Journal of Turkish

Operations Management

Lifetime extension approach for decreasing e-wastes

Sermin Elevli

Department of Industrial Engineering, Faculty of Engineering, Ondokuz Mayıs University, Samsun, Turkey
e-mail: sermin.elevli@omu.edu.tr, ORCID No: https://orcid.org/0000-0002-7712-5536

Article Info

Article History:
Received: 21.01.2022
Revised: 31.05.2022
Accepted: 15.06.2022

Keywords:

Deterioration,
E-waste,
Lifetime extension

Abstract

Electrical and electronic products (e-products) enabling human being benefit from higher standards of living has become an indispensable part of daily life. Since the e-products obsolete very quickly because of accelerating technological changes and consumption rates, e-waste is believed to be one of the most critical waste issue of coming future. E-waste is any electrical and electronic products that are unwanted, not working, and nearing or at the end of their useful life. The increasing levels of e-waste depending on usage of short lifespan e-products are significant threat to the environment and to human health. Lifetime extension is considered as one of the approaches to decrease or control e-wastes. A computer as an e-product is a system consisting of components, some or all of which may deteriorate over time at different rates mainly due to commercial and technological reasons. In this study, lifetime extension approach has been recommended for computers in which significant components are upgraded to attain threshold performance value.

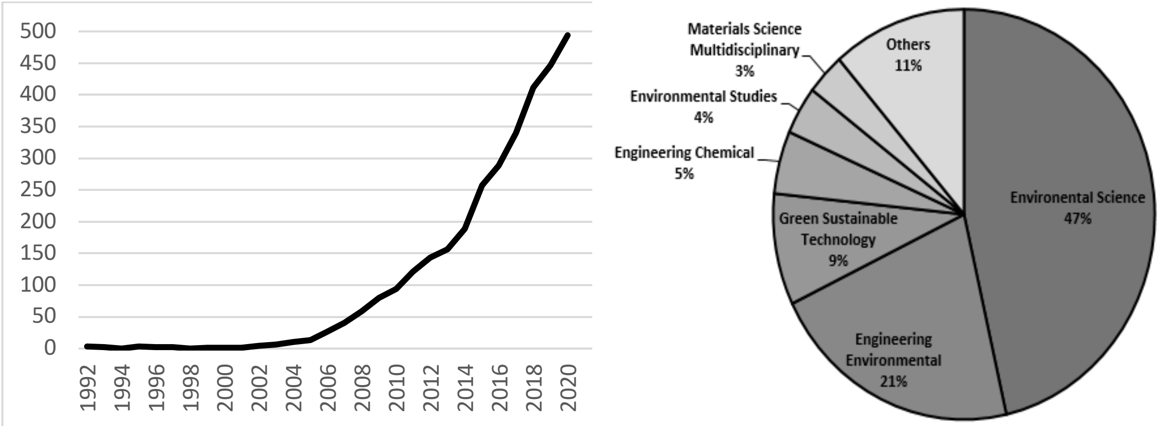
1. Introduction

Electrical and electronic products (e-products), any household or business asset with electrical or battery powered circuit, are a major part of modern society. From essential kitchenware's to computers, they make lives and works more practical and efficient. However, all e-products have a shorter life expectancy compared to other assets. When they stop working or new technology makes them obsolete, they must be disposed of. Electronic waste (e-waste) is a term used for any type of e-product that have been disposed of as waste without the intention of reuse (Parajuly et al., 2019). E-waste also refers to any house, consumer and business electronics, and information technology hardware in the end of its useful life (Khurrum et al., 2011).

Product lifetime/lifespan is the duration of the period that starts at the moment a product is started to use after manufacture and ends at the moment a product becomes obsolete (Bakker and Schuit, 2017). Today's extensive and rapid consumption of e-products having short lifespan lead to huge amounts of e-waste. Because of containing substances hazardous that are often released into the environment, e-waste is a threat for human health and nature. 50 million tons of electronic waste is generated per year worldwide, with an average of 6.5 kg per person (Forti et al., 2020). In addition, more waste is also generated when these devices are produced. Even developed countries with well-established waste management systems have been struggling with the huge amount and complexity of e-waste. Because of this, extending the lifespan of electronic devices emerges as an important requirement.

There is a growing attention on e-waste because of its fateful environmental consequences. "Web of Science" search results indicate that number of articles from different categories such as environment science, environmental engineering, green sustainable technology, etc. on e-waste has increased especially after the 2000s. (Figure 1). Chowdhury and Patel (2017) analyzed literature on e-waste in order to summarize the information available and to create common knowledge. Their findings indicates need for standardized method to estimate e-waste generation, policy for proper e-waste management, legal framework and awareness programs.

DOI: 10.56554/jtom.1060746



a) Number of Articles b) Subject Category

Figure 1. Literature Review on e-waste (1992-2021)

Technological advances have contributed to shorter product lifespan (Cole et al., 2016). Increasing demand for e-products with reduced product lifespan, leads to more frequent replacement/ renewal of them resulting e-waste stream. In order to protect planet against this kind of negativeness, United Nations adopted 17 Sustainable Development Goals in 2015. The extension of product lifespan can be regarded as a tool under the goal of "Responsible Consumption and Production" (Bakker and Schuit, 2017). Extending the lifetime and delaying obsolescence of e-products can significantly reduce the environmental impacts and contribute to meeting environment, climate and sustainability goals. Lifetime extension of all washing machines, notebooks, vacuum cleaners and smartphones in the European Union for one year was reported to save around 4 million tons of carbon dioxide (CO2) annually (EEB, 2021). This value equals to take over 2 million cars off the roads for a year (Table 1).

Table 1. Annual Carbon Dioxide Save of Extending the Lifetime of e-products by 2030 for European Union (million tons)

	1 Year	3 Years	5 Years
Smartphones	2,1	4,3	5,5
Notebook Computers	1,6	3,7	5
Washing Machines	0,25	0,66	1
Vacuum Cleaners	0,1	0,3	0,5

A personal computer lasts about 3-4 years from commercial perspective since the demand for running all application are increasing over the years. For example, hardware with certain capacity and performance capabilities is required for software installation. That is, in spite of its technical lifetime being longer, performance of a computer decreases over the time.

Technological change rate has led to PCs becoming functionally obsolete within short periods and made investments on PCs an ongoing operational expense instead of one-time expense. In case of there exists such a rapid technological obsolescence, purchasing new computer may not be the proper option. Because of this, it is reasonable to switch to the longer intervals of the replacement cycles by extending the lifetime of PCs.

This study first gives a brief background on environmental impacts of e-wastes. System deterioration and lifetime extension approach are then outlined followed by a framework for personal computers supported by literature. Finally, personal computer as a multicomponent e-product was used to illustrate the lifetime extension approach through component replacements.

1.1 System Deterioration

Deterioration (degradation) follows the principle of the second law of thermodynamics which is ''disorder caused by the entropy of an isolated system increases with time" (Kang et al, 2020). Since the deterioration is inevitable, e-products just like other assets have a certain life time. Life expectancy of asset is defined as the time until the

DOI: 10.56554/jtom.1060746

asset is retired, completely replaced, or decommissioned (Lemer, 2012). For environmental and economical sustainability purposes, it is necessary to ensure that the assets stay in operation as much as possible and do not deteriorate faster than necessary (or expectation) during lifespan.

Functional value deterioration and physical value deterioration are the factors that cause gradual change in a product's performance over time (Fang and Rau, 2017). Obsolescence resulting from rapid technological development and/or changes in consumer expectation/ behavior is considered under functional value deterioration. On the other hand, aging and wearing off are accepted as the reason of the physical value deterioration.

Degradation analysis, a tool for assessing the lifetime distribution in reliability analysis, includes the measurement and extrapolation of degradation or performance data directly related to the presumed failure of the product under consideration (Reliawiki, 2021). In degradation analysis, the lifetime of a product is defined as the time in which the value of a chosen component reaches a predetermined threshold (Yu and Fuh, 2010).

For a system deteriorating with time, and subject to continuous cumulative deterioration, the deterioration evolution is usually modeled by a stochastic process (Huynh et al, 2011). Let $X(t)$ be the cumulative deterioration (or degradation level) at time t and X^* be the degradation threshold level. Then, timelife (T) will be as follows:

$$T = \inf\{t \geq 0 : X(t) \geq X^*\} \tag{1}$$

Deterioration can be represented as a curve in a diagram showing deterioration on the y-axis and the time on the x-axis (Figure 2). This curve shows the relationship between asset condition under the effect of technical or economical obsolescence, and time.

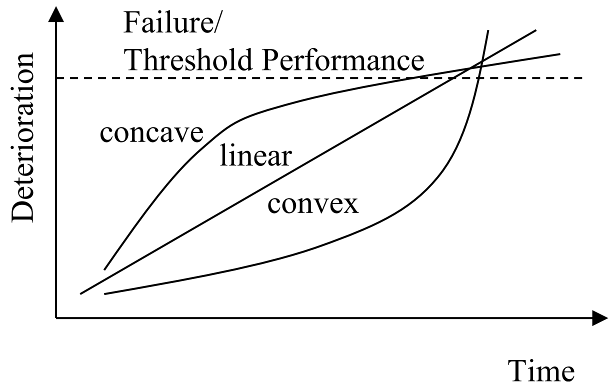


Figure 2. Possible shapes for deterioration curves (Welte, 2008)

In degradation analysis, performance data that can be directly related to the presumed failure of the product in question is measured. The performance of the system under consideration needs to be measured over time, either continuously or at predetermined intervals. After recording this information, the performance measurements are extrapolated to the defined threshold level in order to estimate failure or the end of life. Some basic models for modeling empirical degradation measurements are as follows (Reliawiki, 2021):

Linear	:	$X(t) = a + bt$	(2)
Exponential	:	$X(t) = ae^{bt}$	(3)
Power	:	$X(t) = at^{b}$	(4)
Logarithmic	:	$X(t) = a + bln(t)$	(5)
Gompertz	:	$X(t) = ab^{c^t}$	(6)
Lloyd- Lipow	:	$X(t) = a - b/t$	(7)

DOI: 10.56554/jtom.1060746

where *X(t)* represents the performance, *t* represents time, and *a*, *b* and *c* are model parameters. The method consists of fitting one of those models to degradation data and to extrapolate it until it reaches the failure threshold (Letot and Dehombreux, 2009). After estimating the model parameters for each sample *i*, a time t_i can be extrapolated, which corresponds to the defined level of failure or performance-*X(t)*. The computed t_i values is then used as times-to-failure for subsequent life data analysis (Reliawiki, 2021).

Product/asset life-time extension as a part of asset management process is relatively new concept which aims to increase the lifetime of assets. Life-time extension (LTE) is defined as 1) extending the asset's economical and/or technical life-time (Van Dongen, 2011) 2) postponement or reversal of the obsolescence of a product through deliberate intervention (Bakker and Schuit, 2017). By lifetime extension, the deterioration can be postponed and the lifetime of a component is extended (Bakker et al, 1998).

Figure 3 in which normal line displays the normal deterioration of the asset and the dotted line displays the points of LTE shows the impression of LTE over time. Simple life curve of an asset shown by normal line indicates continuous deterioration up to the point of failure. In LTE, the component is restored to its acceptable condition by delaying the deterioration or improving the current condition (preventive replacement, upgrade, refurbishment, etc). Establishing the current state of deterioration is an important requirement to determine of the remaining life of the equipment (Sugier and Anders, 2010)

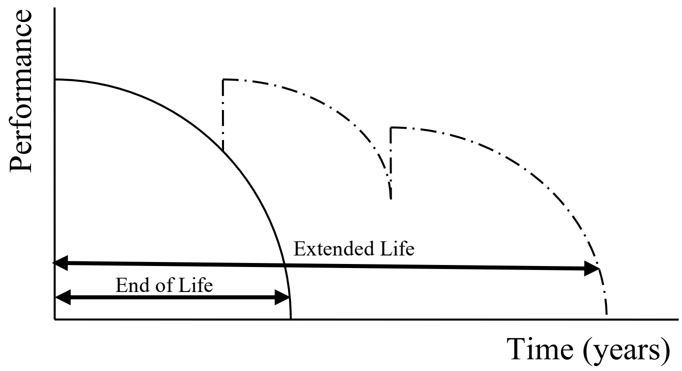


Figure 3. Impression of LTE over time (Adopted from Van Dongen, 2011)

1.2 Personal computers

A PC lifecycle is defined as the usefulness of a desktop or laptop computer to the users, from its initial acquisition through its ultimate disposal (DIR, 2013). End-user needs, technological changes, support technology and cost are main determinants of lifecycle. The current industry standard for a desktop and laptop computer is 4-5 years and 2- 3 years respectively (DIR, 2013).

Computer performance can be defined as the amount of useful work accomplished by a computer system compared to the time and resources used (Wikipedia, 2021). In order to measure the computer performance, some metrics such as availability, response time, channel capacity, latency, completion time, service time, bandwidth, throughput, etc can be used.

The overall speed and the capabilities of a PC do not change over time if every component works properly. However, different versions of any software cannot be compatible with old computers. That is, how well the computer is doing the work it is supposed to do may not be good enough for modern hardware and software. Thus, in spite of being completely functional, a computer cannot exploit modern capabilities and becomes useless. This kind of situation can be called as commercial deterioration/degradation/ageing. A main aspect of lifetime extension is the decision of replacement of deteriorated components or buying a new computer by disposing the old one (Griese et al., 2004).

In their study examining the relation of age and technical characteristic to price, Antonopolus and Sakellaris (2011) have found that consumers do not value ages of the computers. That is, age is not an important factor due to minimal physical deterioration. Additionally, CPU speed, amount of RAM and hard disk capacity have been found by them as the most important technical characteristics. Antonopolus and Sakellaris (2011) have also found that

DOI: 10.56554/jtom.1060746

prices of computers decline exponentially over age of them. Ferrer (1997) presented some experimental results concerning the values of a PC's components, which deteriorate as time increases. The monetary value of these components were found as $V=V_o t^{-a}$, where t is time computed in periods and each period corresponds to one month, V_o is the component's value at t=0 and a>0. Griese et al (2004) examined the market for reusing computers and environmental assessment of reuse and repair. Rachaniotis and Pappis (2008) proposed a decision-making model for reassembling different deteriorating subsystems and components of a complex system from used and new parts. The performance value functions for CPU, motherboard and hard disc which are exponential, power and logarithmic respectively, were calculated depending on t by using the least-squares method.

2. Problem statement and mathematical formulation

Multicomponent system is defined as a system consisting of several units of components or pieces, which may or may not depend on each other. The assumptions considered under this study are as follows:

1. Consider e-product as a multicomponent system consisting of m independent components.
2. Let T be lifespan of whole system (end-of-life)
3. Assume no component changes in system due to failure
4. Each component is subject to commercial / technological deterioration which follows power model (Equation 4).
5. At system' start up time ($T=0$), performance of whole system will be $P_0 = \sum_{i=1}^{m} P_{i0}$ with the performance of any component being P_{i0}, $i = \{1, 2, ..., m\}$
6. Let P_{min} be threshold performance
7. Let times between successive inspections of performance be denoted by τ.
8. $\tau = \tau_j - \tau_{j-1}, j = 1,...., n$ will be held constant such as 3 months, 6 months and, yearly.
9. Since τ_n will be the cumulative time of n^{th} inspection, then lifespan will be $T = \tau_n = n \times \tau$
10. Let b be a constant for deterioration according to power model.
11. If performance of any component is $P_{i\tau_j} = P_{i0}.\tau_j^{-b}, j = 1,2, ..., n$ then performance of whole system is $P_{0\tau_j} = \sum_{i=1}^{m} P_{i\tau_j}$.
12. Let k be a variable representing the total number of replacements in the $[0,T]$ interval.
13. Let S(k,m) be a sequence of the component which will be replaced. Components are replaced by following $S = \{S_1, S_2, ..., S_m\}$.
14. Once all components are replaced once, the Lifetime is reached as soon as the minimum threshold performance is reached.

In case of comparing system performance ($P_{0\tau_j}$) at any periodic inspection point (τ_j) with threshold performance ($P_{\min}$), two possibilities arise: 1) Intervene the system (Renewal) and 2) Keep working with the current system (Do nothing). Figure 4 shows the flowchart of lifetime extension model under the assumption that every component is replaced once.

3. Lifetime extension for PC

The following assumptions have been made to illustrate how the lifetime extension model works on a computer system.

1. Consider computer as a multi-component system consisting of three components which are CPU, RAM and Hard Disk (m=3)
2. Let the deterioration of each component follow the same behavior
3. Let the performance be expressed as a percentage. The performance of any component at T = 0 is P_{i0}=%33 and the performance of the whole system is P_0=%100
4. Let the system be checked on a monthly basis to determine the performance (τ=1).

DOI: 10.56554/jtom.1060746

5. Let the performance of whole system be calculated according to $P_{i\tau_j} = P_{i0}.\tau_j^{-b}$ with b=0.15 at any inspection.
6. Let the minimum performance threshold be P_{min}=%60.
7. Consider each component be upgraded/ renewed once. This assumption has been taken into account due to the high probability of compatibility problems with old parts as a result of repetitive component renewals in computer systems.

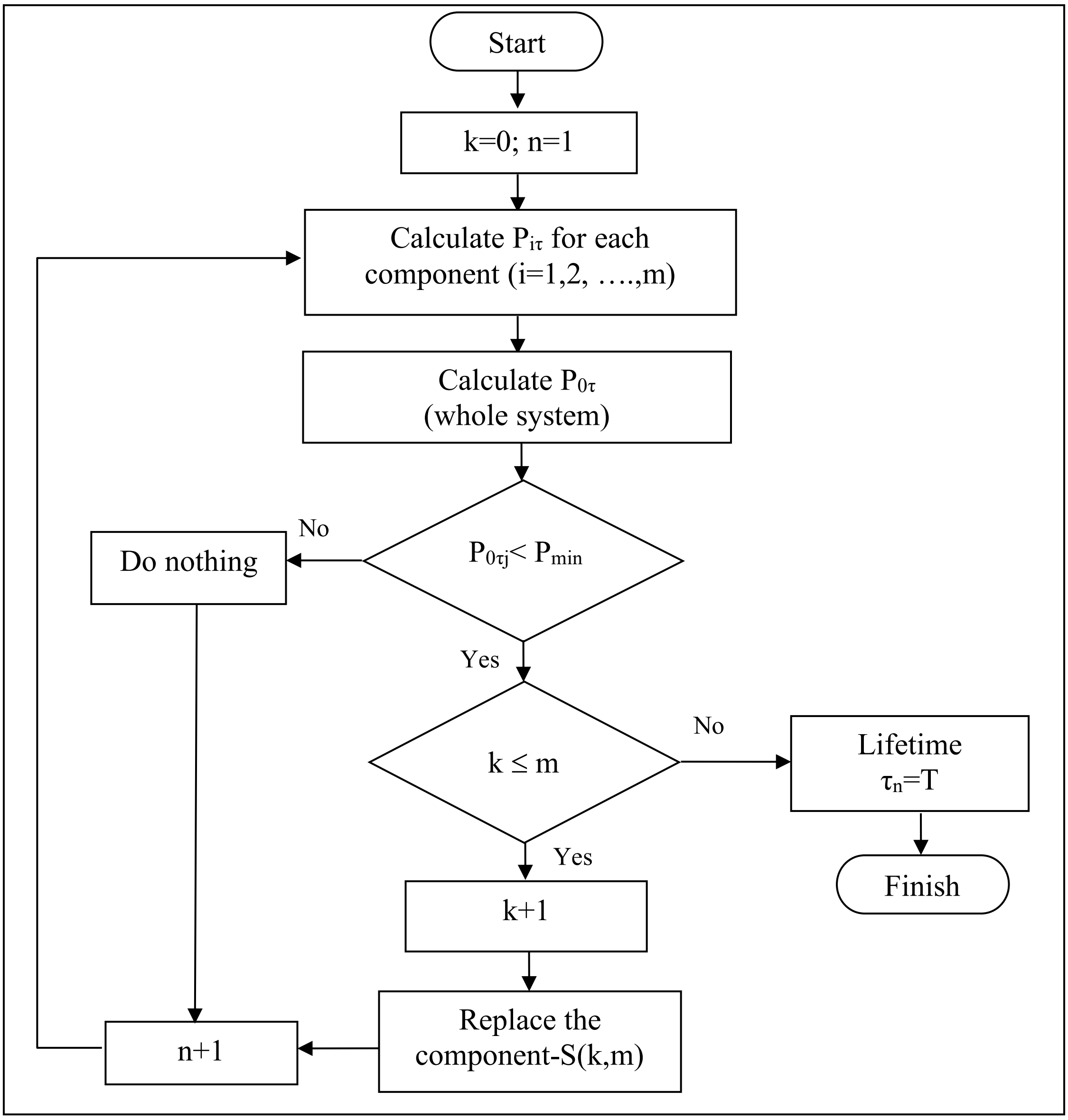


Figure 4. Flowchart of Lifetime Extension Model

In Figure 5, the results are presented graphically. Since the performance percentage fell below the 60% threshold in the periodic inspections performed at 30, 44 and 58th months, the component in sequence was upgraded to the next model. The time used to determine the deterioration of the respective component after replacement was reset.

DOI: 10.56554/jtom.1060746

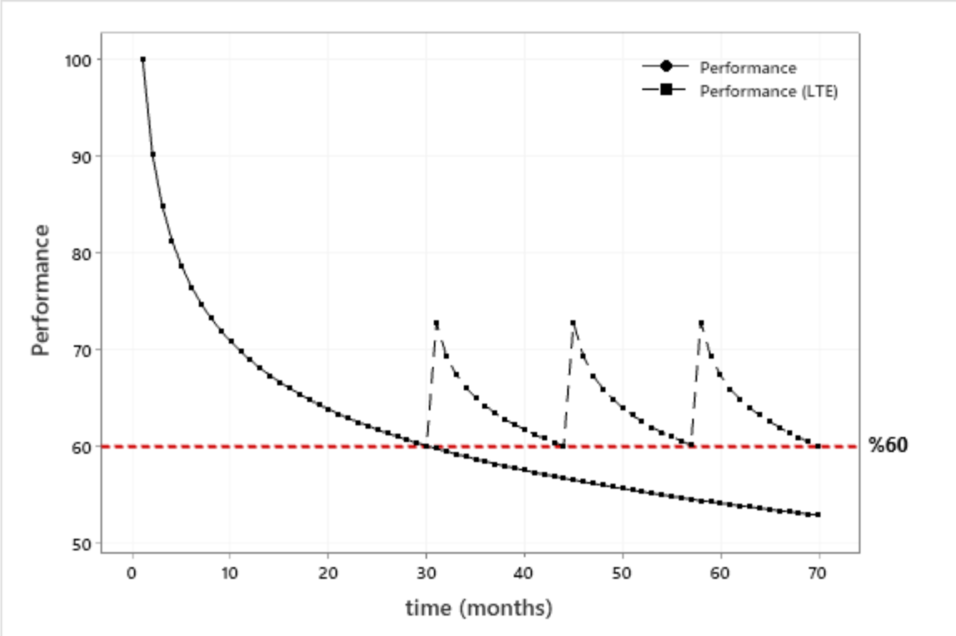


Figure 5. Results of LTE for Computers

4. Results and discussion

If a function of an e-product is no longer efficient enough during its use phase, it has reached at end of its useful life. Since this kind of e-products, called as e-waste, has been increasing due to rapid technological changes and consumption rates and creating a large environmental burden, the alternative of extending the lifetime of e-products should be considered.

In this study, "Lifetime Extension" approach, which includes the activities of extending the economic and / or technical life of the products, has been examined. A mathematical model was developed for computer which is an e-product. According to the application results, under current assumptions, if the components are not upgraded/replaced, the life of the system (computer) under consideration will be 30 months. As a result of the component renewals based on periodic inspection, it seems possible to extend the life of the computer to 70 months. This study showed that lifetime extension approach is a way to minimize the environmental impacts of e-wastes such as saving energy and reducing greenhouse by extending the e-products' lifespan. However, standards addressing best practices for lifetime extension of each e-product must be created and adopted as indicated by Hazelwood and Pecht (2021).

Conflicts of Interest

The author declared that there is no conflict of interest.

References

Antonopoulos C. and Sakellaris P. (2011). Estimating computer depreciation using online auction data, Economics of Innovation and New Technology, vol.20, No.2, 183-204. DOI: https://doi.org/10.1080/10438590903385095

Bakker C.A. and Schuit C. S. C. (2017). The Long View: Exploring Product Lifetime Extension, UN Environment, ISBN: 978-92-807-3661-8

Bakker J. D., van der Graaf H. J. And van Noortwijk J. M. (1998). "Model of Lifetime- Extending Maintenance", Proceedings of the 8th International Conference on Structural Faults and Repair, London, United Kingdom, 13-15 July 1999. Edinburgh: Engineering Technics Press

Chowdhury A. and Patel J. (2017). "E-Waste Management and its Consequences: A Literature Review", Prestige e-Journal of Management and Research, vol.4, Issue 1

DOI: 10.56554/jtom.1060746

Cole C., Cooper T. and Gnanapragasam A. (2016). "Extending product lifetimes through WEEE reuse and repair: Opportunities and challenges in the UK," 2016 Electronics Goes Green 2016+ (EGG), Berlin, 2016, pp. 1-9 DOI: 10.1109/EGG.2016.7829857

DIR- Department of Information Resources (2013). PC Life Cycles- Guidelines for Establishing Life Cycles for Personal Computers, Austin, Texas

EEB- European Environmental Bureau (2021). Cool Products Don't Cost The Earth, https://eeb.org/library/coolproducts-briefing/, 04.02.2021

Fang Y.T. and Rau H. (2017). "Optimal Consumer Electronics Product Take-Back Time with Consideration of Consumer Value", Sustainability, 9, 385 DOI: https://doi.org/10.3390/su9030385

Ferrer G. (1997). "The Economics of Personal Computer Remanufacturing", Resources, Conservation and Recycling, vol.21, 79-108. DOI: https://doi.org/10.1016/S0921-3449(97)00030-X

Forti V., Balde C.P., Kuehr R. and Bel G. (2020). The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam

Griese H., Poetter H., Schischke K., Ness O. and Reichl H. (2004). "Reuse and lifetime extension strategies in the context of technology innovations, global markets, and environmental legislation", IEEE International Symposium on Electronics and the Environment

Hazelwood D. A. and Pecht M. G. (2021) "Life Extension of Electronic Products: A Case Study of Smartphones", IEEE Access, Volume 9, 144726-144739.

Huynh K.T., Barros A., Bérenguer C. and Castro I.T. (2011). "A periodic inspection and replacement policy for systems subject to competing failure modes due to degradation and traumatic events", Reliability Engineering & System Safety, Volume 96, Issue 4, Pages 497-508

Kang R., Gong W. and Chen Y. (2020). "Model-driven degradation modeling approaches: Investigation and review", Chinese Journal of Aeronautics, 33(4): 1137–1153

Khurrum M., Bhutta S., Omar A. and Yang X. (2011). Electronic Waste: A Growing Concern in Today's Environment, Hindawi Publishing Corporation, Economics Research International, Volume 2011, Article ID 474230, 8 pages DOI:10.1155/2011/474230

Lemer A. C. (2012). Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook, National Academies of Sciences, Engineering, and Medicine, The National Academies Press, Washington, DC https://doi.org/10.17226/22782.

Letot C. and Dehombreux P. (2009). A toolbox to assess reliability and degradation models, ETE' 2009 Second EUREKA International Symposium on Environmental Testing Engineering, Belgium.

Parajuly K., Kuehr R., Awasthi A. K., Fitzpatrick C., Lepawsky J., Smith E., Widmer R., Zeng X. (2019). Future E-waste Scenarios, StEP (Bonn), UNU ViE-SCYCLE (Bonn) & UNEP IETC (Osaka)

Rachaniotis N.P. and Pappis C.P. (2008). Preventive Maintenance and upgrade system: optimizing the whole performance system by components' replacement or rearrangement, International Journal of Production Economics, vol.112, 236-244.

Reliawiki (2021). Degradation Data Analysis, http://reliawiki.org/index.php/Degradation_Data_Analysis, 04.02.2021

Sugier J. and Anders G. J. (2010). Modelling Equipment Deterioration vs. Maintenance Policy in Dependability Analysis, Computational Intelligence and Modern Heuristics, Al-Dahoud Ali (Ed.), ISBN: 978-953-7619-28-2 DOI: 10.5772/7826

DOI: 10.56554/jtom.1060746

Van Dongen P. (2011). Value& Innovation Through Asset Life-time Extension, Erasmus University, Economics and Informatics

Welte T. (2008). “Deterioration and Maintenance Models for components in hydropower plant”s, Ph.D. thesis, Norwegian University of Science and Technology , Faculty of Engineering Science and Technology, Department of Production and Quality Engineering

Wikipedia (2021). Computer Performance, https://en.wikipedia.org/wiki/Computer_performance, 08.02.2021
Yu I. and Fuh C. (2010). Estimation of Time to Hard Failure Distributions Using a Three-Stage Method, IEEE Transactions on Reliability, vol.59, No.2, 405-412 DOI: 10.1109/TR.2010.2044610

DOI: 10.56554/jtom.1060746