Circular consumption and production of electronic devices: an approach to measuring durability, upgradeability, reusability, obsolescence and premature recycling

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Abstract

What is circular consumption of electronics? Is it measurable? Can we set goals or compare with other consumers? A principle of circular economy is durability, prolonging the useful life of products. If we move the principle to the function of consumption, we would have that: circular consumption is to make the most of time resources by ensuring that in the end they are recycled, but never before time or prematurely, but only when they can no longer be used or reused by anyone else. In this article we propose a set of measures, metrics and progress indicators to measure the use of resources that consumers make in their use phase. With these metrics we can identify which consumers are the most circular; those who are able to use the same electronic devices for the longest time, either internally, or by collaborating with external agents so that these devices are reused and recycled properly. We have been able to validate usage performance metrics and premature recycling in the analysis of more than 3,000 desktop and laptop type electronic devices. These devices have been discarded by hundreds of organisations in 2018 and 2019. Finally, we propose the metrics of durability and obsolescence for models and brands of devices, which although it does not allow us to know the reasons for a low durability; absence or high cost of spare parts, difficulty of repair, etc., it does allow us to elaborate a ranking so that consumers can reward with their consumption choice, manufacturers who make products that reach high thresholds of durability.

Keywords: Resource efficiency, ICT for sustainable consumption, responsible and collaborative consumption, Circular Economy

1. Introduction

What is circular consumption of electronics? Is this measurable? Can we set goals or compare with other consumers? A principle of the circular economy is to extend the useful life of products. If we transfer this principle to consumption, we would have that: circular consumption consists of making the most of resources by ensuring that they are recycled, but never before time or prematurely, but when they can no longer be used or reused by anyone else.

In this article we propose a set of measures, metrics and progress indicators about the use of electronics, in fact computing devices, related to decisions that consumers make along the use phase of these devices. Electronics is in a dare situation, the majority of electronics is underused, not used while still useful, and the majority of it ends up in landfills. We are talking about 45 MT of e-waste in 2016 (UNU, 2017) and only 20% is documented to be collected and recycled, and quickly growing, with an expectation of 150 MT by 2050. The estimated value of raw materials in e-waste in 2016 was at 55 Billion Euros, more than the 2016 GDP of most countries in the world. The transition from 'linear' to 'circular' models that maximises usage and minimizes waste is key, and digital devices can help as most components have identifiers, even serial numbers, and data can be extracted from them (Franquesa et al., 2015).

In section two we argue this requirement and other challenges for measuring circularity in the consumption of electronic devices. We also explain where the data used to carry out the proposed methodology and study comes from. According to our criteria, we have two basic measures; the "hours of use" carried out during the life cycle of the more than 3,000 devices analysed and the "use value" or potential of their performance. Combining these specific quantifications, and their context attributes (life cycle phase, etc.), we define new metrics and indicators. For instance, looking at the upper percentiles of the distribution of total hours by models, we can obtain the durability metric per model. Combining these averages, metrics and their attributes we also propose how to calculate the potential for reusability, to estimate the obsolescence of a model or to detect premature recycling by a consumer. The methodology and metrics are presented in section three.

Section four presents an analysis of a dataset from more than 20 organisations over three years and more than 3,000 devices. It is used validate our hypothesis, the methodology that allows us to measure progress towards a circular economy in the consumption of electronic devices. We offer the dataset and the source code where the reader can generate the proposed metrics and variants of these. Section five is for discussion, section six is for conclusions, followed by acknowledgements.

2. Requirements for circular and collaborative consumption of electronic devices

To explain what we mean by circular consumption of electronic devices we will introduce the terms of reuse, recycling and the differences between them: The terms recycling and reuse are often used as synonyms, but this is incorrect: “recycle” refers to the process in which a raw material is used again to create something new, while “reuse” means use a product or its components again for the same purpose or find another use for the item.

Reuse of electronics

Reuse of electronic devices such as desktops, laptops or mobile phones applies to devices that have already been manufactured and are no longer in use (ready for disposal) and will be recycled unless they are not repaired, refurbished and/or redistributed to other users. The reuse process ends when, after a few years, the device or a component returns to the disposal state, which means its use value then, or potential if improvements were made, does not allow its reuse again. That should end up in recycling, a process that transforms computational use value into raw material use value (Franquesa et al., 2018).

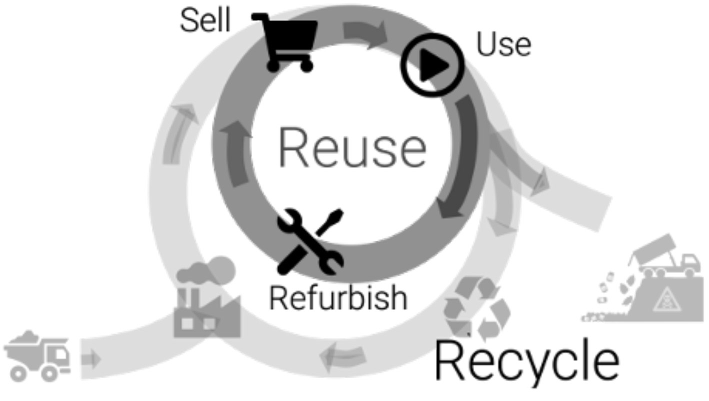

Figure 1: *Closed loops in the circular economy*

We say that a device or component is reusable if it has any use value for someone. We use the word "potential" because when a device is not currently in use it will only be reused if a refurbish process is applied and the same user or another user finally uses it again.

We refer by "use value"[1] to the capacity of a device to satisfy a need, in our case of computing (storing, computing, viewing data, etc.), and not to the "exchange value" of a device on the market. The value of exchange depends on factors such as the value of its resources used during its life cycle, the work added to make raw materials computing usable, or supply and demand, and other factors not currently considered, such as the social impact on the extraction of materials, labour aspects or the pollution generated.

We say that the use value of a device is universal and does not depend on a specific geographical location. It does not depend on the value given by the current user that wants to dispose a given device, which is its subjective perception of value, that one person may consider it too low while there may be someone else not too far away willing to recondition and use it.

If the use value of the device is high enough, it means that there is somewhere a potential user for that device as it is, and only a basic refurbishing processes is required, such as erasing data or restoring the operating system. If the use value is too low, its use value can be increased through several types of actions of refurbishment: repairing, replacing damaged components and updating or upgrading.

Ensure non-premature recycling

The concept of Circular Economy (CE) can become very elastic. Its meaning can vary drastically depending on the interests of the person who defines, uses and implements it. For example, it is considered circular to burn waste for the generation of energy. If accepted, will the burning of a product that could have been reused continue to be considered as circular? In order to achieve a circular economy of electronic devices we should ensure at the time of recycling that devices have low use value, so there is no premature recycling.

We include in the CE of electronic devices the non-premature recycling requirement. This necessarily implies the need of performing all viable reuse processes (economically and voluntarily) until, at a disposal point, the device's use value, or potential if improvements were made, would not allow its reuse. In this way, ensuring that there is no premature recycling, our society would not lose value from the computational resources in circulation (the one already made) and we would make more efficient use of our resources (minerals, work, pollution capacity, etc).

The reality is that today only about 20% (UNU, 2017) of the electronic devices manufactured are properly recycled, and many of the devices that are properly recycled are still recycled despite they are usable by someone. How can consumers avoid premature recycling? From our viewpoint, this poses a new challenge, the collaboration.

Collaborative consumption of electronic devices

We define collaboration understood as the collective management of resources (Franquesa et al., 2017). Common property systems include social arrangements that regulate the preservation, maintenance, and consumption of natural or human-made resource systems, also called common-pool resources or CPR (Ostrom,

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[1] Use value refers to the tangible features of a commodity (a tradeable object) which can satisfy some human requirement, want or need, or which serves a useful purpose. In Karl Marx's critique, any product has a labor-value, use-value, and if it is traded as a commodity in markets, it additionally has an exchange value, a money-price. [https://en.wikipedia.org/wiki/Use_value]

1990). These CPRs consist of a core resource (e.g., computation use) that provides a limited quantity of extractable fringe units that can be harvested or consumed (e.g. raw materials such as coltan, devices).

An example of collaborative consumption would be carried out in the following way: when the device goes to disposal, the collector point does not recycle it, but derives it to a new agent that ensures only be recycled if it is not reusable. Agents such as manufacturers, refurbishers, retailers and recyclers, will interact, increasing and distributing the value to other users who, at the same time, commit themselves to ensure non premature recycling. Recyclers, who do not recycle what still has use value, must be compensated in some way, and they should also return the raw materials to their owner or the manufacturer to build a new device.

Datasets for a monitored circular economy

The socio-economic-environmental interactions take place among the people involved in the CE as they manage and govern the material commons constituted by a pool of devices, components and raw materials, among the big data sets that include traceability information, among that community with the natural environment.

The data to elaborate this article have been given by the members of eReuse in an anonymous way. Below we briefly introduce the reader what is eReuse, its mission and members.

eReuse.org is an association dedicated to the transition to a collaborative and circular consumption of electronics. The eReuse community is formed by activists, local groups, researchers, universities, educational centres, businesses, circular economy entities (refurbishers, retailers, recyclers), institutions and, in general, all persons and entities that promote the economy of reuse and recycling of electronics.

eReuse members are able to ensure to their customers and partners the data that certify they are doing circular economy, so any device that has been collected, refurbished and resold by them, is ultimately recycled, but ensuring not in a premature way.

3. Measuring consumption and production of electronic devices

In this section we develop our proposal to measure the consumption and production of digital devices. We focus on measuring the usage hours of the devices and the assessment of their capabilities in their use phase. From the analysis of these two measures then we elaborate metrics to evaluate how circular is its consumption and production.

The related work covers a wide spectrum depending on the focus of interest. In the context of the use of digital devices, quality is generally referred as fitness for purpose, about fulfilling requirements (ISO 9000). The "Eight dimensions of product quality management" (Garvin, 1987) allows to analyse different quality characteristics, and these can be grouped in terms of either how well it serves (performance, features, conformance, aesthetics and even perceived quality), or how long it serves (reliability, durability, serviceability). These last three result in the length of a product's life (lifespan) that lasts until it is no longer economical to operate. However, the lifespan of an electronic product can include maintenance, repair, upgrade, transfer to a new user (reuse), until no one can use it (it breaks down or its use value is below a threshold).

The perspective of the circular economy focuses on the consumption of resources that are finite, and therefore on closed loop circuits where resources are restored, transformed and never disposed or wasted. That demands a systemic view of the flow of resources (products and companies). Focusing exclusively on technical cycles and materials from non-renewable sources, the Material Circularity Indicator (MCI) (McArthur, 2017) compares "the proportion of the product being restored (through component reuse and recycling) and coming from reused or recycled sources [...] as the restorative part of the flow, while the linear part of the flow is the proportion coming from virgin materials and ending up as landfill (or energy recovery)”. Therefore, MCI provides an indication of how much a product's materials circulate, but not on the usable product during its lifespan.

For this reason, we need indicators at the level of devices that provide services to their users.

In terms of requirements, we can summarize them in the need to measure:

- The durability potential of a device as part of a set (model)
- The effective duration, extended use of a device across multiple users (reuse), phases (repair), and final recycling when use is no longer feasible. This is also applied to a unit or group of units.

A measure is the result of a unique and specific quantification of data. The measurement is directly related to quantifying the data at an acceptable level of quality and includes the precise operational definition of exactly how the data is collected. The distance of 10 centimetres is a good example, as centimetres are a standard, and we have the instruments to make the measurements (ruler, etc.). We will introduce it later, but in our case one of the measures would be the usage hours of a device.

Metrics are combinations of multiple measurements, often proportions, and represents an extrapolation or mathematical calculation of the resulting measurements in a derived value. For example, the metric "potential durability in hours of a device" can be defined as a high proportion of durability samples; if the 90th percentile of hours of use of the device I am using is of 10 thousand hours, we could assume that the potential hours of use of my device is of 10 thousand hours. In order to calculate percentiles, we need a dataset to position the values.

Indicators are a representation of a measurement or metric in a simple or intuitive way to facilitate its interpretation against a reference or goal. Continuing with the previous example, if at a given time I want to know how much I have used my device, I could make the quotient between the hours of use made so far and the potential durability of my model; if I have used my device 5 thousand hours and this has 10 thousand potential hours, it means that I am around 50% of utilization.

Measures

Hours of device usage. It is an (objective) measure that indicates the number of hours that a particular device has been in usage. The capture method is currently the result of an estimate made through a software that analyses variables on the hard disk of the device. A limitation is that in cases where the drive has been replaced, we will not be able to count the hours of the previous drive. Details are provided in (Franquesa et al., 2018).

Use value[2] per device. It is a measure (evaluative), although it could also be interpreted as a metric, which makes an assessment or score of the performance of a device. It aggregates in a single value the measures for all its components. A software collects the performance of the devices at component level and scores them according to a comparison with other devices registered in the system. For example, if the write speed of a hard drive is at percentile 10, this feature would get 10% of the possible points of the hard drive's speed feature. The characteristics of the components (e.g. write/read speed, size) and the components (e.g. disk, memory) are then merged together by weighted harmonic averages. The resulting value ranges from 0 to 5, never reaching 5. The use value of a device over time tends to decay as its performance declines to lower percentiles. Details are provided in (Franquesa et al., 2018).

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[2] We refer by "use value" to the capacity of a device to satisfy a need, in our case of computing (storing, processing, viewing data, etc.), and not to the "exchange value" of a device on the market.

Metrics

Hours of lifecycle usage per device. It is a metric that indicates the number of hours that a device has been in each usage cycle. According to the period of capture, they are classified between hours in the first usage cycle and total usage hours. The hours in the first cycle are performed by the consumer who purchases the device for the first time, and the totals include all consumers who have ever had the device in question.

The capture method is a software that estimates the hours associated with a device unequivocally, from internal counters, and the capture channel is the user or reuse provider. The period is at the end of the first cycle of use, which would be at the time when the consumer organisation discards a device. The capture channel is the consumer's reused device provider.

In those cases in which the drive has been replaced, we will not be able to count the hours of use of the previous drive. In order to overcome this limitation when replacing the drive, the hours of use of the drive can be reported periodically or specific moments to the device's traceability system.

Hours in the first usage cycle per device = Sum of usage hours of drives from the first usage cycle of that device

***Figure 1**. Hours in the first usage cycle*

The capture method is the same as the previous one. The period is at the end of the last cycle of use, which would be at the time when the last consumer organisation discards the device. As in the previous case, when the drive is replaced, the drive usage hours must be reported to the traceability system where the first consumer registers the device.

Total usage hours per device = Sum of usage hours of all drives the device had during all usage cycles of that device.

***Figure 2**. Total usage hours*

Durability per model in usage hours. It is a metric that indicates us the estimated duration of operation in hours that a device model can reach to have. Its value is calculated by ordering from lowest to highest the total usage hours or total duration by model of observations in the system. We use the 90th percentile, which would represent the durability value reached by 10 percent of the observations. For example, if the 90th percentile of hours of use of my device model is 10 thousand hours, we will assume that the potential usage hours are 10 thousand hours. The capture method is based on a statistical database created and maintained by the community of eReuse.org system users, as explained in Section 2.

Durability per model = # The 90th percentile of the total usage hours recorded in the system for a given model.

***Figure 3**. Durability per model*

Performance in usage hours per device. This performance is a progress indicator that measures the extent to which this device has been used compared to other devices of the same model. It is the ratio between the usage hours performed by the device and the durability of the model. For example, if a laptop of a given model has been used for 5 thousand hours, and its model has an estimated durability of up to 10 thousand hours, then the performance in usage hours per model has been 50%, which is the quotient of 5 thousand / 10 thousand.

Performance in usage hours per device =
Usage hours of a device / Durability of the model.

Figure 4. *Performance in usage hours per device*

Maximum use value per model. It is a metric that indicates the maximum use value a model has reached. Its value is the maximum use value among the model's observations.

Maximum model usage value = Maximum use value of a
model across all observations

Figure 5. *Maximum usage value per model*

Device improvability. It is an indicator that shows the potential for improvement that a device has. The maximum use values for the same model are compared to find out in what proportion the device can be improved. For example, if the maximum usage value of the device model is 4, and the usage value of the device is 3, it means a 25% improvement could be made.

Improvability of the device in use value = 1 –
(Device use value / Maximum model use value)

Figure 6. *Improvability in use value per device*

Current reusability per device. It is an indicator that shows how reusable a device is. It is a proportion between the number of devices that continue to operate with a similar model and the use value for those that have been recycled. In this case we look at the current reusability without taking into account the improvements we could make; for example, if my laptop has a use value of 3 and there are currently 50% of my model laptops in use and 50% have been recycled, we can say in some way that my laptop is 50% reusable.

Current reusability = % devices of a model in usage phase
with similar use value.

Figure 7. *Current reusability per device*

Potential reusability per device. An indicator that tells us the theoretical reusability potential of a device. It is a proportion of the devices that continue to operate of a similar model but with a higher value of use because they have been improved, in relation to those that have been recycled.

Reusability potential = % devices of a model in usage phase
with higher use value.

Figure 8. *Reusability potential per device*

Obsolescence per model. It is an indicator of the obsolescence level of a model. It compares the devices of a model in the recycling phase with other devices of other models that are still in use, both with similar use value. The maximum difference with another model gives us the obsolescence value. A model should become obsolete because its use value is low and not for other reasons; if in a model we find a set of devices that still have use value to be in use, but are discarded, it means that there is some kind of obsolescence that is not a function of the model's characteristics. Examples of obsolescence could be that the devices are locked by the manufacturer or the software cannot be updated. That is, the device's performance is sufficient, but there are other barriers that prevent it from being used. The greater the difference, the greater the obsolescence. For example, from a certain model and with use value 3 there are 40% of devices, and 60% have been recycled, while with the same use value we find other models with 80% of devices in use and only 20% recycled. The indicator is 200% induced obsolescence by the model which is calculated as (80/40) x 100%.

Model obsolescence = maximum difference between percentages of model devices that are in the recycling phase compared with other devices from other models that are still in usage, both with similar use value

***Figure 9**. Model obsolescence*

Premature recycling per device. It is an indicator that shows the potential for reuse that we are discarding if we recycle the device. This indicator is the same as the "Potential reusability of the device" indicator.

Premature Recycling per Device = Potential Reusability

***Figure 10**. Premature recycling per device*

***Table 1.** Measures, metrics and indicators of circular consumption of devices*

Name	Description	Capture methods	Channel & capture period	Frequency
Hours of device usage	Measure, the number of hours a particular device has been in use all your life as a product	Usage hours estimation software. When the drive has been replaced, we cannot count the preceding hours	Calculated by the user or reuse provider. Depending on the period (in use, in disposal, in recycling) new metrics can be created	-
Use value per device	Measure, a score of a device's performance to meet computing needs, values range 0 to 5	Device performance rating software. Computes a score compared to other devices registered in the system	Calculated by the user or reuse provider. Depending on the period (in use, in disposal, in recycling) new metrics can be created	-
Hours in the first usage cycle per device	Metric, number of hours a device in use by the consumer who purchases the device for the first time	Usage hours capture and estimation software. Sum of usage hours of the hard drives in the first cycle of usage of that device	Calculated by the user or reuse provider at the end of the first usage cycle	4-7 years
Total usage hours per device	Metric, number of usage hours for a device by all consumers in the device usage cycle	Usage hours capture and estimation software. Sum of usage hours of all hard drives the device had during all its cycles of use	Calculated by the user or reuse provider at the end of the last usage cycle	7-15 years
Durability per model in usage hours	Metric, the number of total hours a device model can accumulate	Formula: 90th percentile of the total usage hours recorded in the system for a model	Metric available in the system	Daily

Performance in usage hours per device	Indicator, percentage of utilization performed in usage hours on a device	Usage hour estimation software. Formula: ratio between usage hours made by the device and the durability of the model in usage hours	Calculated by the user to know the current performance	Daily
Maximum model use value	Metric, the maximum usage value that a model has reached	Formula: The maximum use value per model of the observations recorded in the system	Metric available in the system	Daily
Device improvability	Indicator, percentage of possible improvement of a device compared to the maximum use value reached by the model	Device performance rating software. Formula: 1 - (Device Use Value / Maximum Model Use Value)	Calculated by the user to find out the current use value	Daily
Current reusability per device	Indicator, probability of it being reusable according to the proportion of devices of the same model and use value that are in operation	Usage hour estimation software and performance valuation software. Formula: Current reusability - % devices of a model in usage phase with similar use value	Calculated by the user to know the current use value	-
Potential reusability per device	Indicator, probability that it will be reusable if we improve the components. Considering devices of the same model in usage phase with maximum use value	Usage hour estimation software. Formula: % devices in a model in usage phase with higher (max) use value	Calculated by the user to know the current use value	Daily
Obsolescence per model	Indicator, compares model devices in the recycling phase with other devices of other models that are still in usage, both with similar use value	Performance valuation software. Formula: Maximum difference between percentages of model devices in the recycling phase compared with other devices from other models still in usage, both with similar use value	Metric available in the system	Daily
Premature recycling per device	Indicator, the reuse potential that we are discarding if we recycle the device	Idem: Potential device reusability		

4. Analysis

The following analysis is based on data reported by more than twenty organisations between February 2016 and May 2019. We have a total of 3,045 observations and 281 models for desktop and laptop devices. We have selected only those models for which we have at least 10 observations. This has reduced the number of models to 51 and that of observations to 2,460. From all these observations we have the measure of "hours of device usage", and from these, 1,611 observations with the measure of usage value.

From this data we have been able to validate the metrics of: first cycle hours of use of the device, total hours of use of the device, durability of the model in hours of use, performance of the device in hours of use, maximum use value of the model and current upgradeability of the device. As we do not have measurements of devices in their usage phase, we have been able to validate the metrics of current and potential reusability, model obsolescence and premature recycling. In this public repository[3] the reader can access the data set and the source code we have used to elaborate the metrics.

The following Table 2 shows the ten models with highest durability in usage hours, carried out on a dataset with 2,460 observations. The model with the highest durability is the Lenovo ThinkCentre 7071.

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[3] https://github.com/DSG-UPC/circular-electronics-metrics

Table 2. *Top 10 models by model durability in usage hours*

Model	Manufacturer	Model Durability
ThinkCentre 7072	Lenovo	53,535
EB1007	Asus	51,146
HP Compaq 6005 Pro	Hp	44,199
HP Compaq dc7600	Hp	43,805
B202	Asus	42,258
ThinkCentre 9644	Lenovo	40,686
ThinkCentre 7200	Lenovo	38,821
HP Compaq dc5700	Hp	37,435
ThinkCentre 7300	Lenovo	36,664
ThinkCentre 97047	Lenovo	35,083

Table 3 below shows the ten devices with the highest number of usage hours. We also present the metric introduced in the previous section "Performance in usage hours per device", which is the quotient between the hours performed and the estimated model durability. In the case of Dell Latitude E6300, there is a user who has achieved a performance in hours of up to 643%.

Table 3. *Top 10 devices by drive usage hours*

Model	Manufacturer	Hard Drive Usage Hours	Model Durability	Performance in usage hours per device
Veriton M400	Acer	65,332	30,043	217%
HP Compaq 6005 Pro	HP	64,228	44,198	145%
Veriton M400	Acer	64,050	30,043	213%
Veriton M400	Acer	63,941	30,043	213%
OptiPlex 700	Dell	62,891	34,267	184%
Veriton M400	Acer	62,650	30,043	209%
Latitude E6300	Dell	62,469	9,709	643%
HP Compaq DC5700 Microtower	HP	60,858	30,151	202%
75227	Lenovo	60,617	29,678	204%
OptiPlex 700	Dell	59,684	34,267	174%

The following Table 4 presents a device for each model and its indicator of "device improvability by use value". The improvement potential is the difference between the use value of the device and the maximum value observed in a model. For instance, in the case of the Dell Optiplex 700 we see that there is a potential for improvement of 50.2%, so that adding new components or improving the existing ones it could reach the rating of 4.16.

Table 4. *Device improvability by use value*

Model Maximum Use Value	Date	Model	Manufacturer	Use Value	Device Upgradeability Use Value P

4.2	2019-05-15	OptiPlex 7000	Dell	4	4.8%
4.16	2016-12-01	OptiPlex 700	Dell	2.07	50.2%
4.11	2017-04-11	All Series	Asus	4.01	2.4%
4.06	2018-06-14	Veriton M400	Acer	3.81	6.2%
4.04	2019-03-13	HP Compaq 6000 Pro MT	HP	4.04	0.0%
3.98	2018-04-20	2349	Lenovo	3.93	1.3%
3.97	2018-07-31	HP ProBook 600	HP	3.96	0.3%
3.96	2018-04-18	HP Compaq DC7900	HP	3.74	5.6%
3.95	2018-04-20	HP ProBook 4500	HP	3.93	0.5%
3.95	2016-11-20	5400	Lenovo	3.92	0.8%

5. Discussion

In order to know the durability of the device in all its usage phases it is necessary to analyse all the hard drives it had. When a hard disk is discarded, data is usually erased. We propose that it is just at the time of data erasure when data is reported: serial number of the hard disk, the serial number of the device and the hours made by the hard disk. Is it a trusted and irreversible data repository (a blockchain) the place where to store this information in order to be able to analyse it and know the total durability?

To be able to elaborate the metrics for improvement, reusability, obsolescence and premature recycling, it is necessary to know the proportions of devices that are in use and recycling phases, grouped by use value and model. For this it is necessary to collect measurements of the use value in different states and changes of usage of a device. We believe that only the following would be necessary: 1) at some point in its use phase before increasing its value, 2) when its performance and therefore its use value are improved, 3) when the device is discarded and ceases to be used, 4) each time it enters a new usage phase, 5) when it is definitively discarded for recycling.

Knowing metrics such as the durability or improvability of devices is a metric that, combined with the cost of acquisition and other variables, allows us to know the return on investment and ultimately optimize our consumption. This means that collecting these measures is not an ad-hoc process and therefore makes it more feasible in terms of costs to measure them.

We present a proposal to estimate the programmed obsolescence of a device model. The sample is not representative enough to make this estimate, so it remains to determine how many devices would need to be analysed and in what contexts to be able to generate reliable metrics that could serve consumers.

Furthermore, if the goal were to influence decisions and improve circularity, there are areas to explore to create incentives. Incentives can be developed with the implementation of a certified public or permissioned repository, a notary system and contracts to award compensations (a distributed ledger with smart contacts as being explored by eReuse in the Ledger project), that promote the declaration and sharing of data and even certain beneficial actions from consumers (e.g. increasing reuse, repair, donation) that later serve to compute indicators in a reliable and statistically significant way. Recycling can also benefit (recycle value) from incentives, since recycling cost/value is often negative (it costs more to recycle a device than the value in recovered raw materials to generate): an economic deposit associated with a device can compensate recyclers to make profitable more recycling to recover more raw materials.

There are limitations, as a) we cannot know the intensity of recycling, understood as the percentage of recovered raw materials (McArthur, 2017); b) a device is counted by the usage hours of its hard drive, so we are assuming that it has not been replaced. If replaced, the impact would be negative because the usage hours of the previous drive would not be counted; c) influence of manufacturers, initial device suppliers, reuse and recycling suppliers: their performance directly impacts the circularity performance and quality of consumer organisations; d) privacy versus accountability, as traceability and device related data is required to keep track of circular processes, but should never come at the expenses of lack of privacy from the people or organizations involved; e) the first and the last element of the lifespan of devices has a key role to bridge with other parts of the circular economy: the manufacturer can link component and device data, such as serial numbers, to raw materials, factories, workers and their labour rights, as Electronics Watch monitors labour conditions or environmental organizations monitor conflict minerals; and the recycler can link to the flow of recovered raw materials.

Related to the performance of reuse and recycling suppliers. A consumer organisation can establish collaborations with external entities that guard the devices, promoting their reuse and final recycling. Their performance would directly impact the circularity performance of consumer organisations. Related metrics:

1. Creation of value by repair and update. This metric shows the extent to which the reuse provider has increased the value of the devices it has received. New usage value is created from the processes of repairing and updating components. For example, an external organization receives 100 units of value, and applies improvement that increase it to 120 units. In this case the KPI would be 120%.
2. Extension of usage hours: time in operation in external users. If the consumer organisation has used 100 hours and externally 20, this would represent an extra value of 20%.
3. Device Loss/retention KPI: It evaluates the extent to which devices that are reused externally end up being recycled at the end of their usage. A 100% indicates that all devices that are reused end up being recycled. We calculate it in terms of use value, although it would be desirable to calculate it in terms of the value of the raw materials they contain as this is the real value lost.

6. Conclusions

Our approach to measuring circularity in the consumption and production of electronic devices is to focus on the performance achieved in their use phase. We have two measures: the usage hours and the use value. Performing these measurements at certain times of their usage cycle and with their respective instruments we define the metrics proposed to measure the circularity of consumers and products.

The necessary instrument to collect the measurement of usage hours is a software that analyses the variables in the hard drive. In order to know the durability of the device throughout its usage phase, it is necessary to analyse all the hard drives it had. We propose that each time the data is wiped from the drive, either because there is a drive replacement or because it is reused by another user, the data erasure software employed notifies the serial number of the device, of the hard drive and the usage hours. Aggregating this information would allow to have all the hours of its usage cycles.

The necessary instrument to measure the use value is a software that assesses the capabilities of a device. In order to elaborate the metrics of usability, reusability, obsolescence and premature recycling, it is necessary to collect these measures of the use value in the following states and changes in the state of use of the device: 1) at some point in its use phase before increasing its value, 2) when its performance is improved and therefore its use value, 3) when the device is discarded and ceases to be used, 4) each time it enters a new usage phase, 5) when it is finally discarded for its recycling.

Combining these two measures we create metrics such as durability, usability, reusability, planned obsolescence or premature recycling. For example, with the total durability of all the devices of a model we can estimate the total durability of a model, or with the maximum use values per model we can know how much better a device can become.

The study carried out with more than 3,000 devices has allowed us to validate the metrics of: first cycle hours of use of the device, total hours of use of the device, durability of the model in hours of use, performance of the device in hours of use, maximum value of use of the model and current improvability of the device. As there are no measurements of devices in their use phase, it has not been possible to validate the metrics of current reusability, potential, obsolescence by model and premature recycling.

In conclusion, we believe that these measures, measurement instruments and metrics are effective in measuring circularity in the consumption and production of electronic devices. The measurements needed to generate traceability data and valuation of the devices makes sense in the day of an organisation to optimise consumption and obtain a higher return on investment, and this means that they are not ad-hoc and makes their measurement more viable in terms of costs.

Future work includes collecting proportions and values of device usage in use phase versus in recycling phase in order to validate the metrics of current reusability, potential, obsolescence by model, and premature recycling, however, these have been formulated at theoretical level.

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