to a level below its user's acceptance. An action that can influence these two reasons for product disposal is maintenance. Maintenance improves the reliability and performance of a product, and also slows down the aging of the component. This paper investigates the effect of maintenance on the longevity of IT products, specifically under imperfect preventive maintenance policy.

Typically, a component has a fixed life and Figure 2 demonstrates the segments of such [17][18]. The *burn in life* is the infancy stage of life where component mortality is high due to design flaws. Such flaws are normally corrected before marketing the product. The *useful life* is the period when the reliability of the component is stable, and it is also when the component is normally marketed to minimise both user and manufacturer cost (e.g. warranty). The *burn out life* is the period which is brought about by component aging, wear and tear, etc. It is therefore of interest if the useful life of a component can be extended through maintenance activities.

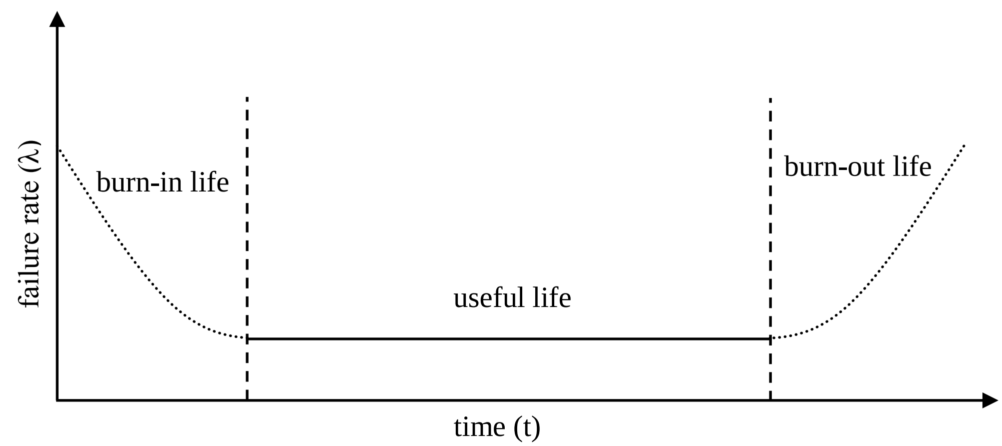

Figure 2. Segments of Component Life

Maintenance may consist of several activities including cleaning, topping, oiling, tightening, adjusting and minimal repair. Any or combination of these activities performed on a component slows down the rate at which its damage accumulates, thereby reducing the occurrence of its failure. Maintenance improves the reliability and availability of a component and that of its overall system [19]. When maintenance is planned and performed at fixed intervals, this is referred to as preventive maintenance (PM), and is the focus in this paper. PM activities are expected to be performed according to prescribed procedures and also at the appropriate time such that it is not too early or too late. The implication of performing PM too early is that component reliability is still at an acceptable level and cost may be incurred unnecessarily. If PM is however performed too late, the component may fail before the planned PM time.

In an earlier work in [20], Nggada et al investigated how component and system reliability and availability are improved based on the age reduction model under perfect preventive maintenance (PPM). In their later work in [21], the appropriate PM times for respective components of a system was addressed by optimising preventive maintenance schedules also under PPM. PM activities that restore the condition of a component to as good-as-new (GAN) is termed perfect preventive maintenance, whereas that which improves its condition to a certain degree is termed imperfect preventive maintenance [22][23]. When PM activities performed have no effect on the condition of the component, then this is termed bad-as-old (BAO) where the component continues to age normally [19]. This may suggest that the PM was performed:

(i) at inappropriate time,

(ii) not in accordance with prescribed procedure,

(iii) by non-skilful personnel, or

(iv) the component is beyond its useful life.

3.1. Effect of Maintenance on IT Products Longevity

In investigating the effect of maintenance on the longevity of IT products, this section seeks to establish that *PM can extend the useful life of a component* (or IT product) under IPM policy based on the proportional age reduction (PAR) model. Additionally, the total component cost per unit time under IPM is also investigated. This allows for comparisons of extended lives against respective costs.

The PAR model assumes that each maintenance activity reduces proportionally the age gained from previous maintenance [24]. This means that the component is made younger and the new age is referred to as *effective age*. The effectiveness of such gained age depends on the *improvement factor* f of the PM, where $0 \leq f \leq 1$. When $f = 1$, the PM results into GAN, whereas if $f = 0$ the PM results into BAO. The PAR model was first introduced by Malik [25] and this is frequently adopted in developing optimal maintenance policies due to its flexibility [26].

3.1.1. Age reduction and age gained following PM activities: According to equation 9 found in [24], PM activities conducted at the *j-th* PM stage and time t_j, with an improvement factor f_j reduces the component age W_j to:

$$W_j^+ = (1 - f_j)t_j \tag{1}$$

Where t_j is the time at which the *j-th* PM is carried out, the plus sign symbolises that the effect of age reduction applies only after the PM activity is completed.

By using equation 1, the component age after the first PM stage ($j = 1$) is:

$$W_1^+ = (1 - f_1)t_1 \tag{2}$$

Similarly, the age after the second PM stage ($j = 2$) is:

$$W_2^+ = W_1 + (1 - f_2)t_2 \tag{3}$$

By substituting equation 2 into 3, equation 3 is transformed into 4 as follows.

$$W_2^+ = (1 - f_1)t_1 + (1 - f_2)t_2 \tag{4}$$

Therefore by the principle of mathematical induction, the age of a component following n PM stages, with $t_0 = 0$, can be modelled as follows.

$$W_n^+ = \sum_{j=1}^{n} (1 - f_j)(t_j - t_{j-1}) \tag{5}$$

Under periodic maintenance, PM is performed at regular interval T_p, implying that $t_j = T_p$; $j = 1 .. n$. Equation 5 then reduces to 6. Equation 6 assumes a varying improvement factor, the concept of which is applicable in a real problem where the effectiveness of PM for some components may decrease with time due to the level of wear and tear. For components whose level of PM improvement is assumed to be constant, equation 6 can still be used in evaluating the effective age.

$$W_n^+ = \sum_{j=1}^{n} (1 - f_j) T_p \tag{6}$$

Considering the concept of improvement factor, the age of a component is reduced at each PM stage and thus age is gained, implying an elongation of component useful life. Assuming the useful life of a component is represented by L, new useful life by L_N and total gained life by X_T, then the following applies.

$$L_N = L + X_T \tag{7}$$

One assumption is that age is gained after each PM stage and the total age gained X_T is the summation of the ages gained after each PM stage throughout the useful life of the component.

After the first PM stage, the gained life X_{T_1} can be calculated as follows.

$$X_{T_1} = T_p - W_1^+ \qquad ; j = 1$$

$$X_{T_1} = T_p - (1 - f_1) T_p \qquad ; j = 1$$

$$X_{T_1} = T_p f_1 \qquad ; j = 1$$

After the second PM stage, the gained life X_{T_2} is calculated as follows.

$$X_{T_2} = X_{T_1} + T_p f_2 \qquad ; j = 2$$

$$X_{T_2} = T_p f_1 + T_p f_2 \qquad ; j = 2$$

In general the total gained life following *n* PM stages is as follows.

$$X_{T_n} = \sum_{j=1}^{n} f_j T_p \tag{8}$$

Equation 7 can then be transformed into equation 9 below, where $X_T = X_{T_n}$.

$$L_N = L + \sum_{j=1}^{n} f_j T_p \tag{9}$$

3.1.2. Component total cost per unit time under IPM: The total cost per unit time of a component can be estimated as follows.

$$C_T = \frac{\left(C_c + nC_{ipm} + C_{mr} \int_{W_{j-1}^{+}}^{W_i} \lambda(t)dt\right)}{nT_p} \tag{10}$$

Where C_T is the total component cost under IPM
C_c is the unit cost of the component (i.e. purchase cost)
C_{ipm} is the cost of performing IPM
C_{mr} is the cost of performing minimal repair
$\lambda(t)$ is the hazard rate of the component and thus $\int_{W_{j-1}^{+}}^{W_i} \lambda(t)dt$ gives the numbers of failure between the previous effective age and the current PM stage

According to equation 4.5 found in [23], $\lambda(t) = -\frac{dR(t)/dt}{R(t)}$ and therefore;

$$\int \lambda(t)dt = -\int \frac{dR(t)/dt}{R(t)} \tag{11}$$

Assuming component failure characteristics follow the Weibull distribution, then solving for equation 11 and using the limits of integration, the following is obtained.

$$\int_{W_{j-1}^{+}}^{W_i} \lambda(t)dt = \frac{1}{\theta^{\beta}} |t^{\beta}|_{W_{j-1}^{+}}^{W_j} \tag{12}$$

Hence, equation 10 becomes;

$$C_T = \frac{\left(C_c + nC_{ipm} + C_{mr}\left(\frac{1}{\theta^{\beta}} |t^{\beta}|_{W_{j-1}^{+}}^{W_j}\right)\right)}{nT_p} \tag{13}$$

Where β and θ are Weibull slope and scale parameter respectively.

3.1.3. Estimation of varying improvement factor: For a constant improvement factor, f_j ($j = 1 .. n$) is constant. In a situation where the value of the improvement factor is assumed to vary with time, its estimation is here proposed. The estimation is based on *improvement factor base time* T_0 and *initial improvement factor* f_0. T_0 is the time beyond which the value of the improvement factor begins to drop, while f_0 is the value of the improvement factor within such time. In this paper, the value of f_0 and T_0 are assumed to be specified by an expert. However, it is possible to calculated f_0 using Tsai et al's equation 7 found in [27].

To estimate the value of improvement factor f_j at the *j-th* PM stage, relationships can be defined with respect to f_0 and T_0. For instance, the value of f_0 can be set to monotonically decrease with time, where its value at t_j will equal f_j. In this paper, the value of f_j is mathematically defined as expressed in equation 14 with the precondition that for $t_j \leq T_0$, $f_j = f_0$.

$$f_j = \frac{T_0}{t_j} f_0 \tag{14}$$

4. Evaluations and Results

A virtual component was used to evaluate the findings. Firstly the effect of IPM on the extended useful life of the component was evaluated considering different PM times under varying improvement factor. Secondly, the effect of IPM was also evaluated for same different PM times but under constant improvement factor. In both cases, the effect of IPM on the cost of the component is also evaluated to aid users and engineers especially, to making cost effective decisions.

In addition to other failure data used, the following were also used. Weibull slope parameter $\beta = 2$ and scale parameter $\theta = 1000$ (time units). Additionally, the scale parameter was considered as the useful life of the component.

The results obtained for the evaluations are shown in Table 1 and Table 2. Further illustrations of these results are presented in graphic forms for visual comparisons. Table 1 is an evaluation with varying improvement factor while Table 2 is with constant improvement factor. In both evaluations, three values were considered for the initial improvement factor, 0.985, 0.885 and 0.585 while five values for the PM times were used, 60, 120, 180, 240 and 300. The different evaluations provide room for sufficient comparison and also demonstrate the effect of PM on the choice of PM times. The difference in the two evaluations is that in Table 1 each improvement factor decreases with time whereas in Table 2 they all remain constant throughout.

Table 1. Total extended useful life and cost under IPM with varying improvement factor

PM Times	Total Extended Useful Life			Total Cost		
	$f_0 = 0.985$	$f_0 = 0.785$	$f_0 = 0.585$	$f_0 = 0.985$	$f_0 = 0.785$	$f_0 = 0.585$
$T_p = 60$	1199.8	1159.23	1118.66	3.49037	3.49082	3.49128
$T_p = 120$	1160.63	1128.01	1095.4	2.17616	2.17704	2.17793
$T_p = 180$	1134.94	1107.55	1080.15	1.80612	1.80749	1.80887
$T_p = 240$	1123.13	1098.13	1073.13	1.55425	1.55594	1.55764
$T_p = 300$	1108.35	1086.35	1064.35	1.49629	1.49847	1.50067

Table 1 shows that the highest initial improvement factor (in this case, $f_0 = 0.985$) provides the best useful life extension and with the lowest cost. This is illustrated in Figure 3. Similarly, the most frequent PM time (in this case $T_p = 60$) provides the longest extended useful life of the component, it is however the most expensive. This is illustrated in Figure 4. These characteristics are as expected. In Figure 4, the total cost per unit time for each varying improvement factor for a given PM time appears to be the same. This is because their differences as seen in Table 1 are in fractions, though significant.

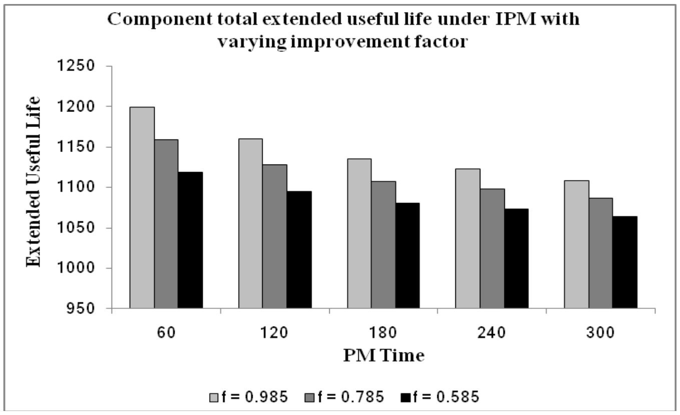

Figure 3. Component extended useful life under varying improvement factor

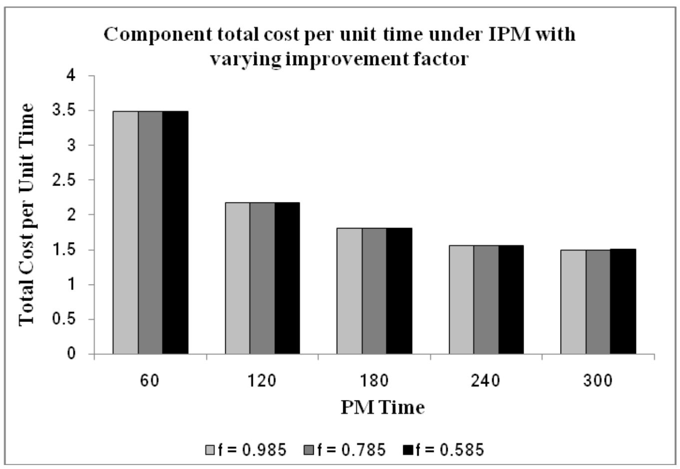

Figure 4. Component total cost per unit time under varying improvement factor

Table 2. Total extended useful life and cost under IPM with constant improvement factor

PM Times	Total Extended Useful Life			Total Cost		
	f = 0.985	*f = 0.785*	*f = 0.585*	*f = 0.985*	*f = 0.785*	*f = 0.585*
$T_p = 60$	1945.6	1753.6	1561.6	3.46778	3.47089	3.47499
$T_p = 120$	1945.6	1753.6	1561.6	2.13166	2.13785	2.14594
$T_p = 180$	1886.5	1706.5	1526.5	1.74106	1.75027	1.76223
$T_p = 240$	1945.6	1753.6	1561.6	1.46807	1.48029	1.49608
$T_p = 300$	1886.5	1706.5	1526.5	1.39157	1.40672	1.42612

The assumption of constant improvement factor (also known as detection rate in some literatures) as in Table 2 is sometimes chosen for simplicity, and hence independent of the number of times the component may have been previously maintained [28]. Additionally, it does not take into account the degradation of the component and thus for a given PM time the age gained is same throughout PM stages. It is therefore not surprising that the evaluations of the extended useful life of the component subjected to some of the PM times (e.g. $T_p = 60$, $T_p = 120$ and $T_p = 240$, also $T_p = 180$ and $T_p = 300$) in Table 2 are same. This characteristic is illustrated in Figure 5, and the use of the horizontal gridlines vivifies the comparison. However, the evaluations of their respective cost as illustrated in Figure 6 differ due to the consideration of the numbers of failure in-between PM stages in the cost model of equation 13.

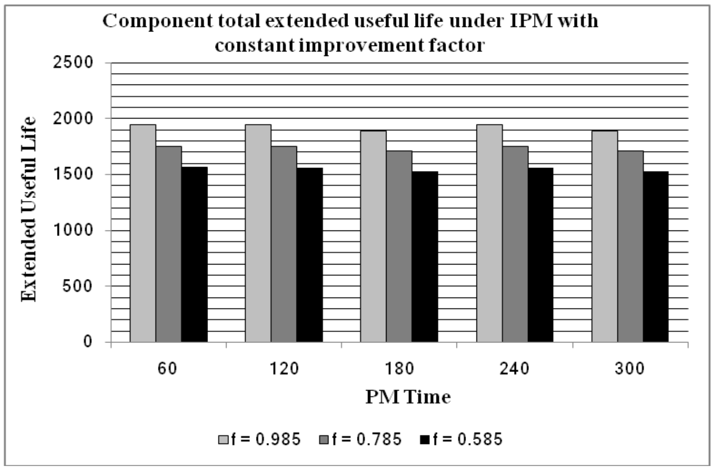

Figure 5. Component extended useful life under constant improvement factor

In Figure 6, the total cost per unit time for each constant improvement factor for a given PM time appears to be the same, similar to the case with varying improvement factor in Figure 4. This is also due to the fact that their differences as seen in Table 2 are in fractions, though significant.

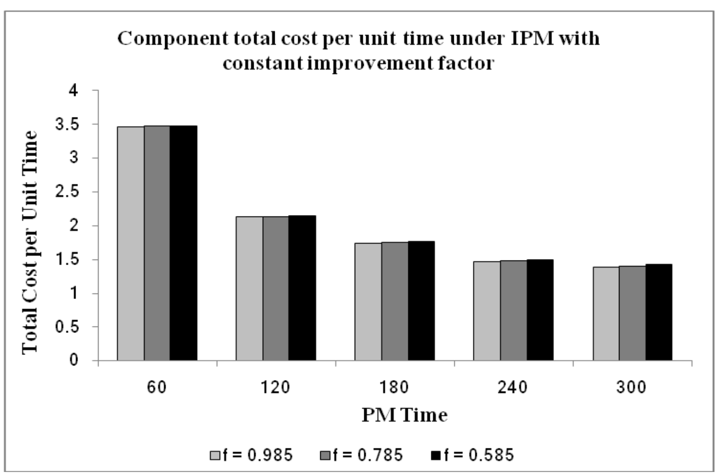

Figure 6. Component total cost per unit time under constant improvement factor

In general, the evaluations show that component useful life is extended in a scenario where the assumption of imperfect preventive maintenance on a component (or IT product) is possible. The degree of the extension of the component useful life and cost depends on the effectiveness of the maintenance.

5. Conclusions

This paper has investigated the challenges existing in green computing as well as some of the advances made in mitigating them. One of challenges which has not been addressed extensively in literature is the handling of IT products, which includes care. One way to care for a product is through maintenance where the problem was addressed in this paper by considering imperfect preventive maintenance (IPM) policy based on the proportional age reduction model. As a result, evaluation models were established for component extended useful life and cost. These models were evaluated on a virtual component which is sufficient for the required analysis. However, the methodology could be extended to evaluating the extended life of a subsystem or system where the IPM policy is applicable to identified components.

The component was subjected to five different PM times and each independently evaluated with three different initial improvement factors. Two cases were considered; firstly, in a scenario where the initial improvement factors vary with time (i.e. decreases with time) and secondly where they are constant throughout. The evaluations show that component useful life is extended under IPM. This implies that IPM can extend the useful life of IT products, thereby slowing down its time to dispose. This will significantly reduce the rate at which the amount of e-waste goes into landfills. This in turn slows down the rate at which greenhouse gases enter the food chain and the atmosphere.

The findings in this paper have propelled requirement for further research in the following areas.

- To investigate the effect of preventive maintenance on component useful life based on other maintenance models such as the shock model.
- To optimise preventive maintenance time based on extended life and cost.

References

[1] J.E. Hairston, “How Nature Recycles And Purifies Water: The Hydrological Cycle” [online], Available: http://www.aces.edu/waterquality/articles/0130001/0130001.pdf [Accessed 31 March 2011], Alabama Cooperative Extension System, USA, 2001.

[2] R. Houe, and B. Grabot, “Assessing the Compliance of a Product with an Eco-label: From Standards to Constraints”, International Journal of Production Economics, 121(1), 2009, pp. 21-38.

[3] J. Campbell, 2010, “100% Recycling – Not Just a Dream” [online], Available: http://www.cqs.com/erecycle.htm [Accessed 01April 2011], Natural Therapy, 2010.

[4] M.I. Mazhar, S. Kara, and H. Kaebernick, “Remaining Life Estimation of Used Components in Consumer Products: Life Cycle Data Analysis by Weibull and Artificial Neural Networks”, Journal of Operations Management, 25(6), 2007, pp. 1184-1193.

[5] Energy Information Administration, “What are Greenhouse Gases” [online], Available: http://www.eia.doe.gov/oiaf/1605/ggccebro/chapter1.html [Accessed 12 May 2011], Energy Information Administration, USA, 2004.

[6] U.S. Environmental Protection Agency, “Greenhouse Gas Emissions” [online], Available: http://epa.gov/climatechange/emissions/index.html [Accessed 13 May 2011], Environmental Protection Agency, USA, 2011.

[7] National Center for Electronics Recycling, “Laws” [online], Available: http://www.electronicsrecycling.org/public/ContentPage.aspx?pageid=14 [Accessed 19 May 2011], National Center for Electronics Recycling, 2011.

[8] J. Cassells, "PC Power Management", APC Journal, 28(1), 2008, pp. 98-99

[9] B. Howell, "Electronic Waste: The Danger" [online], Available: http://www.p2pays.org/ref/02/01010.pdf [Accessed 16 May 2011], Hazard Technical Information Service Bulletin, 11(6), 2001.

[10] S. Binns, E. Kretzmann, M. Kurpiewski, S. Lee, S. Carlson, S. Marke, A. Reilly, C. Senefelder, S. Wade, S. Wilson, and S. Cohen, 2006, "Electronic Waste Recycling Promotion and Consumer Protection Act" [online], Available: http://www.columbia.edu/cu/mpaenvironment/pages/projects/summer06/ewastefinalReport.pdf [Accessed 16 May 2011], The Workshop in Applied Earth Systems Management I, Columbia University, 18 August 2006.

[11] EMPA, "Hazardous Substances in e-Waste" [online], Available: http://ewasteguide.info/node/219 [Accessed 16 May 2011], Swiss Federal Laboratories for Materials Science and Technology, 2009.

[12] NComputing, "Lower the Environmental Impact of Computing: White Paper Green Computing" [online], Available: http://www.publicsector-efficiency-expo.co.uk/wp-content/uploads/2011/01/Green-Computing-White-Paper-NComputing.pdf [Accessed 12 May 2011], Public Sector Efficiency Expo Website, 2010.

[13] Ian, "Green Computer with Biodegradable Peripherals" [online], Available: http://www.aboutmyplanet.com/science-technology/green-computer-with-biodegradable-peripherals/ [Accessed 16 May 2011], AboutMyPlanet Website, 2006.

[14] A. Speedie, "How to Choose a Computer Disposal Method" [online], Available: http://www.sitd.co.uk/How-to-Choose-a-Computer-Disposal-Method.pdf [Accessed 19 May 2011], Secure I.T. Disposals Limited, 2009

[15] G. Anderson, P.J. Corriveau, D. DeVetter, F. Engelman, S. Ganapathy, R.F. Reed, and A. Ross, "Power Efficiency and Sustainable Information Technology", Intel Technology Journal, 2008, 12(4), pp. 303-311.

[16] Citrix Systems, "What is Desktop Virtualization?", [online], Available: http://support.citrix.com/servlet/KbServlet/download/12888-102-16540/Citrix_Desktop_Virtualization.pdf [Accessed 18 May 2011], Citrix Systems, 2006.

[17] N. Storey, "Safety-Critical Computer Systems", Addison Wesley Longman, London, 1996.

[18] C.E. Ebeling, An Introduction to Reliability and Maintainability Engineering, McGraw-Hill, USA, 1997.

[19] K.S. Moghaddam, and J.S. Usher, "Preventive Maintenance and Replacement Scheduling for Repairable and Maintainable Systems using Dynamic Programming", Computers & Industrial Engineering, 60(4), 2011, pp. 654-665.

[20] S.H. Nggada, Y.I. Papadopoulos, and D.J. Parker, "Extending HiP-HOPS with Capabilities of Planning Preventative Maintenance", 6th Annual International Conference on Computer Science and Information Systems, Athens, Greece, 25-28 June 2010.

[21] S.H. Nggada, D.J. Parker, and Y.I. Papadopoulos, "Dynamic Effect of Perfect Preventive Maintenance on System Reliability and Cost Using HiP-HOPS", IFAC-MCPL 2010 5th Conference on Management and Control of Production and Logistics, , Coimbra, Portugal, 8 - 10 September 2010.

[22] H. Wang, and H. Pham, "Availability and Maintenance of Series Systems Subject to Imperfect Repair and Correlated Failure and Repair", European Journal of Operational Research, (174)3, 2006, pp. 1706-1722.

[23] A.C. Márquez, The Maintenance Management Framework: Models and Methods for Complex Systems Maintenance, Springer Series in Reliability Engineering, Springer, London, 2007.

[24] A. Sanchez, S. Carlos, S. Martorell, and J.F Villanueva, "Addressing Imperfect Maintenance Modelling Uncertainty in Unavailability and Cost Based Optimization", Reliability Engineering and System Safety, (94)1, 2009, pp. 23-32.

[25] H. Pham, and H. Wang, "Imperfect Maintenance", European Journal Operational Research, (94)3, 1996, pp. 425-438.

[26] I. Shin, T.J. Lim, and C.H. Lie, "Estimating the Parameters of Intensity Function and Maintenance Effect for Repairable Unit", Reliability Engineering and System Safety, (54)1, 1996, pp. 1-10.

[27] Y. Tsai, K. Wang, and H. Teng, "Optimizing Preventive Maintenance for Mechanical Components using Genetic Algorithms", Reliability Engineering and System Safety, (74)1, 2001, pp. 89-97.

[28] J. Zhao, A.H.C. Chan, C. Roberts, and K.B. Madelin, "Reliability Evaluation and Optimisation of Imperfect Inspections for a Component with Multi-defects", Reliability Engineering & System Safety, 92(1), 2007, pp. 65-73.

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