Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 61 (2017) 275 – 280

www.elsevier.com/locate/procedia

The 24th CIRP Conference on Life Cycle Engineering

Development of Resource Efficiency Index for Electrical and Electronic Equipment

*Wang Juntao, Nozomu Mishima

Akita University

* Corresponding author. Tel.: +81-18-889-2978; fax: +81-18-889-0405. *E-mail address:* smartwjt@163.com

Abstract

The paper divides resource efficiency of smartphone into three stages; they are resource efficiency of manufacturing, utilization and end-of-life treatment. Output-input evaluation method is used for manufacturing. A real used value of each functionality of smartphone is developed for utilization. An index of resource efficiency for recycle stage is proposed. For each stage, an environmental impact coefficient and TMR are used. Finally the total resource efficiency of a smartphone is derived. This index evaluates resource efficiency both considering mechanical aspect and the real used value by people related to consumption of resources.

Peer-review under responsibility of the scientific committee of the 24th CIRP Conference on Life Cycle Engineering

Keywords: Resource efficiency; environmental impact coefficient; TMR; real used value; functionality; accumulated; total resource efficiency

1. Introduction

Resource use is a very hot topic in the world nowadays, especially modern life heavily depends on natural resources which make the demands rapidly increasing. And it is believed that the total amount of natural resources in the world is finite. What's worse, the environmental problems are becoming more and more serious with the consumption of resources. To satisfy the continuous increasing demands for natural resources and to establish a sustainable world, resource efficient use is needed. In order to achieve resource efficiency, one of the important things need to do is to establish a common and easily understandable index that can evaluate the resource efficiency of a product easily and comprehensively.

In former researches, many kinds of methods were invented or used directly or indirectly to evaluate resource efficiency. The initial and basic method can be seen as the ratio of production and total consumption, but actually this method is more likely the productivity of science and technology. It is not only without thinking the utilization and end-of-life treatment of the product, but also fails to make a comprehensive evaluation rather than only technology and quantities. A very similar method to the above one is monetary based evaluation method, this kind of index can be described as 'resource productivity'. One of monetary based evaluation methods can be used to evaluate resource efficiency by GDP divided by Domestic Material Consumption (euro/ton) [1]. However, the big problems of these methods are lack of ability to consider the environmental impacts which are very important and matter too much right now as well as without considering the utilization value by people. Instead of evaluating resource efficiency directly by calculation of the ratio of output and input, another kind of methods focusing on the whole life time of product from resources to end-of-life treatment to analyze consumption of resource and utilization of product. This king of method aims mostly at finding out what happened along with the consumption of resources, and tries to quantify the impacts generated by the consumption of resources. Among them, a very welcomed one is life cycle assessment (LCA). LCA is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle [2]. Even LCA can be used to evaluate and rank the resource efficiency related to environmental impacts, and is helpful for assisting achieve more sound environment and sustainable world while utilizing resources. However, too much attention on the environment is not the initial expectation and final goal of utilization of resources, also necessity of a large amount of

Peer-review under responsibility of the scientific committee of the 24th CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.11.172

database makes LCA limited. Essentially, the initial expectation and final goal of development and utilization of resources is to satisfy with the demands of people, which means to serve people. At the same time, to make a better living circumstance and finally achieve a sustainable world, the risk of environmental impacts regarded to consumption of resources need to be well controlled. Considering these, this paper is aimed at solving these problems with a proposal of index of resource efficiency.

The index in this paper starts from the real utilization of resources, and considering mechanical aspect and used value by people, also environmental impacts all over the whole life time of utilization of resources from cradle to grave. And based on the electrical and electronic equipment, the total resource efficiency index is derived. The rest of the paper is organized as follows. Section 2 takes an overview of the whole lifetime of product and based on these section 3 brings out a proposal to make a comprehensive evaluation of resource efficiency. Finally, section 4 draws a conclusion for this paper.

2. Whole life of a smartphone

As the amount of EEE (Electrical and Electric Equipment) being larger in the world, Smartphone, as one of the very important kind of EEE, is making a big difference in the resource market. It is said that there're more than two billion smartphones being used right now [3]. Moreover, the changing speed of a smartphone is very fast. Some papers and investigations estimate that current replacement time are between 1 and 2 years, while manufactures believe that the technical lifetimes are in the order of 10 years [4]. The unreasonable development and utilization of smartphones and rapidly changing speed not only make the functionalities of a smartphone do not get the maximum use, which lead to a very big waste of resources, but also generate tremendous volume of waste that have a deep impact on the environment[5]. So it is necessary and urgent to achieve resource efficiency of smartphones and any other EEE to help build up a sustainable world. To achieve resource efficiency, a whole understanding of the utilization process of resources is very important. To sum up, the utilization process of resources contains three main stages, which means the process from resources to product, the process of utilization of product, and the process of resources returned from product.

2.1. Structure from resources to product

Resources are the fundamental physical composition of a product. This process is a chemical and mechanical process to achieve the transformation from resources to product. Actually, from a view of engineering, the goal of this process is to convert a certain amount of resources to another amount of resources. Even though the function of different products may vary very much, in terms of this process, achieving the transformation with as less as resources consumption and waste of resources will definitely make better use of the resources.

2.2. Process of utilization of product

Products are made to support some functions that can be used by people to achieve some benefits. Normally, for batch products, people's demands for them are undoubtedly demands representation for different kinds of functions that supported by the product that consists of a certain amount of resources. People's demand urges people to purchase a product for its functions, but as time goes and technologies develop, demand will drive up to a point that the owner decide to change the product. During the whole process of utilization of the product, the actual utilization extent of each function by people will change along with time, at the same time, the usage value that people benefit from each function of product will be accumulated with time. Considering the whole life cycle of a product, from production to end-of-life treatment, the whole usage value will be accumulated.

However, the used value does not mean the initial overall function value of a product, especially for an equipment with rapidly upgrade speed, like smartphone. This kind of EEE always have a 'more reserve capacity of function'. Whenever people is aimed at choosing one product, the very important point is to choose one with more capacity of function that cannot be used directly right now, which reserves to serve the future requirements. And for the overall function value of a product, in some studies, it's said that it decreases along with time due to obsolescence and other physical factors [6]. It can be showed in Fig.1. Based on these, here a definition of used value is made.

As one of the scenarios, we will make the product out of life when the used value in a point equals to the overall value. While under this scenario, the 'disposal point' can be showed as Fig.1. And then the accumulative used value will be gained as the shadow in Fig.1. Obviously, for a product with so many functionalities as smartphone, no matter the accumulative used value, nor the overall value decrease is the integration of all the functionalities of a smartphone.

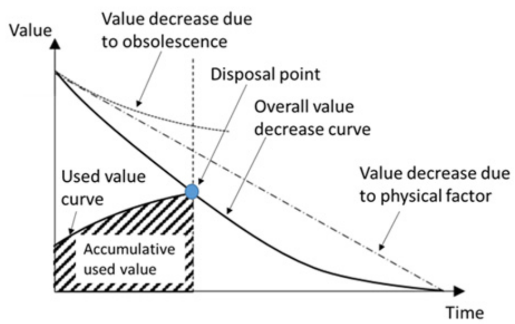

Fig.1.Accumulative Used Value while Used Value equals to Overall Value

Besides the 'disposal point' mentioned in the first scenario, sometimes people change their products without considering the utilization extend of functionalities, simply to say, just change it for its old and some subjective reasons, or sometimes insist on using even though it cannot satisfy with the utilization level. These scenarios can be expressed as Fig.2 and Fig.3. In Fig.2, the 'disposal point' is early before reaching to the overall value decrease curve, which means that the product never operates full of its functionalities along the whole utilization life by people. And that obviously make the product very waste of resources. Fig.3 shows that even the product normally or in fact cannot meet the utilization requirement of people, but for some reasons, people still keep using the product and prolong the use of product. Then the accumulative used value consists of two parts, one is the accumulative used value accumulated below the used value curve, while the other is the shadow below the overall value decrease curve.

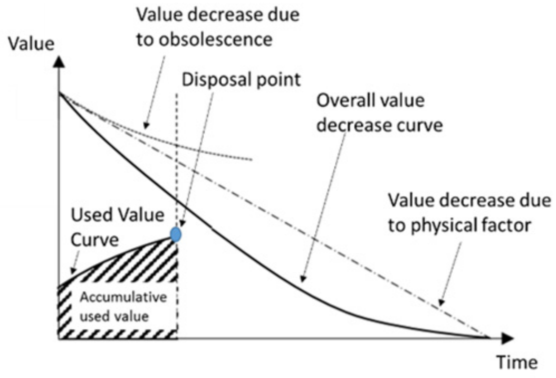

Fig.2. Accumulative Used Value while Used Value less than Overall Value

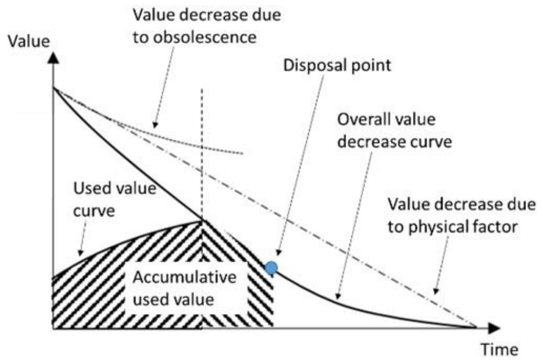

Fig.3. Accumulative Used Value while after the point that Used Value equals to Overall Value

Actually, to make full use of a product, we should try as much as we can to enlarge the accumulative used value while at the same time minimize the part that above the used value curve and below the overall value decrease curve accumulated with time. The accumulative used value not only singly related to original use of the product, any relationship between products and human beings can be analysed by this model, like reuse and repair and so on.

2.3. From product to resources

After all the utilization period of products by people, then the product will be run-out of its lifetime. Since we have sorted all the activities of products related to human beings into the process of utilization of product. Here 'From product to resources' means all the functionalities of product are out of utilization. Traditionally, we would landfill the product while there's no use of it[7]. However, the behavior of landfill not only bad for the environment, but also make a lot of resources that contained in the product cannot be used any more, which means that "urban mines"[8] with large amounts of valuable resources, such as rare metals in electric and electronic products being waste. All of these are bad for the establishment of sustainable world. To reduce the waste of resources, the process of recovery resources from 'urban mine' is very important[9]. And this process can be regarded as the process from product to resources. Even though this process is to smelt resources from product, it looks like that the resources is the benefits, however, essentially speaking, from a view of the whole lifetime of a product, the benefits of this process are actually achieving the goal that making the same product consists of the original total amount of resources that serves the same functions to human beings while reducing the total amount of resources.

3. Resource efficiency of a product

From the analysis of above section, an overview of a whole lifetime product that from cradle to grave is showed. Based on these, the resource efficiency evaluation method of product is proposed here. Before talking about resource efficiency, here is a definition of efficiency: Efficiency is often measured as the ratio of useful output to total input, which can be expressed with the mathematical formula r=P/C, where P is the amount of useful output ("product") produced per the amount C ("cost") of resources consumed[10]. Combining the whole life time of product and the basic definition of efficiency, resource efficiency of a product is defined at each period of the whole life time, and finally the total resource efficiency of a product is got.

3.1. Definition of resource efficiency of each process of a product

3.1.1. From resources to product

As analysis in section 2, this process actually is the one to achieve the goal that converted from a certain amount of resources to another amount of resources. In this process, the benefit is the product consists of a certain amount of different resources, and it is clear that the input is the total amount of resources (here only consider material resources, pay no attention on the energy). To consider the importance and rare extent of different kinds of resources, here an index of TMR (total material requirement) [11] is used. TMR is defined as the total amount of crude metals, ores, soils, removed surface soils, etc. to obtain a unit amount of refined metals. Based on these, then the definition of resource efficiency from resources to product can be derived by eq.(1).

$$\mathrm{E}_1 = \frac{TMR_P}{TMR_T} \tag{1}$$

E_1: Resource efficiency of the stage from resources to

product;
TMR_P: TMR of the resources contained in the product;
TMR_T: TMR of resources needed to produce the product

3.1.2. Process of utilization of product

Utilization of product is the most important process in the whole life time of resource use, the initial expectation and final goal of development and utilization of resources is to satisfy with the demands of people, which means to serve people. So the resources used during utilization of product period and the used lifetime can decide the output value of the resources. Based on this, resource efficiency of this process can be derived as eq.(2).

$$E_2 = \frac{TMR_{used}}{TMR_P} \tag{2}$$

E_2: Resource efficiency of the process of utilization of product;
TMR_{used}: TMR of the resources really used in the product along with time

Since the really used materials in the product are changing with time and it's impossible to measure due to invisible, so it's necessary to translate into another measurable parameter. So here, one assumption made as below:

①: Assume in one fixed product, the relationship between each function and the amount of resources used for constituting the function is linear, which means $Value\ of\ function\ (i) = a_i\, TMR_i$;

TMR_i: TMR of the resources contained in each function (i) of the product;
a_i: The linear ratio between each function (i) and the resources needed to support each function (i) in one fixed product.

According to this assumption, the resources used in this process can be changed into the value of each function used by people. With the used value defined in section 2 and the assumption above, the resources used in one product can be translated into used value of each function. Since from the product point of view, there must exist a set of data w_i make $TMR_i = w_i TMR_p$ and it is obviously that $\sum w_i = 1$. Here w_i means the ratio of resources for one function and resources of the total product.

So eq.(2) can be converted to eq.(3)

$$E_2 = \frac{TMR_{used}}{TMR_P} = \sum w_i \frac{V_{used(i,t)}}{V_{overall(i,t)}} \tag{3}$$

$V_{used(i,t)}$: Accumulative used value of each i function in the product along with time;
$V_{overall(i,t)}$: Accumulative overall value of each i function in the product along with time. If value of each function keeps constant all the way, $V_{overall(i,t)} = V_{initial(i,t)}$; if value of each function changes with time, $V_{overall(i,t)} \neq V_{initial(i,t)}$, as Fig.4. shows.

Considering the reuse and other methods maybe used to prolong the utilization of product[12], then the accumulative used value can be showed in Fig.4. which defined as eq.(4).

$$V_{used(i,t)} = \mathrm{V}_1 + \mathrm{V}_2 + \cdots = \mathrm{V}_{1-1} + \mathrm{V}_{1-2} + \mathrm{V}_{2-1} + \mathrm{V}_{2-2} + \cdots \tag{4}$$

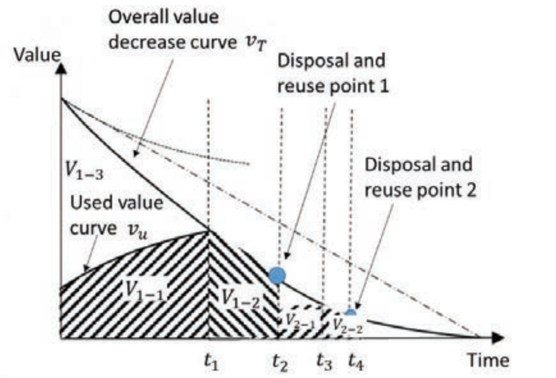

Fig.4. Accumulative used value and overall value of a product in a whole lifetime

Also, the overall value can be gained from Fig.4. in eq.(5).

$$V_{overall(i,t)} = V_{1-1} + V_{1-2} + V_{1-3} + V_{2-1} \ldots = \int v_T \tag{5}$$

3.1.3. From product to resources

To calculate resource efficiency in this stage, firstly we need to find out what happened in this process. After final utilization of any functionalities of product, to reduce the environmental burden and gain resources from the so called 'urban ore', some methods are applied to this process. However, since resource use is a speaking from the aspect of human beings, the resources smelted finally in this process does not actually belong to the 'useful output' from the whole life of a product and the aspect of people according to the original total amount of resources. Simply to say, what we do with the original total amount of resources is not to get the recycled resources. So to evaluate the resource efficiency, the first thing to do is the essential analysis of this process.

As section 2 mentioned, the benefits of this process, essentially speaking, are to achieve the goal that reduce the total amount of resources while making the same product that serve the same functions to human beings. In other words, this process achieves the benefit that needed original total amount of resources by the real depleted amount of resources, which the real depleted amount of resources means that the original total amount of resources minus the recovered resources in the end-of-life of product. From the analysis, resource efficiency of this process can be described as eq.(6).

$$E_3 = \frac{TMR_T}{TMR_T - TMR_R} \tag{6}$$

TMR_T: TMR of the resources needed to produce the product;
TMR_R: TMR of the resources recycled;

Actually, resources recycled in the whole lifetime of a product can be subdivided into two parts, one is recycling from the scrap, while the other is recycling from the end-of-life product [13,14].

3.2. Coefficient of environmental impacts

Take an overview of the whole lifetime of product, one important problem or bad effect is the impact on environment. Take the Greenhouse gas emissions(GGE) for example, it is said that the total greenhouse gas emissions are 54kg for a whole lifetime of 32GB iphone6s [15]. Besides for GGE, some toxic materials and heavy metals are also bad for the live circumstance and then bad for human beings. For human beings, benefit from the product consists of resources and at the same time bear the risk and harm while benefit from the whole lifetime of product. So it is necessary to consider the environmental impacts here, to help evaluate resource efficiency. According to these, as a complementary, the coefficient of environmental impacts is introduced.

The initial goal of utilization of resources is to benefit people, however, the environmental impacts that caused by the utilization of resources during the whole lifetime of product from cradle to grave are bad for human beings. So it is obviously that make sure achieving as bigger as the benefits while reducing the environmental impacts that definitely bad for human beings simultaneously can be regarded have a positive relationship with resource efficiency. Based on an eco-efficiency[16] idea and the benefit from product by people, the coefficient of environmental impacts is defined as eq.(7).

$$\sigma = \frac{TMR_{used}}{Environmental\ Burden} = \frac{TMR_P}{Environmental\ Burden}\sum w_i \frac{V_{used(i,t)}}{V_{overall(i,t)}} \qquad (7)$$

3.3. Integrated resource efficiency index

Resource efficiency considering the whole life of product has been defined and subdivided into three stages, finally the integrated resource efficiency of product can be calculated as followed eq.(8).

$$\mathrm{E} = E_1 E_2 E_3 = \frac{TMR_P}{TMR_T} \times \frac{TMR_{used}}{TMR_P} \times \frac{TMR_T}{TMR_T - TMR_R} = \frac{TMR_p}{TMR_T - TMR_R}\sum w_i \frac{V_{used(i,t)}}{V_{overall(i,t)}} \qquad (8)$$

From the eq.(8), we can easily find out that resource efficiency not only related to the mechanical technology, but also has a relation with the used condition from human beings. Considering environmental impacts along with utilization of resources, the coefficient of environmental impacts defined before need to be covered while evaluate resource efficiency, which showed as eq.(9).

$$\text{Total Resource Efficiency} = (\mathrm{E}\,, \sigma) \qquad (9)$$

Actually, this method calculates the total resource efficiency with two indices from multi-dimensions. The method not only evaluate resource efficiency with the index of integrated resource efficiency consists of three stages of resource efficiencies of a product from mechanical and human beings' aspects, but also using the coefficient of environmental impacts as a complementary to cover the aspect of environment. When to evaluate resource efficiency, the result may be laid in any of the four areas, which can be expressed as table.1.

Table 1. Results and analysis of resource efficiency

Results	Bad E, Bad σ	Good E, Bad σ	Bad E, Good σ	Good E, Good σ
Analysis	Worst performance	Good at resources utilization, bad for environment performance	Bad for resources utilization, good at environment performance	Best performa-nce

From the results and analysis, a figure can be drew to show directly the performance of resource efficiency of a product, which is expressed as Fig.5. Obviously, section A is the worst resource efficiency of all while section C is the best performance of resource efficiency. Besides, this figure can be used for comparing total resource efficiency of different products. If one analysis showed that one product has a low integrated resource efficiency(E) and a very low coefficient(σ) of environmental impacts, which distributed in the A area, while another product has a high integrated resource efficiency(E) and also a very low coefficient(σ) of environmental impacts, which distributed in the B area, we can easily make a comparison between the two products and find out that the latter product is better than the former one in resource performance. Moreover, it is useful for indicating which is urgent and what can be done to improve resource efficiency. As a product with a worst performance in total resource efficiency, which located in A area, we know that it's urgent for improving both integrated resource efficiency and coefficient of environmental impacts. And with balancing of importance of resource consumption and environmental impacts, we know what we need to do firstly to solve the problem, such as firstly from resource utilization aspect or firstly from environmental aspect. Then a technology improvement measure or some policy can be proposed to improve the total resource efficiency. All of these make this evaluation method a comprehensive and multi-dimensions to achieve evaluating resource efficiency and making comparison.

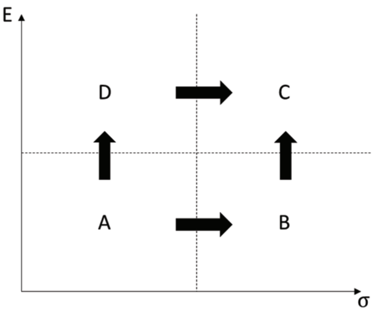

Fig.5. Figure of resource efficiency

4. Conclusion

This paper focuses on analysis of resource efficiency of EEE (Electrical and electronic equipment). First, an analysis of whole life of a product is made, and based on the utilization stage of resource and product, a whole life of product is divided into three stages, which are from resources to product, the process of utilization of product and from product to resources. An overview of the core of each stage is given, of which a model of used value is proposed and analyzed. Based on the analysis of each stage, then a calculation of resource efficiency of each stage is defined. The TMR (total material requirement) is used here to consider the importance and critical of different resources while at the same time the mathematical methods to calculate accumulative used value and overall value of a whole life of product are put forward. Furthermore, since nowadays, environmental problem is becoming more and more critical and bad for lives of human beings, so a coefficient of environmental impacts is proposed to make a complementary to calculate resource efficiency. The coefficient of environmental impacts is derived from the combination of the definition of eco-efficiency and the used condition of product by the aspect of human beings. And finally, a comprehensive and multi-dimensions method to evaluate total resource efficiency is brought out.

The method proposed in this paper is believed not only can evaluate the resource efficiency of a product from aspects of mechanical, utilization of people and environment, but also can be used to help improve resource efficiency with the analysis results directly.

Based on the method proposed here, a total analysis of resource efficiency of different smartphones and different life stages of smartphones should be performed as future work.

References

[1]Http://ec.europa.eu/environment/resource_efficiency/targets_indicators/roadmap/index_en.htm. Accessed August 10, 2016.

[2] Life Cycle Assessment. Http://www.unep.org/resourceefficiency/Consumption/StandardsandLabels/MeasuringSustainability/LifeCycleAssessment/tabid/101348/Default.aspx. Accessed July 20, 2016.

[3] Number of Smartphone Users Worldwide from 2014 to 2020 (in Millions). https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/. Statista.. Accessed July 2016

[4] Geyer, R., & Blass, V. D. The economics of cell phone reuse and recycling. *Int J Adv Manuf Technol*; 2010. 47:515-525.

[5] S.N.M.Menikpura, Yasuhiko Hotta, Atsushi Santo. Sustainability Assessment of Waste Electrical and Electronic Equipment (WEEE) Recycling in Japan. 5th International Conference on Sustainable Build Environment 2014, Kandy, Sri Lanka. 2014.

[6] Shinsuke Kondoh, Keijiro Masui, Mitsuro Hattori, Nozomu Mishima, Mitsutaka Matsumoto. Total Performance Analysis of Product Life Cycle considering the Deterioration and Obsolescence of Product Value. International Journal of Product Development 2008; Vol.6, No.3. Print.

[7] http://cligs.vt.edu/mobile-phones/Where Do Mobile Phones Go When They Die? By: Ellen Graap Loth. Accessed 2016.

[8] M. Nanjo. Bulletin of the Research Institute of Mineral Dressing and Metallurgy. Tohoku University, vol. 43, No. 2 (19880325). 1988; pp. 239–251.

[9] Raffaello, C., Ian D. Williams. Urban mining: Concepts, terminology, challenges. Waste Management. 2015. p.1–3.

[10] https://en.wikipedia.org/wiki/Efficiency. Accessed July, 2016.

[11] Nakajima,K., Yamamoto,K., Nakano, K., Kuroda, K., Halada, K., Nagsaka, T. Journal of Life Cycle Assessment Japan, Vol. 2, No. 4. 2006; pp.341-346.

[12] Carlos Montalvo, David Peck, Elmer Rietveld. A Longer Lifetime for Products: Benefits for Consumers and Companies. Accessed 2016. http://www.europarl.europa.eu/RegData/etudes/STUD/2016/579000/IPOL_STU. 2016.

[13] C. Hicks,. R. Dietmar, M. Eugster,. The recycling and disposal of electrical and electronic waste in China:legislative and market responses. Environmental Impact Assessment Review 25. 2005; 459-471

[14] Luciana Harue Yamane, Viviane Tavares de Moraes, Denise Crocce Romano Espinosa, Jorge Alberto Soares Tenorio. Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers. Waste Management 31.2011; 2553-2558

[15] iPhone 6s Environmental Report. http://images.apple.com/environment/pdf/products/iphone/iPhone6s_PER_sept2016.pdf. Accessed 2016.

[16] Desimone. L., Popoff. L. Eco-efficiency-the Bussiness Link to Sustainable Development-Cambridge, MA: MIT Press; 1997.