Article

A Service-Learning Based Computers Reuse Program

Fermín Sánchez-Carracedo [1,*] and **David López** [2]

1 Department of Computer Architecture, University Research Institute for Sustainability Science and Technology, Universitat Politècnica de Catalunya—UPC-BarcelonaTech, 08034 Barcelona, Spain

2 Department of Computer Architecture, Universitat Politècnica de Catalunya—UPC-BarcelonaTech, 08034 Barcelona, Spain; david.lopez@upc.edu

* Correspondence: fermin.sanchez@upc.edu

Abstract: Higher Education Institutions are facing a challenging situation: how to introduce concepts such as Sustainability or the Circular Economy into their curricula. This study presents how to organize a Computer Reuse Program, an educational proposal for the Reuse, Repair, Refurbishment, Remanufacture and Recycling of computers into a Curriculum and a case study. The proposal is based in the Service-Learning methodology, by which students develop technical and professional skills while undertaking a project that has a direct and real impact on society. Students work on old or broken computers provided by donors, thereby acquiring technical skills. These now flawlessly functioning computers are donated to NGOs and other non-profit organizations, thus endowing the equipment with a much longer life as well as reducing e-waste, one of the fastest-growing waste streams in the world. As a case study, this paper presents the UPC Computer Reuse Program, carried out at Universitat Politècnica de Catalunya UPC-BarcelonaTech. Since the program started in 2004, some 2500 computers have been donated to 359 different organizations in 29 countries, and more than 5200 students have participated. The paper analyzes the impact of the program on society, on the reduction of e-waste, on the environment and on student awareness regarding social justice and sustainability.

Keywords: sustainability; education for sustainable development; service learning; computer reuse; repair; refurbishment; remanufacture and recycling

1. Introduction

In recent years, several Higher Education Institutions (HEI) have redesigned their curricula in order to promote competencies for sustainable development [1–3], during which Education for Sustainable Development (ESD) has become a consolidated scholarship at all educational levels [4], with the adoption of various strategies for implementing sustainability in higher education [5–12].

With regard to the best educational methodologies for introducing sustainability into the curricula, some studies [13–15] highlight the use of active methodologies such as Jigsaw, Project- and Problem-Based learning, Learning Case Studies, Service Learning, or Role Play. It is commonly accepted that society in the future would benefit from the education and training of professionals in sustainability skills [16–19], a question that cannot be reduced simply to the acquisition of knowledge about sustainability. The emotional involvement of students is also necessary to arrive at deep learning and a fundamental change in attitude [20,21].

Such emotional involvement can be achieved by using the Service Learning Pedagogy (SL), where students learn by performing a useful service to the community to which they belong. According to the Corporation for National and Community Service [22], SL consist of developing useful and integrated work in a structured curriculum designed to stimulate students to reflect and to expand on what they are learning in the classroom. Some authors suggest that the SL methodology has the potential to impact in ways that are lacking in

educational methodologies, since it is able to deliver value to the community by serving a real need, which encourages students to reflect on real problems and real-life issues [23–26].

The theoretical underpinning for SL was developed by Kolb in 1984 (see updated version [27]). Godfrey et al. [28] identified three elements in successful SL experiences, namely, the "3Rs of Service-Learning": Reality, Reflection and Reciprocity. Reality refers to the introduction of academic content into real-world experiences, affecting competencies such as teamwork, communication innovation and the ability to readily adapt and respond to changing conditions [29,30]. The reflection process has an impact on identity, self-esteem, self-awareness and persistence [31–33]. Reciprocity extends the idea that students should become "equal and trusted partners, able to see the roots and consequences of social issues with great clarity" [28]. Students participating in SL programs demonstrated significant gains in attitudes towards themselves and attitudes towards school learning, civic engagement, social skills and academic performance [34,35].

In 2004, the authors of this work embarked on the design of a Reuse Workshop based on the SL methodology. In this Workshop, student volunteers reconditioned old and broken computers provided by donors, thereby acquiring technical skills. These now flawlessly functioning computers were donated to schools, NGOs and other non-profit organizations, thus endowing them with a much longer life while at the same time reducing e-waste. Over the years, the original Workshop has evolved into the UPC Reuse Program (UPC-ReuTIlitza [36]), a complete system for salvaging, repairing and donating computers. The UPC-ReuTIlitza Program contributes to create a circular economy (CE).

The concept of the circular economy (CE) is increasingly attracting the attention of institutions and industry [10,37–41]. Rather than minimizing the cradle-to-grave flow of materials, the goal of CE is to generate cyclical cradle-to-cradle flow by creating a synergistic relationship between ecological and economic systems [42]. Potting et al. [43] defined a framework of targets for the CE, referred to as the 10 Rs: R0 (Refuse); R1 (Rethink); R2 (Reduce); R3 (Reuse); R4 (Repair); R5 (Refurbish); R6 (Remanufacture); R7 (Repurpose); R8 (Recycle); and R9 (Recovery). Five of these 10 Rs are covered in the UPC Reuse Program: R2 (Reduce), R3 (Reuse), R4 (Repair), R5 (Refurbish) and R8 (Recycle).

This paper presents the design basis of a Computer Reuse Program (CRP), as well as the description of the implementation carried out at the Universitat Politècnica de Catalunya UPC-BarcelonaTech (see Appendix A for details).

Given that this is an SL initiative, the results should be analyzed in the light of both the impact on students' education and the impact on society. The impact of most SL initiatives on society is usually analyzed by taking into account the social impact (i.e., people who benefit from the initiative). Due to the very nature of the project, a study of the social impact is insufficient, and an in-depth analysis of the impact on both the reduction of e-waste and on the environment is required.

Rapid technological developments in modern life have fueled the consumption of information and communication technology (ICT) products, the production phase of which requires a huge amount of raw materials, including base metals, precious metals and rare-earth elements [44] as well as energy and, therefore, GHG emissions [45–47]. Upon the conclusion of the useful lifespan of these products, they become a special type of waste known as electronic or e-waste. This is one of the fastest-growing waste streams in the world [48]: e-waste was approximately 44.7 Mt in 2016 and is expected to grow to 52.2 Mt by 2021 [49]. Although some studies exist on the economic impact of correctly recycled e-waste [50,51], reducing e-waste is not always conducted in the appropriate conditions [52], with the consequent detrimental effects on human health and the environment. Since a CRP is focused on extending the lifespan of ICT products, and thus on the reduction of both e-waste and new ICT products, a model has been developed to evaluate the impact on resource reduction and on the environment. The model is briefly described in the present paper, and a more detailed explanation is provided in Appendix B.

The objectives of this work are described below:

1. Present a methodology to design a Service-Learning-based CRP in the field of an educational institution where technical training related to computers is provided to students
2. Present a model to evaluate the impact of the CRP
3. Present, as an example, a case study in which the two methodologies described in objectives 1 and 2 have been applied.

2. Materials and Methods

This section presents (1) a methodology to design a CRP and (2) the model and metrics used to evaluate its impact. The implementation of the program in UPC-BarcelonaTech is described in detail in Appendix A as a case study.

2.1. The Computer Reuse Program

The CRP described in this paper is based on SL, so it is oriented to be applied in educational organizations such as HEIs. However, the methodology can be applied with small changes to other types of entities. The goal of a CRP is to give a second life to computers that are considered obsolete. Moreover, as part of the service that HEIs and other educational institutions provide to society, obsolete computers belonging to other organizations are also reconditioned. These computers can be donated to external social entities or remain within the organization itself for use in environments that require little computational power.

Support from the institution is necessary for assistance with the CRP logistics. In particular, a warehouse is necessary for the storage and repair of computers. The reconditioned computers must be delivered to the receiving entities throughout the year, so it is necessary to maintain a stable (short) work team. However, in order for a large number of students to participate in the SL activity, a workshop can be organized during the course (the Reuse Workshop). Students of various subjects can participate in the Reuse Workshop, which is the academic aspect of the CRP.

2.1.1. Objectives of the CRP

The objectives of the CRP and the Reuse Workshop may be summarized as follows:

*   CRP1: To provide technological resources to non-profit social entities so they can carry out their projects.
*   CRP2: To increase the lifespan of computers and facilitate recycling when they become obsolete, thus reducing e-waste.
*   CRP3: To increase the students' technical competencies and increase their commitment to sustainable development.

2.1.2. Workforce

Two independent teams have been defined to manage the CRP: the communication team and the technical team. Both teams work independently but in coordination. Both teams can be made up of volunteer students combined with institution staff to give proper continuity to the program.

*   The technical team is responsible for reconditioning the computers to function properly. It can be formed by a small group of especially motivated students (voluntaries) or supported by students of VET (Vocational Education and Training) courses who carry out their practices in the program (in the UPC-ReuTIlitza Program, the internship is unpaid). Voluntary students may dedicate typically between 10 and 20 h per week to the CRP, depending on their availability. One of these students, or a staff member, acts as the coordinator of activities. The number of students in the technical team will depend on the volume of computers reconditioned monthly. In our experience, at least one student for every 10 computers/month is required for this task.
*   The communication team maintains contact with external entities, both suppliers (the CRT may accept computers from external enterprises) and receivers of computers.

The team is responsible for (1) keeping in touch with their own university or external companies to receive their obsolete computers, (2) managing applications from entities requesting computers, and (3) keeping in touch with receiving entities throughout the donation process. To simplify the management of the program, all procedures must be managed through a web page, and the information must be stored in a database.

Representatives of the two teams should meet regularly (we recommend once a week) to analyze the donations and applications received and to decide which of them are accepted and how many computers are assigned to each application. The institution must have previously decided which kind of social entities are suitable to receive computers and the minimum technical requirements a computer must have to be reconditioned.

As the CRP is a SL program, students must be aware at all times that, in addition to improving their technical skills, they are performing a service to society by facilitating social entities to perform their work in better conditions. Students of both teams must have direct contact with members of social entities so that the CRP has the SL component. In the case of the communication team, this is achieved through direct contact between students and social entities when managing the donation process. In the case of the technical team, this is done during the computer delivery process. In some cases, members of the technical team can also offer training to social entities to help them use the computers or to install the software they need.

2.1.3. The Reuse Workshop

In the Reuse Workshop, products received by donors are tested by students. Sometimes important parts of the computer, such as the processor or the motherboard, are either broken or too old to fulfill the basic requirements defined for a computer to be donated. In such cases, the functioning parts should be recovered for future use and the rest must be sent to an accredited Recycling Company, which will undertake the correct procedure to recover basic elements such as gold, platinum and so on, the rest being processed in a way that is safe for human society and the environment, thus addressing target R8 (Recycle). Sometimes, the computers require only some maintenance work or minor repairs that can be performed with the use of spare parts already in stock. This is in compliance with targets R4 (Repair) and R6 (Remanufacture). Once the computer is running properly again, students check to see whether any hardware updates are needed (more memory or disks, a CD driver and so on), and then install a low-demand, free software that meets the requirements of the recipient organizations, thus addressing target R5, (Refurbish, i.e., restore an old product to bring it up to date). Finally, the computers will be donated to entities for future use, thereby extending their lifespan and thus fulfilling target R3 (Reuse).

The Workshop is directly related to the "learning" aspect of SL. The students that participate in the Workshop should be studying some subjects of the curriculum that have technological content, preferably related to the operation of computers. For the introduction of these subjects from the curriculum as hands-on activities in the Workshop, commitment from both the institution and lecturers from these subjects is required.

The students participating in the Workshop should be divided into three groups:

- The first group is in charge of opening the computers, cleaning them (basically, dusting them) and checking their correct functioning. These students separate computers into two categories: those that work correctly and those that do not work or are incomplete. This task can be entrusted to students with little or no computer training.
- The second group is in charge of repairing and remanufacturing the computers. Components that work properly on computers that are otherwise beyond repair will be used for the repair of other computers. The parts that do not work will be taken to a recycling point. These students must have received previous training in some technical subjects.
- The third group is responsible for refurbishing computers, installing the most appropriate free software in the computer (it is advisable to install a Long Term Support (LTS) version to ensure that, as far as possible, the operating system will be supported

throughout the time the computer is in use at the receiving entity) while taking into account the computers' hardware limitations, the needs of the receiving entities and ensuring that the software has technical support for updates during the expected extended lifespan of the computer. These students must have received previous training.

Students must understand the purpose of the workshop and be aware of the end use of the computers they are reconditioning. To this end, prior to participation in the workshop, they receive a short briefing session on the objectives of the CRP, their relationship with reuse and recycling and the projects and entities that will receive the computers.

In order to promote student awareness, it is important to carry out other activities during the reuse workshop, such as talks, debates, documentary viewing, presentation of cooperation projects, exhibition of photographs of cooperation projects and so forth, with the aim of helping students to acquire a holistic view of the importance of their decisions as engineers in the environment and in society.

All products and components discarded by the program must be sent to a local Recycling Company for appropriate processing and with safe procedures for the recovery of raw materials as part of the so-called urban mining. Furthermore, all the entities receiving ICT products from the program should sign an agreement stating that they will send the computers to an appropriate Recycling Company when they reach the end of their useful lifespan. This pledge should assure that all the ICT products involved in the program will be properly recycled, thereby minimizing the impact on human health and the environment as well as reducing the need of mining for raw materials.

The technical team is responsible for organizing the Reuse Workshop. Since all computers will be tuned during the workshop, the mission of the technical team on a day-to-day basis is to verify that the computers work correctly (and include the appropriate software) before being delivered to entities, and to repair or promptly install those computers that require it. The technical team must also provide adequate training to those entities that request it.

Last but not least, the following tools are required for the implementation of a CRP:

- A software tool to analyze the computer hardware and to store information of every computer in a database. With this information, the program can trace the life of all computers and components, as well as analyze the durability of these components [53].
- Hardware and software support to install software to multiple computers simultaneously by using a network.
- A software tool to assure that all data on the computer disks have been erased and cannot be recovered, in order to reassure donors that all information about their companies has been erased.

Figure 1 presents the concept map of the operation of the CRP proposal described in this paper.

There are three key elements in the design of a CRP: the two work teams (technical and communication) and the reuse workshop. The technical team and the communication team are in constant contact thanks to regular meetings, but each one develops their work independently. The technical team is in charge of managing the warehouse (receiving computer donations and delivering the prepared equipment to the receiving entities) and the reuse workshop, as well as the use and maintenance of the analysis and installation tools. During the reuse workshop, the technical team guarantees that the computers are properly prepared by the students. The communication team manages the applications of the entities and verifies that they meet the program requirements for receiving computers. Applications are managed through a website and all information is stored in a database.
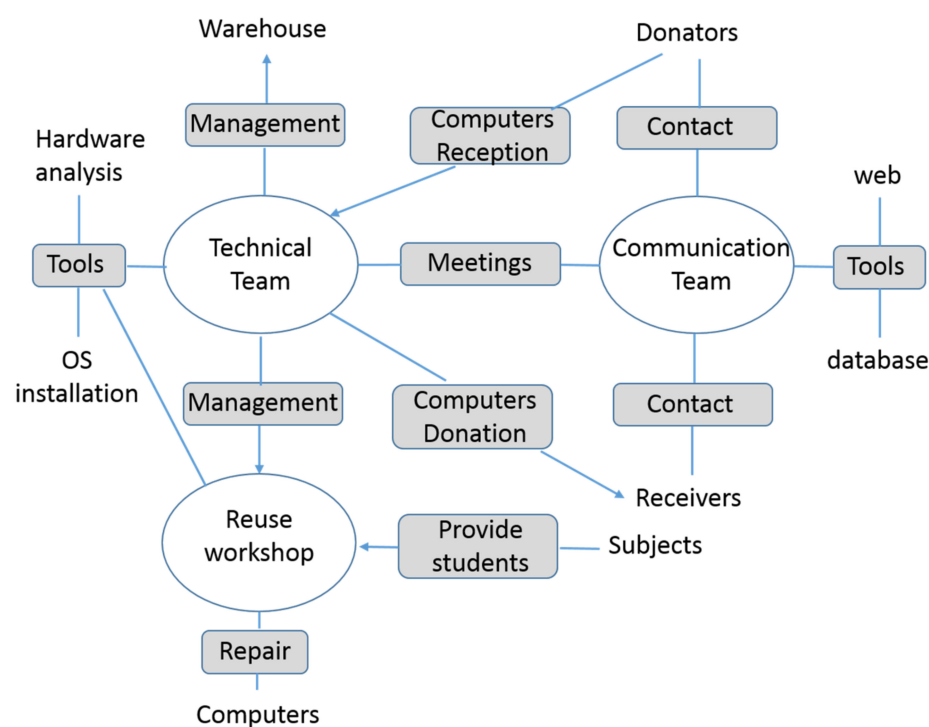
Figure 1. Concept map of the operation of a Computer Reuse Program based on Service Learning.

A computer goes through several phases from when it is received by the program until it is delivered to a receiving entity. Figure 2 presents the flowchart of the computer tuning process.

Figure 2. Flowchart of the computer tuning process managed by the technical team.

Computers considered obsolete are delivered to the CRP and stored in the warehouse until the next Reuse workshop is held. During the Reuse workshop, students repair and install computers as a practical part of their subject. The computers return to the warehouse

ready to be delivered to the receiving entities. However, should any problems arise due to relocation or subsequent breakdowns, all computers are checked before being delivered to an entity.

2.1.4. Minimum Requirements to Establish a CRP

The following elements are required to implement a CRP in an educational institution:

- A stable communication team supervised by one person, and a stable technical team also supervised by one person. The minimum team size depends on the volume of program activity.
- A website to provide information and manage the program.
- A warehouse to store computers, both those repaired in the workshop and those that are pending repair. The warehouse size will depend on the annual number of computers managed by the program.
- A workspace for the technical and communication teams. The size will depend on the number of team members.
- A room for the Reuse Workshop. The size of the room will depend on the number of students participating in each workshop session. For a group of 20 students, a space of at least 70 square meters is recommended, with enough power outlets and 10 tables (students work in groups of two). Repaired computers, pending repair/installation and spare parts must also be temporarily stored in the room during the workshop.
- The installation of the computer operating systems can be performed individually if the volume of computers is not large, but for a volume greater than 20–30 computers per workshop, installation via network using a switch is more recommended.
- A computer hardware analysis software that allows the automatic detection of computer configuration and can save it in a database is recommended. This software will allow traceability of donated computers.

2.2. Impact

This Section presents the instruments developed to evaluate the impact of the UPC-ReTIlitza Program. In order to show the impact over the 16 years of its existence, we use different evaluation methods for assessing the impact on the community, on student learning, on the reduction of resources and on the environment.

2.2.1. Impact on the Community

Some figures are presented to evaluate the real impact on the community: the total number of computers repaired, refurbished or remanufactured; the number of projects and entities which received computers; as well as the type of components and the geographic distribution of the projects.

2.2.2. Impact on Student Learning

A survey has been employed to evaluate the impact on learning. This survey was developed as part of the EDINSOST project [54], a national project funded by the Spanish government. This project involved 10 national universities with the goal of boosting educational innovation in ESD in Spain.

The survey consists of 34 sustainability-related questions using a 4-point Likert scale. The first version was developed by a team of 10 experts and validated using the structured expert judgement method [55] by the Sustainability Competency Working Group of the National Universities Rectors Committee. Once reviewed and revised, it was tested by 52 participants from 6 universities, organized into 8 focus groups composed of between 5 and 9 members with gender equality. Thus, upon conclusion of this process, the mutual exclusion, homogeneity, relevance, objectivity, fidelity and productivity of the survey can be assured.

In order to test the impact of the Reuse Workshop on student learning, the survey described above was used in a pre–post study. The survey was held during the first and

last weeks of the last three semesters of the "PC Architecture" subject. The students on this course are those most directly involved in the Service Learning methodology, thus the ones where real impact of SL on sustainability learning can be measured (see Appendix A for details). The Mann–Whitney U test was used to compare the pre- and post-results, and the ρ statistic was used to calculate the overlap between both distributions. Finally, Cohen's D was used to analyze the effect size.

2.2.3. Reducing Resource and Environmental Impacts

It is beyond the scope of this paper to conduct a research into the impact of the CRP using a methodology such as a Life Cycle Assessment (LCA). Nevertheless, it is important to calculate the impact of the CRP on resource reduction and the environment and explain it to the students. To that end, we have developed a simple model based on several LCA studies to show them the impact of their work in the Reuse Workshop regarding e-waste reduction and computer lifespan extension.

An extensive literature on LCA of ICT products exists in which different methodologies are employed (see [56] for an exhaustive study on the different LCA methods and studies). Instead of developing our own study, we simply made assumptions based on other studies. In some cases, we found some inconsistencies that prompted us to consider a rank of values instead of a single value. All the assumptions are listed below and are explained in detail in Appendix B.

Amount of Equipment Affected by the UPC-ReTIlitza Program

An accurate account of ICT products donated over the years (2321 desktop and 164 laptop computers, 1298 CRT and 592 LCD display devices) is kept in the UPC-ReTIlitza Program. Every time that material is offered to the UPC-ReuTIlitza Program, one of our experts evaluates it before accepting the donation. Should the material be too old, or if it does not fulfil the minimum requirements for repair or refurbishment or otherwise guarantee a minimum extended lifespan, then it is not accepted and we refer the donor to the Recycling Company we work with in order to ensure that the material is properly withdrawn and recycled.

Lifespan Extension of the Material Donated

Increasing the lifespan of ICT products has a great impact on the reduction of computer manufacture, thereby reducing resource needs and environmental impact [45,57–59]. Based on the studies by Belkhir and Elmeligi [45], Kumar et al. [60], Prakash et al. [61], and Tecchio et al. [62], a 6-year lifespan is assumed for desktops, 5.5 years for laptops and 7 years for CRT and LCD displays. However, given that the receivers of the material work in a low-demand environment, the lifespan of this equipment may be longer. The model assumes that once they have been repaired and refurbished, the lifespan of these computers could be extended by 3 years (desktop computers), 2.5 years (laptop computers) and 4 years (display devices). This is a conservative estimate based on the authors' own experience.

Weight of the Material

To calculate the weight of ICT donated or recycled products, our review of the relevant literature has revealed certain inconsistences that are mainly due to the evolution of computers over the last 15 years. The weight of the ICT products has been fixed in the model on the basis of works by Chancerel and Rotter [63], Hischier et al. [64], Hischier and Wäger [65], Song et al. [66], Tecchio et al. [62] and Teehan and Kandlikar [47]. We compare the weight presented by these studies (Table A2 in Appendix B) assuming three scenarios: MAX (where we have chosen the maximum weight found in the studies for each item), MIN (minimum weight for each item) and AVG (the mean of all studies for each item).

Material Composition, Material Weight Recycling, Cost of Raw Materials and Environmental Impact

The material composition used in the model is based on those presented by Böni et al. [67], Suresh et al. [68], Van Eygen et al. [59] and Zeng et al. [69]. The Material Weight Recycling (MWR) for each material is based on the studies by Arduin et al. [70], Nelen et al. [71], Van Eygen et al. [59] and Wäger et al. [72]. The cost of raw materials used in the model is the one presented by Zeng et al. in [69]. The impact in kg CO_2-eq in the production phase of an ICT product assumed in the model is the one presented by Belkhir and Elmeligi [45]. Finally, the calculation of trees per year required for sequestering this amount of CO_2 is based on the works by Myers and Goreau [73], Orwa et al. [74] and Toochi [75]. More information can be found in Appendix B.

3. Results

3.1. Evaluating the Impact on the Community

From the start of the UPC-ReTIlitza Program in 2004 until the end of 2019 (2020 is not considered in this paper because it was an abnormal year due to the impact of the pandemic caused by COVID-19), 2497 computers (2321 desktops, 164 laptops and 12 servers), 1298 CRT displays and 592 LCD display devices were donated to 453 projects managed by 359 non-profit entities belonging to 29 different countries.

Figure 3 shows the distribution of computers delivered by country. Spain has been omitted from the figure because 70.1% of the computers (1751 out of 2497) were donated to local entities, and the inclusion of Spain would hinder a reading of the graph. Some countries have received very few computers, either because few projects have been undertaken there or because the projects required very little computer equipment; 17 out of the 29 countries (58.6%) have received fewer than 20 computers.
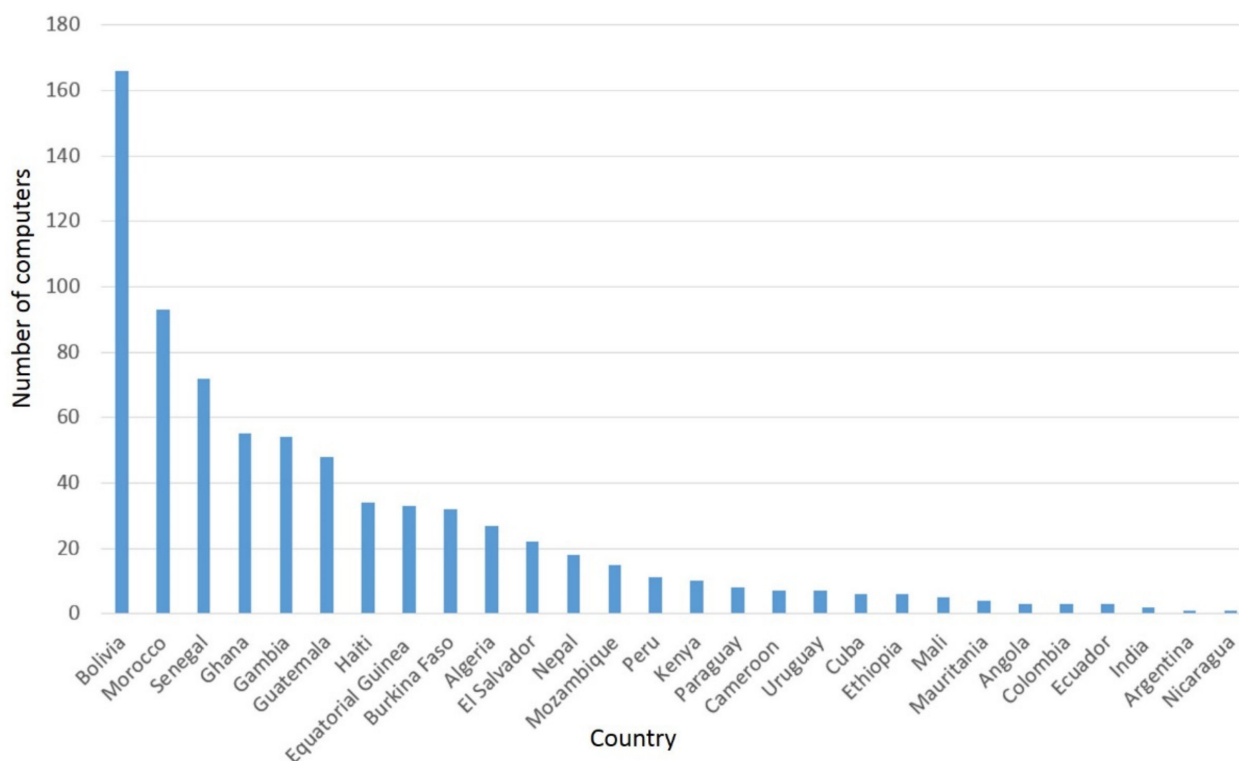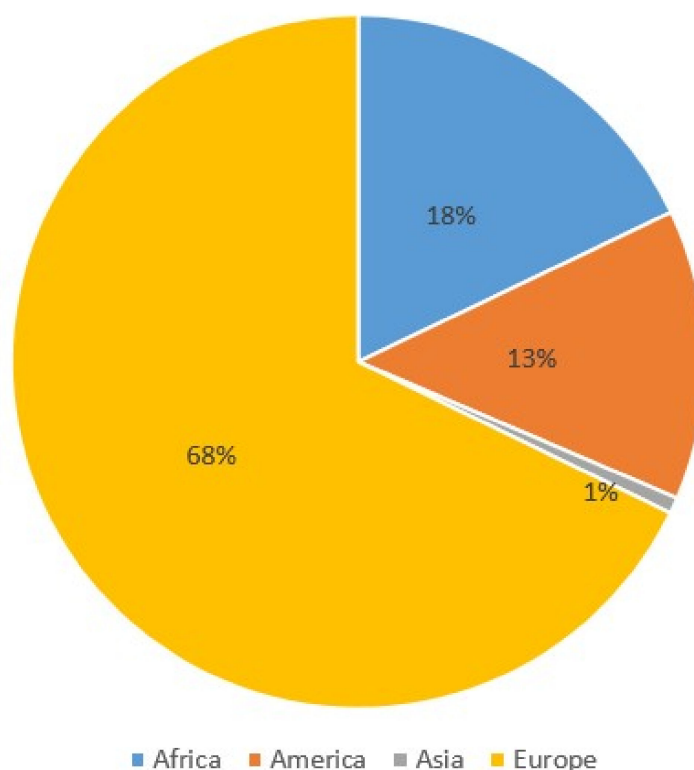

Figure 3. Distribution of computers delivered by country (without Spain).

Figure 4 shows the distribution of computers delivered according to continent. In this case, donations to Europe have been made only to projects undertaken by entities operating in Spain. It can be observed that few computers have been donated to projects in

Asia (1%, just 20 computers), while Africa and Latin America account for nearly 30% of the donated computers (416 devices for Africa and 310 for Latin America, respectively).

Figure 4. Distribution of computers delivered by continent.

Figure 5 shows the annual evolution of the number of ICT products delivered. No data are presented for the year 2000 because, in that year, a change was made in the accounting, and the UPC-ReuTIlitza Program was moved from calendar years to the academic years account. Devices are classified into laptops, desktops and others (servers, printers, routers and so on). Display devices are not accounted here. The figure clearly shows that most computers are of the desktop type, and only in recent years has the UPC-ReuTIlitza Program begun to donate laptops. One may also observe that no pattern exists for the number of computers donated annually, since this depends on the requests made by entities.
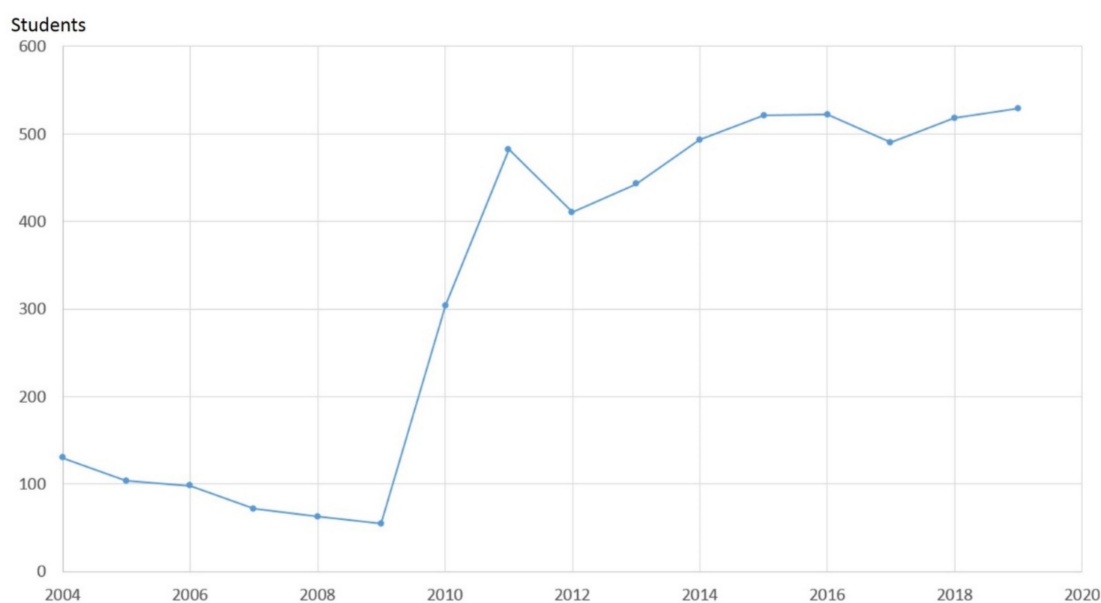
To illustrate the impact of the UPC-ReuTIlitza Program, it is interesting to note some examples of entities which received the donations. For instance, an NGO working in the Saharawi refugee camp in Tindouf (Algeria) received 5 laptops and 10 desktops from the UPC-ReuTIlitza Program in 2016 and 12 more desktop computers in 2018. These computers were used in local schools. In fact, most of the computers donated in foreign countries are dedicated to schools (such as the 10 desktops donated to schools in Mali and Senegal, or the 12 laptop computers donated to Nepalese schools), but sometimes they provide local organizations with ICT equipment for their own management organization, such as the 30 desktops donated to the Royal Victoria Teaching Hospital in Banjul (Gambia). As for local projects, one example is the local Food Bank (a non-profit, charitable organization that distributes food to those who have difficulty purchasing enough to avoid hunger), which has received 45 desktop computers over 10 years. These computers were used to organize the logistics of the collection, storage and distribution of food. Other local receivers are Senior Citizens' Centers, local NGOs, and so on.
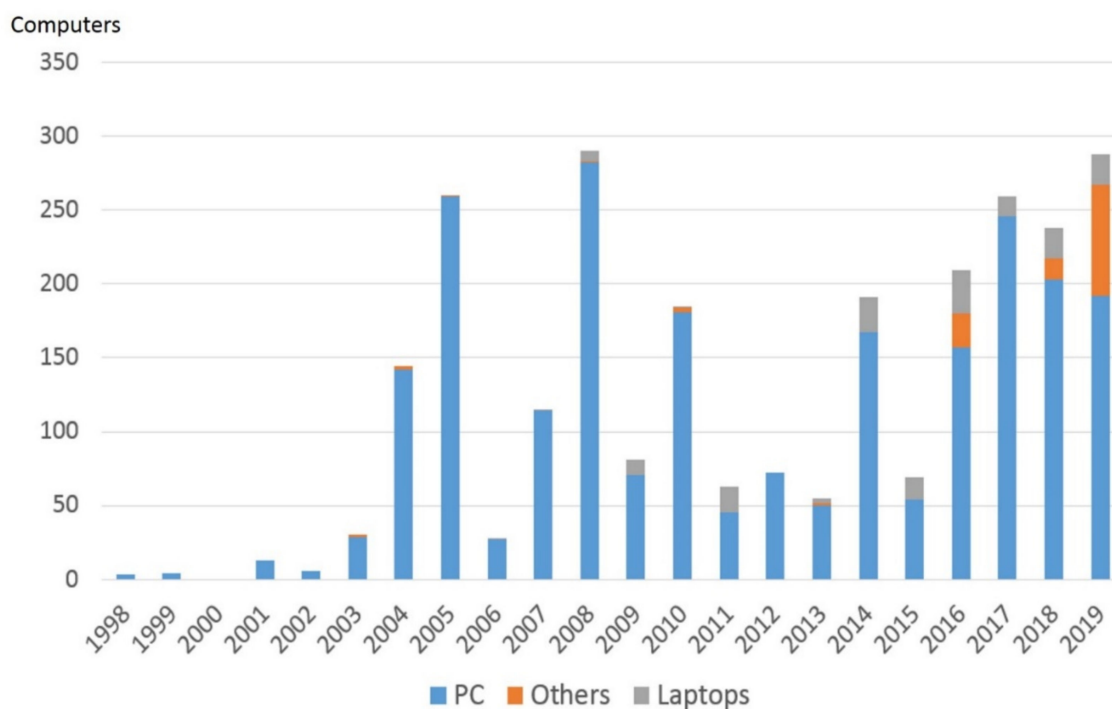
Figure 5. Equipment distribution by year. The Y-axis is the number of computers donated.

A total of 5239 students have participated in the Reuse Workshop since it started. However, most of them have only participated in activities (talks, round tables, et cetera) not directly related with the SL activity of repairing and refurbishing computers. Students with a greater involvement and those who get in touch with the entities receiving donations are students enrolled in the "PC Architecture" subject. A total of 439 students have enrolled in "PC Architecture" since 2004.

Figure 6 shows the annual evolution of the number of students participating in the UPC-ReuTIlitza Program. The figure shows the important quantitative leap since the introduction in 2010 of the Reuse Workshop.

Figure 6. Number of students participating in the UPC-ReuTIlitza Program since 2004.

3.2. Evaluating the Impact on Student Learning

Evaluating the impact of the UPC-ReuTIlitza program on the learning of participating students is not an easy task because students dedicate very few hours of their lab practices to the program, and not all of them dedicate the same number of hours. All students of the FIB's Bachelor Degree in Informatics complete at least one practical within the "Circuit Interfaces" subject, which is compulsory, and some even complete practicals in the four subjects that form part of the program. The learning that students achieve depends, therefore, on the number of times they participate in the Reuse workshop (between 1 and 4).

From the point of view of technical competencies, students who only participate in the practicals of the "Circuit Interfaces" subject learn to identify the different parts of a computer (motherboard, processor, memory DIMMs, hard disk, etc.) and perform basic operations such as modifying the amount of RAM or changing the hard disk. In their theory classes, these students studied the purpose of the different components of a computer but did not have the opportunity to gain practical experience working with real computer hardware.

The students who take the "PC Architecture" subject have studied the operation of the different components of a PC in-depth in the theory classes. During the Reuse Workshop, they have the opportunity to learn how to repair computers that are not working properly. This practical component could not be carried out if the Reuse Workshop did not exist, since it provides them the chance to carry out different real repairs. In addition, these students acquire special training in the field of reuse, since no new spare parts are available for repairing computers and thus must have recourse to components from other computers that have not been repaired and whose functional parts have been removed to be used as spare parts for future repairs.

Finally, students who also participate in one (or both) subjects concerning operating systems learn to install a Linux operating system via the network. This would be a very simple practice for these students if the installation were done individually. However, the computers are installed in groups of 20 simultaneously using a high-bandwidth switch, which adds value to the training of these students, who must also be able to detect when an operating system has not been installed correctly due to a hardware problem.

From the point of view of ESD, at the beginning of each session, all students receive a 10-min talk in which they are instructed in (1) the objectives of the UPC-ReuTIlitza program and (2) the destination of the computers they are charged with fine-tuning. In this way, they are become participants in the "service" they provide with their "learning". They are also invited to volunteer in TxT and are offered the chance to undertake a Final Degree Project in the field of cooperation via the annual call for funded cooperation projects carried out by the CCD.

Of the four subjects belonging to the Reuse Workshop, it is in the "PC Architecture" subject where students receive further training in ESD. Thus, to evaluate the impact on student learning, the survey mentioned in Section 3.2 was conducted with students enrolled in the "PC Architecture" course during the first and last weeks of the last three semesters of that subject, which is that in which students have a deeper involvement in the SL proposal. The data are based on the responses from 65 students enrolled in these three semesters, 60 (92.3%) of whom answered the first-week test and 57 (87.7%) of whom answered the last-week survey.

Although they answered all 34 questions in the survey, in this study, we focus on only 7 of these questions (7, 13, 15, 16, 18, 32 and 33), which are the ones most directly related with the learning objectives of the proposal: understanding environmental costs throughout ICT product lifecycle and concepts such as social justice, resource reuse, circular economy, equity, transparency, diversity and deontological principles. Nevertheless, in order to ensure that these seven questions are internally coherent, the Cronbach alpha test has been calculated, yielding results of 0.91 (overall), 0.82 (pre-survey) and 0.78 (post-survey). As all the results are over 0.6, the set of questions analyzed can be considered reliable.

Table 1 shows the questions chosen (column 1) and the mean differences between the pre- and post-survey (column 2). Column 3 shows the Mann–Whitney U-test; on analysis of the resulting *p*-values, in all cases, a value $p < 0.001$ is found. Thus, there is a statistically significant difference (increment) between the pre- and post-answers, with a level of significance greater than 99.9%. Finally, column 4 shows the Cohen's D effect size; since all the results are over 0.8 (sometimes much larger than 0.8), the effect size can be considered large.

Table 1. Analysis of 7 of the 34 questions of the survey.

(1) Question	(2) Diff	(3) M–W U-Test	(4) Cohen's D Effect
Q7. I understand the environmental costs of ICT-related products throughout their life cycle.	1.05	6.62	1.47
Q13. I know the strategic role that ICT plays in the sustainability of the planet, as well as the concepts of social justice, resource reuse and circular economy.	1.16	6.64	1.49
Q15. I know the problems associated with social justice, equity, diversity and transparency.	0.89	5.25	1.12
Q16. I know the direct and indirect consequences that ICT products and services have on society,	0.80	5.86	1.27
Q18. I understand the need to introduce social justice, equity, diversity, and transparency into ICT projects.	0.68	3.95	0.86
Q32. I know the deontological principles related to sustainability.	1.97	8.65	2.76
Q33. I know how to assess the implications of deontological principles related to sustainability in an ICT project.	1.65	7.79	2.09

3.3. Reducing Resource and Environmental Impacts

To make reading easier, only a few figures are provided in this section. The complete study indicating the source of all data can be found in Appendix B.

3.3.1. Impact of the Donated Material

To calculate the weight of ICT products donated, several studies have been taken into account, and the data for the three scenarios previously described (MIN, MAX and AVG) are shown in Table 2.

Table 2. Weight of ICT components for the three scenarios.

Weight (kg) per Unit for	Scenario MIN	Scenario MAX	Scenario AVG
Desktop computers	10.47	13.523	11.6858
Laptop Computers	1.93	3.055	2.685
LCD display	3.559	6.825	4.699
CRT Display	10.9	16.23	13.565

The products donated by the UPC-ReuTIlitza Program consist of 2321 desktops, 164 laptop computers and 1298 CRT and 952 LCD devices. All laptops, CRTs and LCDs are tested before being accepted and discarded if they do not work properly, since repair of these devices is beyond the remit of the Reuse Workshop. On the other hand, desktops with a minimum configuration are accepted even if they are broken. According to the figures from the latest editions, 3.64% of desktop computers could not be repaired and were sent for recycling once any working parts had been salvaged for use as spare parts. According to these figures, the model indicates that the weight of the ICT material donated amounted to between 40,960.98 kg (scenario MIN) and 57,109.09 kg (scenario MAX), the AVG scenario being 48,050.99 kg.

As all the recipients of the donated products sign an agreement to send these products to a recycling company, it can be assumed that all such products will be adequately

dismantled for recovery of useable material. The calculation of the amount of material that can be potentially recovered is made on the basis of the data from several studies regarding the percentage of material found in each product, and on the MWR (Material Weight Recycling), i.e., the percentage of each material that can be recovered. Only a few materials have been considered: three valuable metals (Fe, Al and Cu), three precious metals (Au, Ag and Pd) and plastics. For each material and for the three scenarios, Table 3 shows the amount of the potentially recoverable materials and their market price. These prices are based on the estimation presented in [69] and are as follows: Fe (USD 120/ton), Al (USD 2300/ton), Cu (USD 6400/ton), Au (USD 47/gr), Ag (USD 1.03/gr), Pd (USD 21/gr) and plastics (USD 890/ton).

Table 3. Weight and economic value of material recoverable from the UPC-ReuTIlitza Program for the three scenarios.

	Weight of Potentially Recoverable Material			Price of Potentially Recoverable Material		
	MIN	MAX	AVG	MIN	MAX	AVG
Fe	11,411.56	15,540.50	13,198.06	1369.388	1864.860	1583.767
Al	1301.5	1788.12	1508.92	2993.443	4112.677	3470.511
Cu	1587.20	2248.95	1880.91	10,158.104	14,393.267	12,037.793
Au	1.103	1.619	1.334	51,857.104	76,081.626	62,708,999
Ag	5.289	7.787	6.404	5447.388	8020.967	6596.031
Pd	2.923	4.334	3.617	61,396.242	91,004.302	75,949.195
Plastics	4339.42	6302.10	5190.80	3862.088	5608.871	4619.810
Total estimated cost (in USD)				137,083.76	201,086.57	166,966.106

3.3.2. Impact on the Reduction of Manufactured Products

The lifespan of products is assumed to be 6 years for desktops, 5.5 years for laptops and 7 years for display devices, which is a coherent assumption with regard to the studied works. Based on our experience, the life extension is assumed to be 3 years for desktops, 2.5 years for laptops and 4 years for display devices. Given these figures, the model assumes that two donated desktops (life extension of 3 years) are equivalent to one new desktop (lifespan of 6 years). Applying this idea to all materials, the donated material is equivalent to 1160 desktops, 74 laptops, 338 LCDs and 741 CRT display devices. These products derived from the life extension of donated products are referred to herein as "saved" because it can be assumed that if they are not manufactured, they will require no raw materials or energy for their production. Table 4 shows the weight of the potentially saved materials and their price for the three scenarios.

Table 4. Material saved due to life extension of donated products.

	Weight of Potentially Saved Material (kg)			Price of Potentially Saved Material (USD)		
	MIN	MAX	AVG	MIN	MAX	AVG
Fe	6854.82	9409.65	7970.19	822.58	1129.16	956.42
Al	776.80	1065.81	899.89	1786.62	2451.37	2069.75
Cu	1146.07	1640.96	1366.92	7334.82	10,502.15	8748.30
Au	0.64	0.93	0.77	29,858.12	43,845.97	36,118.51
Ag	3.07	4.53	3.72	3164.78	4666.52	3835.15
Pd	1.70	2.52	2.10	35,672.23	52,885.35	44,131.99
Plastics	3715.06	5218.64	4362.15	3306.40	4644.59	3882.32
Total estimated cost				81,945,57	120,125.10	99,742.44

Furthermore, the "saved" equipment also reflects the energy saved in their production phase. To calculate the impact in terms of energy, the model assumes the data presented by

Belkhir and Elmeligi [45], where the energy required in the production phase is presented in kg of equivalent CO_2 (kg CO_2-e), which is between 218 and 620 kg CO_2-e for desktop computers, between 281 and 468 kg CO_2-e for laptop computers, 95 kg CO_2-e for LCDs and 200 kg CO_2-e for CRTs. Therefore, since there is no need to manufacture "saved" products, and CO_2 emissions can be reduced to between 453,984 and 943,422 kg.

Since for students, and people in general, kg of CO_2 is not a familiar measure, it was decided that a more accessible measure would be to translate these figures into the equivalent tree/year metric (i.e., the number of trees required for sequestering this amount of CO_2 in one year), even though it is not a common measurement in scientific literature. This measurement conversion was not an easy task since, in the relevant literature, it is explained that a significant difference exists in the sequestration rate depending on the type of tree, its age and whether or not it is found in a tropical or a temperate zone, etc. Finally, the assumption was to consider a rank between 1.14 and 6.35 kg CO_2 per tree per year, which is a commonly accepted rank for trees in a temperate zone such as southern-central Europe (where Spain is located). In conclusion, the CO_2 saved by the UPC-ReuTIlitza Program would have required between 71,493 and 827,563 trees/year to be sequestered.

3.3.3. Limitations of the Model

The model is based on several research papers and is not defined solely as an LCA study, so the data used come from different sources. Nevertheless, instead of taking data from a study, a rank of values is employed in the model. In addition, the weight of computers, material composition, material weight recycling and the price of raw materials all vary over time, and the UPC-ReuTIlitza Program has been in operation for 15 years. In the model, all these figures are assumed to be the same (data from 2015–2016), which can be considered a conservative estimate. Furthermore, for the sake of simplicity, some elements (such as rare earths or rubber), type of plastics and polymers have not been taken into account in the model. Finally, the shipping costs of transporting ICT products (from raw materials to manufactured products) have not been considered. Nevertheless, all the assumed data are consistent across the literature.

4. Discussion

Introducing ESD into the curricula of HEIs is becoming a subject of great importance worldwide. Competencies for sustainable development are seldom developed in Engineering curricula, where there is a lack of dedication to concepts such as understanding the environmental and social costs of technological products, social justice, resource reuse, the circular economy, deontological principles and the development of engineering projects that take equity, transparency and diversity into account.

4.1. The Service Learning Methodology

The Reuse Workshop presented in this paper has demonstrated that an SL methodology has a great impact on the acquisition of these competencies. The results of the survey show a statistically significant increment in the self-assessment of the concepts mentioned above. If the Reuse Workshop had focused only on the repair and refurbishment of computers, the technical competencies would have been acquired but not the competencies for sustainable development, the acquisition of which has been possible thanks to the contact with the recipients of the donations, the knowledge of the projects for which the ICT products are destined for use, the impact that the work undertaken by students has had on the reduction of acquired equipment and the importance of appropriate e-waste treatment in terms of element recovery and the reduction of health and environmental risk.

As in the case of other SL initiatives, the goals of the Reuse Workshop can be divided into Learning Goals and Service Goals.

With respect to the Learning Goals, the Reuse Workshop helps students to acquire technical competencies by means of the hands-on work they perform during the Workshop, where they learn to evaluate architectures and repair computers as well as evaluate user

needs and install the required software. Students also acquire sustainability competencies, learning the real impact that the computer life cycle has on human development and health as well as on the environment.

The UPC-ReuTIlitza program, and in particular, the Reuse Workshop, has the three elements identified by Godfrey et al. [28], namely, the "3Rs of Service Learning".

"Reality" is achieved because students recondition and repair real computers that need to be reconditioned or repaired before they can be used by the entities to which they will be donated. So, students must learn how to adapt to the circumstances and respond to changing conditions [29,30].

"Reflection" is achieved mainly through self-awareness [31–33]. Self-awareness is achieved thanks to the fact that students are aware at all times that they are performing a service and that the computers they are working on will be used by entities with few (or no) resources for achieving their objectives.

"Reciprocity" is achieved by providing students with practical experience in a real environment. Practical experiences are not carried out in the lab of a subject with the aim of improving the students' technical competencies but are rather performed in the environment of a workshop with concrete objectives, or likewise, that of an SL program such as the UPC-ReuTIlitza program, and with real computers destined for use by non-profit organizations for social purposes. In addition, students are aware at all times that they are developing their technical competencies while simultaneously performing a service [34,35].

During the years that the UPC-ReuTIlitza Program has been in operation, we have found some issues that seem relevant to present in this work because they are related to the service that the program provides to social entities:

- Although entities are properly informed throughout the donation process, most of them continue showing, in general, a preference for operating systems based on Microsoft Windows © rather than Linux-based systems. This is due to a lack of familiarity with Linux-based systems. Thus, in some cases, the entity formats computers again in order to install a Windows-based system. Unfortunately, as delivered computers are quite old, most of them fail to function efficiently shortly after a current Windows System is installed, as the system quickly consumes all computer resources.

- Initially, target entities were connected to projects in countries in the Global South, in many of which the transportation of desktops is complicated, and the environmental and electrical conditions are unsuitable for these devices. Therefore, in some cases, they break down quickly. In addition, countries in the Global South usually do not have recycling centers, so damaged computers often end up in a landfill as e-waste. In order to avoid this, the UPC-ReuTIlitza Program prioritizes the dispatch of laptops to these countries. To this end, counterparts in countries in the Global South must be committed to recycling laptops appropriately when they reach the end of their useful life or returning them to Spain if recycling them locally is not possible. Since the entities receiving computers normally work with counterparts based in Spain, the counterpart volunteers are responsible for bringing equipment back to Spain when they cannot be locally recycled.

- In the main, desktops are currently assigned to supporting the needs of local entities. These entities are obliged to deliver computers to a recycling center once their useful life is over. In the case of entities in which computers previously delivered by the program are broken, they are accorded priority for receiving new computers. However, many local entities are currently also asking for laptops.

- The program does not normally accept any material except computers and their corresponding input/output devices (flat screen, keyboard and mouse). However, our university replaces servers and networking equipment that often end up in the program warehouse. This equipment is not normally delivered to social entities because it does not meet their needs. Nevertheless, VET schools that collaborate with the program by providing internship students are delighted to receive this equipment

for developing labs of their subjects, so the servers and networking equipment are also endowed with a second life.

- Laptops and screens usually enjoy a longer useful lifespan than desktops, and therefore they arrive in worse condition (especially laptops). However, the donors have begun to renew flat screens, and in 2015, the program started to receive significant donations and screen stock problems are not expected in the future. The case of laptops is different, as many companies allow their employees to buy back these devices at a nominal price when they are replaced, so these laptops are not donated. Nonetheless, we have detected an increase in laptop donations from 2018, most of them provided by private users.
- Other devices such as printers, phones or tablets are accepted only when an entity has previously requested them. This procedure is followed because there is little demand for this type of equipment and not enough room is available in the warehouse. Printers are also prone to problems with the toners, which are very expensive and have a very short lifetime. Therefore, we do not accept donations of printers unless they are of high quality or are new.
- Some companies expressly request a deep erasure of the hard drives they donate, and a certification of that erasure. The members of the technical team perform this deletion before the computers arrive at the workshop. The UPC-ReuTIlitza Program manager, a UPC-BarcelonaTech teacher, issues the erasure certificate.
- Some donors request a certificate of valuation for donated equipment. This certificate allows them to deduct the donation on their next tax return. To correctly value the equipment, an analysis is made of the current market price of the equipment on different platforms for the sale of second-hand equipment.

The UPC-ReuTIlitza Program is a way for a public university to return to society some of the resources that society itself invests in the university. Moreover, it helps entities devoted to social purposes to develop their work by providing technology free of charge. Typically, these entities are on a tight budget and it is preferable that they dedicate their finances to fulfilling their mission. On the other hand, the life of devices replaced by the university, as well as public institutions and private companies due to obsolescence, is lengthened by being assigned to entities that do not need the latest generation of computers.

Almost all the goals of the UPC-ReuTIlitza Program are achieved thanks to the involvement of university students in an SL activity. Students improve their technical and professional skills by means of their work in the communication and technical teams and in the Reuse Workshop, since the tasks they perform are closely related to the educational objectives of the subjects in which they carry out practical activities. As for the service, the students are aware of the purpose of the workshop and know which entities will receive the computers they are refurbishing.

4.2. Impact on Society and the Environment

The impact on society of the donated ICT products is an issue that is difficult to assess. How can one evaluate the real impact of the use of computers on a school in a developing country? Especially taking into account that, without such donations, these schools would probably have been unable to acquire these products. On the other hand, in the case of donations to local entities (such as the 45 desktop computers received by the local Food Bank), it can be argued that, basically, they save the entity the expense of purchasing ICT products, thus enabling it to spend the money thus saved on other needs. However, reusing ICT products instead of buying new ones is a policy that is closely aligned with the ethical principles of such entities.

One can analyze the Reuse Workshop impact in terms of the extension of product lifespan, the potential saving of e-waste (and correct processing in the dismantling phase, with salvage processes and material recovery), trees/year required to sequester the CO_2 emissions that would result if the saved products had to be manufactured and so forth. The resulting figures are of some interest in a paper such as this, but they are shocking

for people who are unaware of the real impact of ICT products. Some of the students commented to their teachers that they were already "theoretically conscious" of some figures (such as the amount of precious minerals and rare earths in printed circuit boards, or that the energy needed to make a DIMM memory could exceed the energy consumed in the use phase), but the Reuse Workshop figures help them to understand the real extent of the ICT life cycle's impacts, thus increasing their awareness of sustainable issues.

In this paper, an accurate account is given of ICT products donated over the years (2321 desktop, 164 laptop computers, 1298 CRTs and 592 LCD display devices) to the UPC-ReTIlitza Program. On the basis of several studies [45,60–62], a 6-year lifespan is assumed for desktops, 5.5 years for laptops and 7 years for CRT and LCD displays. The model used in this paper assumes that, once the computers have been repaired and refurbished, their lifespan can be extended by 3 years (desktop computers), 2.5 years (laptop computers) and 4 years (display devices).

The weight of the ICT products has been fixed in the model on the basis of works presented in [47,62–66]. We compare the weight presented by these studies (Table A2 in Appendix B) assuming three scenarios: MAX (where we have chosen the maximum weight found in the studies), MIN (minimum weight) and AVG (the mean of all studies).

The data presented in Appendix B show that total e-waste (in kg) is 40,960.98 for the MIN scenario, 57,109.09 for the MAX and 48,050.99 for the AVG. Regarding the price of material potentially saved as a result of the life extension of the products donated, this is EUR 81,945.57 in the MIN scenario, EUR 120,125.10 in the MAX and EUR 99,742.44 in the AVG. Finally, the total kg CO_2-e saved by the UPC-ReuTIlitza Program is 453,984 in the MIN scenario and 943,422 in the MAX.

Hence, in the light of the results, it is demonstrated that the SL methodology is probably the best option for the teaching and learning process of acquiring sustainable competencies because it has a great impact on the learning process as well as exerting a real impact on society and the environment.

This work contributes to the achievement of some of the 17 SDGs. Indirectly, it helps to advance the achievement of all the SDGs, since the computers propagated by the UPC-ReuTIlitza Program are donated to entities whose main mission is to contribute to some of the 17 SDGs in different countries of the world; for example, SDG1 (No Poverty), SDG2 (Zero Hunger), SDG5 (Gender Equality), SDG6 (Clean Water and Sanitation), SDG10 (Reducing Inequality) or SDG16 (Peace, Justice, and Strong Institutions). Where the environment is concerned, computers are also provided to entities whose mission is to advance in the achievement of the objectives of SDG13 (Climate Action), SDG14 (Life Below Water) or SDG15 (Life on Land).

Furthermore, the UPC-ReuTIlitza Program contributes in a very special way to achieving the SDG4 (Quality Education) and SDG12 (Responsible Consumption and Production) objectives.

4.3. Limitations of a CRP Following the Proposed Methodology

The organization of a CRP such as the one described in this paper is subject to certain limitations that should be taken into account when replicating the program. These limitations are detailed below:

- One of the main limitations concerns space. It is necessary to have enough room to store the computers, a place to conduct the Reuse Workshop and a room to undertake the work carried out by the volunteers of the program. The UPC-ReuTIlitza Program has at its disposal a warehouse of one hundred square meters, where computers are stored and volunteers work. For the Reuse Workshop, a classroom capable of housing all the computers to be set up in each workshop is required, with enough space for 20 to 40 students to work simultaneously. This room must be suitably equipped and adapted so that between 10 and 20 computers can be repaired simultaneously, or up to 40 computers can be simultaneously installed. In addition, a room with sufficient space is required to give talks and for projecting documentaries, etc., to all the students.

In the case of the UPC-ReuTIlitza Program, up to 250 students may be enrolled in the "Computer Interfaces" subject, so a room of this capacity is necessary.

- The number of students is a further limitation, and one closely related to the available space, as mentioned above. On the one hand, the number of students participating directly in the program (volunteers and VET students who complete their internships in the program) must be taken into account. The number of these students is fundamental when it comes to determining how many activities can be conducted at the Reuse Workshop, as well as how many computers can be delivered to the social entities each week, since these students are the ones who perform the daily work and are at the front-end of the program for the entities benefitting from the service. Furthermore, the number of students attending the Reuse Workshop constitutes another limitation (also highly dependent on the space available for the workshop). The number of computers that can be set up in each workshop depends on how many students attend the workshop. Taking into account that students work in pairs, between four and six students are required to refurbish each computer (two to check it, two to install it and two to repair it, if necessary.) Bearing in mind that each student dedicates two hours to the Reuse Workshop in the UPC-ReuTIlitza Program, and that part of this time is dedicated to learning rather than to service, our experience shows that, in the case of the "Computer Interfaces" subject, each pair can manage a maximum of three computers in each workshop, up to four or five computers in the "PC Architecture" subject, and up to six to eight computers in the Operating Systems subjects. Therefore, the number of students attending the Reuse Workshop determines the number of computers that can be set up in each workshop.

- The donations received constitute another limitation. First, while the number of requests for laptops is increasing, companies and institutions donate few laptops, so it turns out that desktop computers are often sent to entities that have requested laptops. On some occasions, many desktop computers are received, and on other occasions several flat screens arrive, but rarely are complete computers (i.e., computer, screen and peripherals) donated. The number of computers received is usually greater than the number of screens, so in some cases, requests from entities for equipment have not been met due to the absence of screens in the warehouse. This has also happened with keyboards, mice and connection cables, because screens are usually donated without the cables required for connection to the computer. In such cases, the available material is stored and the entities are placed on the waiting list, so that all the requested material can be delivered to them when it becomes available.

- The last limitation is the number of computers requested by social entities. As the UPC-ReuTIlitza Program has become better known in the local environment, more companies and institutions have been donating their old computers to the program. This has meant that, recently, the program has been able to completely meet the requests of social entities. With rare exceptions, social entities normally request small numbers of computers, either because they are small organizations with limited requirements or because they are reticent to ask for more equipment. More applications from entities are therefore required because the volume of received computers continues to grow. If not enough applications come from social entities, there is a risk that the amount of equipment in the warehouse will increase, and computers will tend to exhaust their lifespan in the warehouse. For this reason, a campaign to increase the number of requests from social entities has been launched.

5. Conclusions

In this study, a methodology for creating a Service-Learning-based Computer Reuse Program is presented to develop student sustainability competencies while also having a direct impact on society and the environment. From the point of view of learning, students acquire technical competencies, but more importantly, they have taken a giant leap in competencies regarding social and environmental issues.

It is important for students to realize that sustainability competencies are not merely a theoretical or secondary issue that are only indirectly related to their profession. Undertaking real work for real people with real constraints and observing the real impact of their work on society and the environment are vital for understanding the implications of their professional work and for acquiring an in-depth awareness of life issues.

Even so, an initiative such as the Reuse Workshop is not easy to develop, so a legal and logistical umbrella such as a Computer Reuse Program is required to implement the Reuse Workshop. The authors wish to encourage other universities to develop Computer Reuse programs, and offer their know-how to all those who may be interested.

The Service Learning model presented herein is easily exportable to other HEIs and intermediate schools. The objective of the paper is to present the methodology used by the program in such a way that other educational institutions can easily replicate it. The limitations detailed in the "Discussion" section show that the existence of various small local Computer Reuse Programs distributed throughout the world is better than just a few large programs.

We consider that the key points for the successful replication of a Computer Reuse Program are as follows:

- An organization responsible for the management of the program, both for the technical aspect and for management and communication with social entities.
- The involvement of permanent staff members of the university in this organization (teachers and administrative staff) in addition to student volunteers.
- A specialized workforce to carry out daily work. Students engaged in practices at their own university or in VET courses can be useful for this purpose.
- Organize two Reuse Workshop every year on dates that do not interfere with examination schedules.
- In the case of HEIs, introduce participation in the Reuse Workshop or the daily tasks of the program into the curriculum of some ICT Degree subjects. Selecting hardware and operating systems subjects is the most appropriate option.
- Gaining the involvement of the school management teams is very important. Involve the university as an entity so that the program forms part of its Corporate Social Responsibility objectives. Involve the technological managers and directors of the university so that all the replaced computers go to the Computer Reuse Program. Request the press office to publicize the program to help obtain donations and recipients. Carry out dissemination among private companies and NGOs.
- Maintain direct and fluid contact with institutions to attain access to third sector entities and publicize the program.
- Have enough space to work, to store computers and to conduct the Reuse Workshop.

This work also proposes a methodology to evaluate the impact of a CRP. The lifespan extension of the ICT products has had a great impact in terms of the recovery of resources with an effective e-waste treatment, as well as the curtailment of the need for new products, thereby reducing the use of raw materials and energy in the production phase of such products.

The methodology to evaluate the impact of CRP used in this work has been previously proposed and tested by numerous authors. In this paper, we consider (1) the lifespan extension of the material donated, (2) the weight of the material, (3) the material composition, (4) the material weight recycling, (5) the cost of raw materials and (6) the environmental impact.

Finally, a case study, The UPC-ReuTIlitza program, is presented and evaluated as an example of the methodology proposed in this paper. From the perspective of service to society, in the UPC-ReuTIlitza Program, more than 4300 ICT products were collected, repaired and refurbished when required and subsequently donated to 453 projects managed by 359 non-profit entities belonging to 29 different countries. These projects have had a significant impact on society, the full extent of which is extremely difficult to evaluate. A total of 5239 students have participated in the UPC-ReuTIlitza program since it started.

Technical degrees have traditionally been focused on the acquisition of technical competencies by students, sometimes ignoring the needs of society. A Computer Reuse Program helps its participants to use their expertise in order to contribute to public welfare and the common good, while gaining awareness and empathy, as well as increasing their commitment to social justice, reuse and recycling while following a deep learning process. It should not be forgotten that the mission of the educational institutions is not only to help students to develop as professionals but also to assist them to become good citizens.

Appendix A. Case Study: The UPC-ReuTIlitza Program

The UPC-ReuTIlitza Program is the CRP at the Universitat Politècnica de Catalunya UPC-BarcelonaTech. The program mainly involves students from the Barcelona School of Informatics (FIB). All FIB students participate at least once in the Reuse Workshop.

The UPC-ReuTIlitza Program started in 2004 with only students of two elective subjects belonging to the bachelor's degree in Informatics at UPC-BarcelonaTech: 'PC Architecture' (PCA) and 'Linux and Free Software Distribution'. In 2010, the curriculum underwent change due to adaptation to the Bologna Process. At this time, two more subjects—"Computer interfaces" and "Operating Systems Management"—were included in the Workshop, which led to an increase in both the number of students involved and the work capacity of the program. The warehouse and the hardware tools were provided by the FIB, and software tools were developed by student volunteers (usually as a capstone project). Finally, an office at UPC-BarcelonaTech, under the name of the Center for Cooperation Development (CCD), gave the logistic and legal support to the UPC-ReuTIlitza Program. The UPC-ReuTIlitza Program has also entered into agreement with several local VET schools for the provision of eight students per year to undertake their internships in the UPC-ReuTIlitza Program.

Appendix A.1. Workforce

The UPC-ReuTIlitza Program is jointly managed by the CCD and Tecnologia per a Tothom (Technology for Everybody, TxT), an NGO formed by workers, students and teachers of FIB. CCD acts as the communication team, and TxT as the technical team.

Entities requiring computers apply through the program's website [36] throughout the whole year. A committee formed by members of the CCD and TXT meets once a week to review applications and decide which of them satisfy the program requirements and

how many computers are assigned. The main condition required by entities for receiving computers is that they should have a social purpose and, to a lesser extent, be non-profit organizations. Should an entity fail to meet the program criteria, it is redirected to other CRP (some of these programs charge a fair price).

The people regularly engaged in UPC-ReuTIlitza Program are as follows:

- Two CCD members and two TxT members, which held weekly meetings to decide on the assignment of computers to entities applying to the program.
- A student recipient of the UPC-ReuTIlitza Program grant, funded through the CCD budget. This student devotes 15 h per week to the program and warehouse management (i.e., delivers the equipment to entities, ensures that the delivered computers work properly, manages the daily tasks of the warehouse, etc.).
- Four students from Vocational Education and Training courses (VET), usually studying "microcomputer systems" or "management of networked computer systems" courses. These students conduct their compulsory internship (workplace training) by supporting the UPC-ReuTIlitza Program. Each student dedicates about 350 h to this task, usually divided into 4 h daily over a period of four months. The UPC-ReuTIlitza Program has agreements with several VET schools in Barcelona and its environs for the training of these students. The collaboration started in 2009 with a single student, and more students joining subsequently as the workload grew. Currently, four VET students participate continuously in the UPC-ReuTIlitza Program. However, due to the health restrictions imposed by the COVID-19 crisis, this number has been reduced to two students.

In addition to these people, TxT volunteers undertake support tasks insofar as their time and dedication to TxT allow them to do so. The most highly motivated of these students join TxT and set up projects with social entities through the ICT volunteer program [76] or carry out their Bachelor Theses at a social entity.

Appendix A.2. Tools

The visibility of the UPC-ReuTIlitza Program and the number of computers managed every year have been increasing gradually. This growth has necessitated the development of tools to facilitate both the computer refurbishing process and the creation of a regular technical team to prepare computers throughout the year, as well as to collaborate in the organization of the Reuse Workshop.

With regard to the tools developed to facilitate management of the program, we would like to highlight the following [53]:

- Website: All requests and donations of equipment are handled thorough the webpage. However, after receiving the applications, communication with the entities (donors and receivers) is conducted via email or phone in a more personalized way.
- Computer Analysis tool: A software tool has been designed to analyze the computer hardware. The tool works in both local and network mode: it analyzes each computer, keeps detailed information about all the components and assigns a unique serial number to each computer based on information from its components. This information is stored in a database, which is able to follow the life of all the components of each computer if they are subsequently registered with the tool. The objective of this tool is twofold: on the one hand, we can analyze the performance and durability of each component, creating an open database of which components offer the best performance in terms of reliability and lifetime and, therefore, are more sustainable. On the other hand, we have the opportunity to create a trace for each computer and component; thus, should it be found outside the recycling circuit, its origin can be traced.
- Network installation of computers: During the Reuse Workshop, the Operating System is installed in many computers simultaneously. To this end, a simple tool has been developed; the computers are connected to a switch that distributes the selected version of the operating system to all the connected computers. The number of

computers in which this installation can be performed simultaneously depends on the capacity of the switch. In the Reuse Workshop, we use switches of up to 40 outputs.

Appendix A.3. Computer Configuration

To ensure the service, some minimum restrictions apply to the equipment. For instance, desktop computers must be less than 8–10 years old to guarantee 3 or 4 years of use once they are delivered to the social entities. Laptops may be older than 10 years, since the program does not receive as many laptops as desktop computers. However, the number of laptops received in the last two years has increased notably. Many of them come from individual donations, unlike desktop computers, which mostly come from institutions or companies. This means that laptops are older than desktop computers. All desktop computers that are currently delivered have a minimum hardware configuration of 1 TB drive, 2 GB of RAM and, at least, a Core 2 Duo or equivalent processor.

With regard to software, computers have been installed with a free software operating system according to its technical features. Currently, an LTS Linux Mint Cinnamon (32 or 64 bits) is being installed in a Windows-like desktop in order to reduce the reluctance expressed by some users towards an operating system different from Windows. For entities from outside Spain, the operating system is installed in the native language of each country. By default, office suite software (LibreOffice), a browser (Mozilla Firefox) and a media player (VLC) are also installed. This configuration satisfies the requirements of most of the target entities. For entities with special requirements, specific software from the Linux software center is installed on demand.

Appendix A.4. The Reuse Workshop

The Reuse Workshop is held twice a year, in April and November, and last for 2 weeks on each occasion. Students from four different subjects participate in the workshop. The work undertaken by students in each subject is as follows:

- "Computer Interfaces": Students open all computers, clean them by using vacuum cleaners and compressed air, review and update the settings and verify their operation by a startup test that checks the status of all devices. Subsequently, they perform a memory test and a hard disk test. Computers that present any problems are set aside to be repaired. After servicing the computers, these students perform a practical activity related to the subject, consisting of identifying the different components and buses of a computer, elements that have been studied in theory classes. For many students, this is the first time they have opened a computer.
- "PC Architecture": Students repair broken computers and replace damaged components. Computers that are not easy to repair (defective motherboards, for example) are discarded, and their useful elements are set aside as spare parts for repairing other computers, either in the future or during the workshop. The damaged cards and the remaining material that cannot be repaired are taken to a recycling center. In this way, students improve their awareness about recycling.
- "Operating Systems Administration" and "Free Software and Social Development": Students install a Linux operating system in computers that work properly and catalog the computers in the program database.

The work done by students during the workshop provides them with a learning experience related to the technical knowledge they learn in the subjects. As "Computer Interfaces" is a compulsory subject, all FIB students participate at least once in the reuse workshop, although some of them may tackle the four subjects in different workshop editions. In the current organization, we estimate that about 400 computers can be set up in every workshop edition, although the number of computers that is reconditioned is in reality much smaller (fewer than 150). During the workshop, students are informed about the final destination of the computers they are refurbishing. In "PC Architecture" and "Free Software and Social Development" subjects, both of which are elective subjects in the last semester, other TxT activities are provided for students and some of the cooperation

projects carried out in the past by the NGO are explained. The goal is to motivate students to develop a cooperation project as a bachelor's thesis, either with a local or foreign entity. Since students usually undertake their bachelor's theses in the following semester, this is the ideal time to explain SL and make students aware that their theses could be developed through a cooperation project.

The number of computers refurbished during the Reuse Workshops is enough to meet all the requests that the UPC-ReuTIlitza Program receives throughout the year. Therefore, during the daily work in the warehouse, it is only necessary to verify the correct functioning of the computers before delivering them. Should one of the computers fail, which happens from time to time, it must be repaired, or installation must be repeated. The new computers received in donation are stored for the next workshop, with the exception of laptops, which are set up at the time they are donated to the program.

In addition to the practical sessions of the subjects addressed in Reuse Workshop, which are performed within the hours scheduled for each subject, other training activities are scheduled for the remaining days of each workshop:

- A talk on the sustainability of ICT is given to "Computer Interfaces" students, in which both the meaning and importance of the workshop and TxT activities are explained. The UPC-BarcelonaTech's ICT volunteer program [76] is also explained, and students are invited to participate in the next edition. Through these activities, new volunteers enroll in TxT each year.
- A documentary concerning the impact of technology on the sustainability of the planet is shown, and a roundtable discussion is also held. Among others, we have shown the documentary *The E-Waste Tragedy* by Cosima Dannoritzer and a short documentary report by Gemma Parellada on mineral extraction in the Congo. In both cases, the makers of the documentaries have participated in the roundtable discussion that followed the projection.
- Every year, the CCD issues a call for cooperation projects with countries in the global south, and a hundred projects are subsidized. During Workshop sessions, posters of the most representative projects are presented to the students to make them aware of the cooperation that takes place in the university and to encourage them to participate in future calls.
- Special activities for students from other schools are also scheduled. For example, a program of open-door days for secondary school students is organized, the goal of which is to acquaint these students with the program and the social and environmental problems it addresses. These sessions are complemented by visits to the FIB museum and to the MareNostrum supercomputer at the Barcelona Supercomputing Center [77].
- Specific training sessions on current issues related to reuse and recycling are scheduled. For example, training sessions are provided on the operation of the eReuse project [53], an open software platform aimed at facilitating the reuse of computer equipment and ensure recycling at the end of its life.
- A Restart Party is held almost on every workshop edition. A Restart Party is an event in which participants bring their broken electrical or electronic devices to be repaired. The restarters are volunteers who, using their own tools, help the participants to repair their damaged devices. Restart Parties are organized jointly with the Restarters Barcelona collective [78].
- Target entities are invited to participate in some of the workshop activities, at the end of which equipment is given to entities that apply for them. If the receipt of equipment from donors is expected in dates close to the workshop, the donation is organized so that it takes place at the start of the workshop, thereby minimizing the movement of computers between the warehouse and the workshop venue.

TxT volunteers organize and collaborate actively during all workshop. However, for the success of the workshop is vital the work carried out by both the UPC-ReuTIlitza scholar and the VET students.

Appendix B. Assumptions for Calculating the Environmental Impact of the UPC-ReuTIlitza

This Appendix describes the studies on which the model used in Sections 3.3 and 4.3 is based.

Appendix B.1. Lifespan of ICT Products

According to Kumar, Holuszko and Espinosa [60] the average lifespan of a desktop computer is 5.9 years, 5.5 years for laptops and 7.4 for LCD display devices; Prakash et al. [61] pointed out that the minimum useful lifespan recommended by the German IT Council for Federal Administration is 5 years for desktops and 3 for laptops; Tecchio et al. [62] indicate a typical lifespan of 6 years for desktop computers and 5 years for laptop computers; Belkhir and Elmeligi [45] assume a lifetime of 5–7 years for all devices (desktops, laptops and displays). The assumption for the model is a lifespan of 6 years for desktops, 5.5 for laptops and 7 for display devices. At the beginning of the UPC-ReuTIlitza Program, most of computers (both desktops and laptops) received were 3 years old, as most donors find it more convenient to replace their computers for new ones when the typical three-year warranty expires (André et al. [57] also highlight the same point). Over the years, the age of the received material has risen to 6 years.

Nevertheless, in a less-demanding environment, most of the received computers can extend their lifespan. In order to estimate a reasonable extended lifespan for the model, a conservative framework has been used on the basis of the experience gathered through the UPC-ReuTIlitza Program, which shows that, after being repaired and refurbished, desktop computers extend their lifespan by 3 years, laptop computers by 2.5 years and display devices by 4 years.

Appendix B.2. Estimation of the Weight of ICT Products

Different papers have been studied in order to calculate the weight of desktops and laptops. Table A1 shows the weight for desktops, laptops and display devices assumed in each study. Chancerel and Rotter [63] based the weights on their own measurements, Hischier et al. [64] on the database Ecoinvent v2.2, Hischier and Wäger [65] on the database Ecoinvent v3.01, Song et al. [66] on a Dell desktop computer unit, but without disclosing which model, Teehan and Kandlikar [47] on analyzing the Dell Optiplex 780 mini tower and the HP 530 laptop 16″, and finally, Tecchio et al. [62] calculate the average weight of a laptop computer based on different studies.

Table A1. Weight for ICT components.

Weight in kg	Laptop	Desktop		
		Computer	LCD	CRT
Chancerel and Rotter [63]	2.84	11.03	3.559 (min)	-
Hischier et al. [64]	3.055 (max)	12.706	4.010	-
Hischier and Wäger [65]	2.8	13.523 (max)	4	10.9 (min)
Song et al. [66]	-	10.47 (min)	6.825 (max)	16.23 (max)
Teehan and Kandlikar [47]	2.8	10.7	5.1	-
Tecchio et al. [62]	1.930 (min)	-	-	-
Average	2.685	11.686	4.699	13.565

The model will therefore assume three possible scenarios: MIN (assuming the minimum weight for element as that found in the revised literature), MAX (likewise, but assuming the maximum weight) and AVG (calculating the arithmetic mean for all studies) with the data shown in Table A2.

Table A2. Weight of ICT components for the three scenarios.

Weight (kg) per Unit for	Scenario MIN	Scenario MAX	Scenario AVG
Desktop computers	10.47	13.523	11.6858
Laptop Computers	1.93	3.055	2.685
LCD display	3.559	6.825	4.699
CRT Display	10.9	16.23	13.565

Appendix B.3. E-Waste Weight Collected by the Computers Reuse Program

Table A3 shows the number of Kgs of material donated once repaired or refurbished, in three scenarios: MIN, MAX and AVG. The number of products is based on real data accounted from the products donated by the UPC-ReuTIlitza Program (2321 desktop computers, 164 laptop computers, 1298 CRT and 592 LCD display devices). In the case of desktop computers, in the model, it is considered that 3.64% of such elements are impossible to repair and are sent to the recycling company (number based on the last editions of the Workshop).

Table A3. Weight of desktop, laptop, LCD and CRT displays in the three scenarios.

		Scenario MIN	Scenario MAX	Scenario AVG
Desktop computers	Weight (kg) per unit	10.47	13.523	11.6858
	Kg of donated material	24,300.87	31,386.88	27,122.74
	Kg of discarded material	88.46	114.25	98.73
	Total (kg)	24,389.33	31,501.13	27,221.47
Laptop Computers	Weight (kg) per unit	1.93	3.055	2.685
	Kg of donated material	316.52	501.02	440.34
LCD display	Weight (kg) per unit	3.559	6.825	4.699
	Kg of donated material	2106.93	4040.4	2781.81
CRT Display	Weight (kg) per unit	10.9	16.23	13.565
	Kg of donated material	14,148.2	21,066.54	17,607.37
Total e-waste (kg)		40,960.98	57,109.09	48,050.99

Appendix B.4. Material Composition and Weight Recycling of ICT Products and Cost of the Raw Materials

Table A4 shows the material composition of computers assumed by the model. The values are those indicated in [59,68]. These studies categorize the materials into ferrous metals, aluminum, copper, precious metals (Ag, Au, Pd), other non-ferrous metals (Pb, Ni, Mg, Sb, Cr, Sn, Zn, Bi, Co, Ba, Hg), various plastic polymers, other organics (such as rubber), minerals and others (Sb$_2$O$_3$, Si, MnO$_2$, Li, Ar, Ne). However, in the model proposed, only Fe, Al, Cu, Au, Ag, Pd and plastics are taken into account. The Material Weight Recycling (MWR) percentage is taken from the same studies.

As the papers referred to above do not categorize precious metals between Au, Ag and Pd, the distribution of these three elements used by Böni et al. [67] is assumed, and the MWR percentage the one from Wäger et al. [72].

Table A4. Percentage of material composition and MWR in desktops and laptops.

		Desktop		Laptop	
		Material %	**MWR %**	**Material %**	**MWR %**
Ferrous		37.2	89	14.2	86
Aluminum		4.61	83	8.44	75
Copper		4.32	78	6.85	85
	Total	0.0113	88	0.029	88
Precious	Au	0.00188	88	0.00819	88
metals	Ag	0.00839	88	0.01458	88
	Pd	0.00103	88	0.00623	88
Other non-ferrous		0.369	29	10.9	90
Plastics		18.8	43	40.6	13
Other organics		0.0914	0	0.0874	0
Minerals		30	0	12.6	0
Others		4.36	0	6.32	0

The average amount of material found in LCD and CRT display devices are those used in [69], with information completed from Suresh et al. [68]. The percentage of Material Weight Recycling (MWR) for LCD display devices is obtained from the studies of Arduin et al. [70] with respect to valuable metals and plastics and Nelen et al. [71] with respect to precious materials. Due to the fact that no specific information has been found for CRTs, the same MWR percentage is assumed. Table A5 summarizes the data used in the model.

Table A5. Composition and MWR of LCD displays.

		LCD		CRT	
		Weight	**MWR %**	**Weight**	**MWR %**
	Fe	18%	82	26%	82
Valuable metals	Al	3.6%	98	2%	98
	Cu	7.2%	70	6.5%	70
	Au	60×10^{-6}	98	40×10^{-6}	98
Precious metals	Ag	300×10^{-6}	97	207×10^{-6}	97
	Pd	25×10^{-6}	98	190×10^{-6}	98
Plastic (%)		25.64%	98	13.19%	98

The market price of resources undergoes large variations over time, and the UPC-ReuTIlitza Program has been in existence for 15 years. To arrive at an approximation, the model assumes the prices shown in Table A6, which are those from [69].

Table A6. Market price for some resources.

	Prize in USD
Fe (in tons)	120
Al (in tons)	2300
Cu (in tons)	6400
Au (in gram)	47
Ag (in grams)	1.03
Pd (in gram)	21
Plastic (in tons)	890

Table A7 shows the weight of potentially recoverable material (in kg) and the price of potentially recoverable material (in USD) for the three scenarios. All the figures are based on the total weight of the material that has been recycled or which is destined to be

recycled, real (donations) and estimated (discarded products), as shown in Table A3. The percentage of material present per kilogram of device and the Material Weight Recycling (MWR) are those presented in Tables A4 and A5, while the marked prices are given in Table A6.

Table A7. Weight and economic value (EUR) of material recoverable from the UPC-ReuTIlitza Program for the three scenarios.

	Weight of Potentially Recoverable Material			Price of Potentially Recoverable Material		
	MIN	MAX	AVG	MIN	MAX	AVG
Fe	11,411.56	15,540.50	13,198.06	1369.388	1864.860	1583.767
Al	1301.5	1788.12	1508.92	2993.443	4112.677	3470.511
Cu	1587.20	2248.95	1880.91	10,158.104	14,393.267	12,037.793
Au	1.103	1.619	1.334	51,857.104	76,081.626	62,708.999
Ag	5.289	7.787	6.404	5447.388	8020.967	6596.031
Pd	2.923	4.334	3.617	61,396.242	91,004.302	75,949.195
Plastics	4339.42	6302.10	5190.80	3862.088	5608.871	4619.810
Total estimated cost				137,083.76	201,086.57	166,966.106

Appendix B.5. Estimated Savings Due to ICT Material Lifespan Extension

As shown in this Section, the model assumes a lifespan of 6 years for desktop computers, 5.5 for laptops and 7 years for LCD and CRT devices. Since the model considers a lifespan extension of 3 years for desktop computers, 2.5 years for laptop computers and 4 years for display devices (both LCD and CRT), the ICT devices that will not be purchased by the entities receiving the donations can be estimated by calculating the percentage of lifespan extension times the number of products donated (Table A8). For instance, one entity may receive a donation of two desktop computers (the second donation 3 years after the first one), thus using two donated desktops for 6 years (each with a 3-year lifespan), or may purchase a new one and make it last for 6 years. Thus, two donations save the entity from having to buy one new desktop computer.

Table A8. ICT products received by entities, thereby precluding purchase.

	Donated	Lifespan	Lifespan Extension	Equivalent Material Saved
Desktop	2321	6	3	1160
Laptop	164	5.5	2.5	74
LCD	592	7	4	338
CRT	1298	7	4	741

The impact of the reduction of ICT products is estimated by the reduction of raw materials required to build these products and the energy saved in the production phase (the recycling cost is not taken into account).

Table A9 shows the raw material saved due to the reduction of the production of ICT devices thanks to the lifespan extension of the UPC-ReuTIlitza Program. The number of devices in Table A8 is assumed, as is the composition of devices shown in Tables A4 and A5, and the weight per product for the three scenarios shown in Table A2.

Table A9. Material saved due to life extension of donated products.

	Weight of Potentially Saved Material			Price of Potentially Saved Material		
	MIN	MAX	AVG	MIN	MAX	AVG
Fe	6854.82	9409.65	7970.19	822.58	1129.16	956.42
Al	776.80	1065.81	899.89	1786.62	2451.37	2069.75
Cu	1146.07	1640.96	1366.92	7334.82	10,502.15	8748.30
Au	0.64	0.93	0.77	29,858.12	43,845.97	36,118.51
Ag	3.07	4.53	3.72	3164.78	4666.52	3835.15
Pd	1.70	2.52	2.10	35,672.23	52,885.35	44,131.99
Plastics	3715.06	5218.64	4362.15	3306.40	4644.59	3882.32
Total estimated cost				81,945,57	120,125.10	99,742.44

With respect to the energy saved in the production phase of these ICT products, the model assumes the kilograms of CO_2 equivalent (kg-CO_2-e) presented in Belkhir and Elmeligi [45] for each element and summarized in the left-hand columns of Table A10. The two right-hand columns are the kg CO_2-e of the model, assuming the number of products saved calculated in Table A8.

Table A10. Energy of the production phase of ICT products per element and saved by the UPC-ReuTIlitza Program.

	Production Phase Energy (kg CO_2-e)		Production Phase Energy Saved (kg CO_2-e)	
	Min	Max	Min	Max
Desktop	218	628	252,880	728,480
Laptop	281	468	20,794	34,632
LCD	95	95	32,110	32,110
CRT	200	200	148,200	148,200
Total kg CO_2-e saved			453,984	943,422

Finally, one common measure used to explain the kg CO_2-e is to present the data in number of trees per year, i.e., the number of trees required for the sequestration of one given amount of CO_2 in the period of one year. This measure is not commonly used in scientific papers because is not easy to measure. However, it is one of the measures with a high impact on audiences, which is one of the objectives when explaining the importance of initiatives such as the UPC-ReuTIlitza Program. The main problem when calculating the number of trees per year is that the rate of carbon sequestration depends on the growth characteristics of the tree species, the conditions for growth where the tree is planted and the density of the wood of the tree. Furthermore, it varies according to the different stages of tree growth, and a difference also exists between tropical tree forests and temperate tree forests. For example, Myers and Goreau [73] indicate that a tropical tree plantation of pine and eucalyptus can sequester 33.26 kg CO_2/tree/year on average, while Toochi [75] indicates that the average sequestration in tropical forests is about 22.68 kg CO_2/tree/year.

Taking into account that the UPC-ReuTIlitza Program has been implemented in a temperate country in Europe, the model is based on data provided by Toochi [75] on the basis of information from the Agroforesttree Database [74]. A rank is calculated in the model, the minimum being 1.14 kg CO_2/tree/year (a 25-year-old maple, beech and birch forest) and the maximum being 6.35 kg CO_2/tree/year (a 25-year-old white and red pine forest). Table A11 shows the number of trees per year for the rank, assuming the minimum and maximum kg CO_2-e calculated in Table A10. The results indicate that the CO_2 emissions for making the ICT products saved by the UPC-ReuTIlitza Program require between 71,494 and 827,563 tree/year to be sequestered.

Table A11. Rank of tree per year required for the sequestration of the CO$_2$-e saved by the UPC-ReuTIlitza Program.

Forest Type		Maple-Beech-Birch	White and Red Pine
Sequestration rate		1.14 kg CO$_2$/tree/year	6.35 kg CO$_2$/tree/year
kg CO$_2$-e (min)	453,984	398,231.58	71,493.54
kg CO$_2$-e (max)	943,422	827,563.16	148,570.40

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