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Service lifetime, storage time and disposal pathways of electronic equipment: a Swiss case study

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<heading level 1> Summary

Product lifetime is an essential aspect of dynamic material flow analyses and has been modeled using lifetime distribution functions, mostly average lifetimes. Existing data regarding the lifetime of electronic equipment (EE) are based on diverging definitions of lifetime as well as different temporal and regional scopes. After its active use, EE is often not disposed of immediately, but remains in storage for some time. Specific data on the share of EE that is stored and the time they remain in storage are scarce. This article investigates the service lifetime, storage time and disposal pathways of 10 electronic device types, based on data from an online survey complemented by structured interviews. We distinguish between new and second-hand devices and compute histograms, averages and medians of the different lifetimes and their change over time. The average service lifetime varies from 3.3 years for mobile phones to 10.8 years for large loudspeakers, the average storage time from 0.8 years for flat panel display TVs to 3.6 years for large loudspeakers. Most service lifetime histograms are positively skewed and show substantial differences among device types. The storage time histograms, being more similar to each other, indicate that the storage behavior is similar for most device types. The data on disposal pathways show that a large proportion of devices are stored and reused before they reach the collection scheme.

Keywords: Service lifetime; storage time, disposal pathways, electronic waste, obsolescence, material flow analysis

<heading level 1> Introduction

The fast pace of innovation cycles for electronic equipment (EE) and the falling prices for new devices lead to short product lifetimes and increasing sales (Prakash et al. 2015). EE contains important material resources, including bulk materials, precious metals, and critical raw materials (Buchert et al. 2012). While the recycling of bulk materials and precious metals is often well established, efforts to specifically recover critical raw materials from EE are only beginning. They are hampered by low content per device, low market prices that make recycling unattractive, limitations of recovery technologies as well as limited knowledge on stocks and flows of these devices. Efficient recycling thus relies on knowledge of anthropogenic material cycles regarding location, lifetime, disposal pathways, quantities, and qualities of EE (UNEP 2010; UNEP 2011; UNEP 2013; van Schaik and Reuter 2010; Reuter 2011) This information enables recycling systems to forecast future mass flows, provide for sufficient recycling capacities, and invest in appropriate recycling technologies (Prakash et al. 2015).

The temporal analysis of material cycles is often based on a dynamic material flow analysis (MFA) approach. The product lifetime or lifespan – these terms are used as synonyms in existing literature - is an essential part of dynamic MFAs, necessary to calculate the development of stocks and outflows from inflow data or inflows and outflows from stock data. It has mostly been modeled in dynamic MFAs so far by assuming lifetime distribution functions, mostly average lifetimes (Müller et al. 2014). In many MFA studies, it has been discussed that stocks and flows are sensitive to the chosen lifetime distribution functions and their parameters (Chen and Graedel 2012;

Liu, Bangs, and Müller 2011; Müller et al. 2006). Data regarding the product lifetime of specific EE are relatively abundant for mobile phones, for example (Cooper 2005; Echegaray 2014; EPA 2004; J.D. Power and associates 2007; Murakami et al. 2010; Polák and Drápalová 2012; Stocker et al. 2013; Wang et al. 2013; Wieser and Tröger 2015), televisions (TVs), for example (Cooper 2005; Echegaray 2014; Gutiérrez et al. 2011; Oguchi et al. 2010; Prakash et al. 2015; Wang et al. 2013; Wieser and Tröger 2015), as well as laptop and desktop computers (Babbitt et al. 2009; Cooper and Mayers 2000; Echegaray 2014; Prakash et al. 2015; Prakash et al. 2012; Sabbaghi et al. 2015; Wang et al. 2013; Wieser and Tröger 2015; Williams and Hatanaka 2005). Data is more scarcely available for printers (Echegaray 2014; Stocker et al. 2013; Wang et al. 2013), radio and HiFi components (Cooper 2005; Gutiérrez et al. 2011; Wang et al. 2013), video equipment (Cooper 2005; Echegaray 2014; Wang et al. 2013), cameras (Wang et al. 2013; Wieser and Tröger 2015), telephones (Cooper 2005; Wang et al. 2013), Monitors (Wang et al. 2013), and speakers (Wang et al. 2013). Most of these studies provide average or median lifetimes. Using average lifetimes in dynamic MFAs, that is, a delta function as the lifetime distribution, leads to modeled outflows that are identical to the often fluctuating inflows and often significantly under- or overestimate measured outflows (Müller et al. 2014). The only studies presenting more information on distributions are Polák and Drápalová (2012) as well as Wang et al. (2013), which provide Weibull parameters for lifetime distributions and Babbit et al. (2009) as well as Stocker et al. (2013), which derive Gaussian lifetime distributions from lifetime histograms.

Studies of product lifetime use different definitions of the phase of the life cycle that is taken into account (Murakami et al. 2010; Oguchi et al. 2010; Babbitt et al. 2009). Many studies highlight that the product lifetime may change significantly over time (Babbitt et al. 2009; Echegaray 2014; Murakami et al. 2010; Oguchi et al. 2010; Prakash et al. 2015; Sabbaghi et al. 2015; Wang et al. 2013). The existing studies all refer to a specific system boundary, that is, a country or a region and a specific time frame. A compilation of available data for mobile phones and TVs (Wieser and Tröger 2015) as well as a study on desktop PCs (Müller et al. 2009) has shown that the product lifetime can vary considerably between countries or regions. All these factors make it difficult to compare studies and adopt data to different settings.

At the time of replacement, EE is often not disposed of immediately, but stored for some time. This leads to, for example, very few mobile phones collected for disposal despite high sales numbers. Comparisons of assumed product lifetimes with the product age at recycling facilities have shown that products are often older than expected (Stocker et al. 2013). Data showing how long the various EE is stored are scarce. Of the literature mentioned above, Polák and Drápalová (2012) report the average storage time of used mobile phones, including reuse, Sabbaghi et al (2015) investigate the storage time of desktop and laptop computers by analyzing used hard disk drives, and Williams and Hatanaka (2005) indicate the storage time for personal computers from a survey. In addition, Milovantseva et al. (2013) and Saphores et al. (2009) analyze the amount of TVs and e-waste in general, respectively, stored in households of the United States. Instead of storage, sometimes, the term hibernation is used, e.g. (Murakami et al. 2010; Daigo et al. 2015), who analyze the hibernating behavior of material stocks of steel in Japan. For how long products or materials are stored (or 'hibernating'), however, is not addressed in these articles.

For every dynamic MFA that takes into account both the use and the disposal phase of a product, the knowledge of disposal pathways and the related transfer coefficients is crucial. The disposal pathways chosen in existing MFAs of EE vary from highly aggregated processes (e.g. recycling, landfilling, export) to very detailed breakdowns (e.g. collection, repair, recycling, second-hand sale, export etc.), for example (Kahhat and Williams 2012; Lam, Lim, and Schoenung 2013; Lau, Chung, and Zhang 2013; Leigh, Choi, and Hoelzel 2012; Steubing et al. 2010; Yoshida, Tasaki, and Terazono 2009).

In this article, we present the results of a survey on the service lifetime, the storage time, and the disposal pathways of EE that we conducted between 2014 and 2016 in Switzerland. The goal of the survey is to obtain detailed 'bottom-up' information of the service lifetime and the storage time (hibernating time) of EE in Switzerland. We further aim at gaining insights in the trigger events to transfer devices between the use, storage and disposal phase. The distinction between service lifetime and storage time as well as the more detailed knowledge on reuse, storage and disposal flows enables a more accurate MFA model of the actual stocks and flows of EE in Switzerland. Such a model is important, for example, to explain the discrepancy between low collection flows and high sales flows, predict the average product age of devices at recycling facilities or account for long phase out periods of technologies that are no longer sold (e.g. CRT TVs and monitors). It can further provide a basis for recycling system managers to understand how different device types are handled in the use phase, forecast future recycling flows based on assumed or extrapolated sales flows as well as provide appropriate and tailored recycling capacities and technologies for the expected composition of the recycling flows. In life cycle assessment (LCA), the total impact should be split into the different phases, such as manufacturing, service, storage and recycling. Thus clarifying the difference between service lifetime and storage time has a potential to recalibrate many LCA studies. Knowledge on the effective service lifetime versus the total lifetime (including storage) and the share of reused devices might also be useful for other stakeholders, in particular: product designers who aim at improving product longevity and product remanufacturers who need this information for their capacity planning.

<heading level 1> Method

The initial data collection consisted of an online survey distributed via social networks and email in 2014. The survey covered 10 electronic device types with a high content of indium, neodymium or gold, so that they cumulatively cover over 90% of these three metals in private Swiss households (Böni et al. 2015). Table 1 lists the considered device types as well as the associated UNU-Keys for comparability with existing studies, e.g. Baldé et al. (2015).

Table 1: Electronic device types included in the survey.

Device type	**Description**	**UNU-Key**
Desktop	Desktop computer (incl. all-in-one computer, without external peripherals)	0302
Laptop	Laptop/Notebook computer	0303
Monitor	Flat panel display (FPD) monitor	0309
Mobile phone	Mobile phone / Smartphone	0306
Headset	Headphones / Headset	0401
CRT TV	Cathode ray tube television (CRT TV)	0407
FPD TV	Flat panel display television (FPD TV)	0408
Loudspeaker small	Portable loudspeaker / Loudspeaker docking station	0403
Loudspeaker large	Loudspeaker set (of Hi-Fi and Home Cinema Systems)	0403
DVD player	DVD player / Blu-ray player	0404

The survey included questions on the service lifetime, the storage time, and the disposal pathways, and targeted at devices that were still in use, devices that were stored, and already disposed of devices. We defined the service lifetime as the *time of active use of a device*. The storage time is defined as the *time between the active use of a device and its final disposal or its transfer to a different user*.

The original questionnaires were provided in two language versions, German and English. In the first part of the questionnaire, we asked the participants how many devices of the considered device types they are currently using, storing or have already disposed of (Table S1 in the supporting information 1 of this article (SI1)).

In the second part, we asked detailed questions for each device the participant had indicated in the first part. For each device, we asked for

- the condition of the device when it was purchased by the current user (new/second-hand),
- the year of purchase and, for second-hand devices, the age of the devices when it was purchased,

- the service lifetime

  a) for devices already stored or disposed of,

  b) for devices still in use including an estimation of the years the user intended to continue to use it,

- the storage time

  a) for devices already disposed of,

  b) for devices still stored including an estimation of the years the user intended to continue to store it,

- the disposal pathway for devices already disposed of.

The questions were the same for all device types with one exception: as headphones or headsets are often abundant, and users have no accurate overview of their usage time, we only inquired the average service lifetime, storage time and disposal pathway of all headsets in use, stored or disposed of (Table S2 to S7 in the SI1).

In the third part of the survey, we asked each respondent for her/his gender, age, and level of education as independent auxiliary variables (Table S8 in the SI1).

In total, the online survey resulted in 441 valid responses from Switzerland and Liechtenstein. Liechtenstein forms part of the Swiss e-waste recycling system and its population structure is very similar to that of Switzerland. We therefore decided to include the survey results for Liechtenstein in the Swiss context. With a Swiss population of roughly 8'000'000, a confidence level of 95% and a margin of error of 5%, we needed a sample size of at least 385 people. However, data from online surveys are often biased due to under-coverage and self-selection. Under-coverage in online surveys happens when the possible survey sample population does not equal the target population, since only respondents with access to the Internet can participate. Self-selection means that the researcher does not control the selection process. Survey respondents are individuals with Internet access who by chance learn about the survey via social networks or email and decide to participate. This means that the survey sample is not randomly selected from the target population and thus the principles of probability sampling are not followed (Bethlehem 2009; Bethlehem 2010; Gosling et al. 2004). While a truly random sampling of the population, for example by telephone-based questionnaires, is clearly preferable, there were not sufficient resources available to do this.

In order to account for the above concerns, we included three independent auxiliary variables in our survey: age, gender and highest level of education (Table S8 in the SI1). The statistical relevance of these variables was tested using the rank-based nonparametric Kruskal-Wallis test or Mann-Whitney U test. Subsequently, we created 30 age-gender-education subgroups and assessed the respondents' distribution to these subgroups compared to the Swiss and Liechtenstein population distribution. For groups that were missing or severely under-represented in our survey we held 23 additional, structured interviews in 2015 and 2016. The interviewees were personally approached by the researchers according to their gender, age and education attributes, therefore the response rate was 100%. In total, the data collection resulted in 464 participants from Switzerland plus Liechtenstein. To correct for the under- or over-represented groups, we introduced weighting adjustments (Bethlehem 2010). Further information regarding the independent auxiliary variables, the age-gender-education subgroups (Table S9) and the weighing adjustments Table (S10) are described in the SI1.

From the survey results, we calculated the year each device was sold as a new product. On this basis, we calculated the service lifetime and storage time for each device. For new devices, 'service lifetime' refers to the time of active use of the device. For second-hand devices, 'service lifetime' refers to the time of active use by the first user. We assume that the time of active use by the first user is equal to the age of the device at the time of resale, although this might include some storage time. The 'second service lifetime' refers to the active use of a second-hand device.

The 'storage time' relates to the time between the active use of a new device and its final disposal or its transfer to a different user. The 'second storage time' relates to the storage time after the active use of a second-hand device. The resulting equations and the references to the survey responses are listed in Table S11 of the SI1.

The service lifetime for devices still in use includes an estimate of the time the user intends to continue to use the device. Literature shows that people tend to overestimate future service lifetimes of their devices (Cooper and Mayers 2000; Echegaray 2014; Wieser and Tröger 2015; Wilhelm, Yankov, and Magee 2011). We thus compared this data with the service lifetime of devices no longer in use, that is, already stored or disposed of, in order to see whether we could confirm this finding. However, the sample of devices no longer in use is biased due to right censoring. Right censoring refers to the fact that for more recent sales years, many devices are still in use and therefore don't appear in the sample. Because only cases of shorter lifetime are included, the sample is distorted. To exclude right censored data, we omitted data for more recent sales years of each device type.

The storage time of devices currently in storage includes an estimate of the time the user intends to continue to store the device. If we only considered the storage time of devices already disposed of, the sample would again be biased, in particular because for many device types, more devices are currently stored than already disposed of. However, for storage time and second storage time, no literature data is available against which we could test the user estimates. Therefore, we analyzed the total sample, including all data from all sales years, keeping in mind that they include rough user estimates.

Based on the above definitions, we calculated for each device type the corresponding weighted and normalized histograms, box plots as well as the weighted averages and standard deviations of the service lifetime, the second service lifetime, the storage time and the second storage time. To analyze the temporal change of the service lifetime and the storage time, we defined 2014 as reference year, as most data was collected in this year. The data was divided into sales year groups. For each sales year group and device type, we computed a weighted and normalized cumulative histogram of the service lifetime and storage time. For the service lifetime, we took into account all available observations, but only display the service lifetime of devices that were stored or disposed of before 2014, in order to exclude prospective user estimates of the service lifetime because they are probably biased. Therefore we display only partial cumulated histograms for more recent sales year groups. For the storage time, we used all available observations.

The disposal pathway results were represented as transfer coefficients. A transfer coefficient refers to the relative share of a specific flow in relation to the total outflow from a specific process. Transfer coefficients are expressed as numbers between 0 and 1 (or 0 and 100%). The sum of the transfer coefficients from a process to all disposal pathways equals 1 for each device type.

More details regarding the data evaluation can be found in the SI1. The microdata of the survey results are provided in the supporting information 2.

<heading level 1> Results and discussion

<heading level 2> Service lifetime

<heading level 3> Median and average service lifetime

Figure 1 shows the box plots of the service lifetime of devices still in use compared to the box plots of the service lifetime and the second service lifetime of devices no longer in use. Each box plot is based on data over all available sales years.

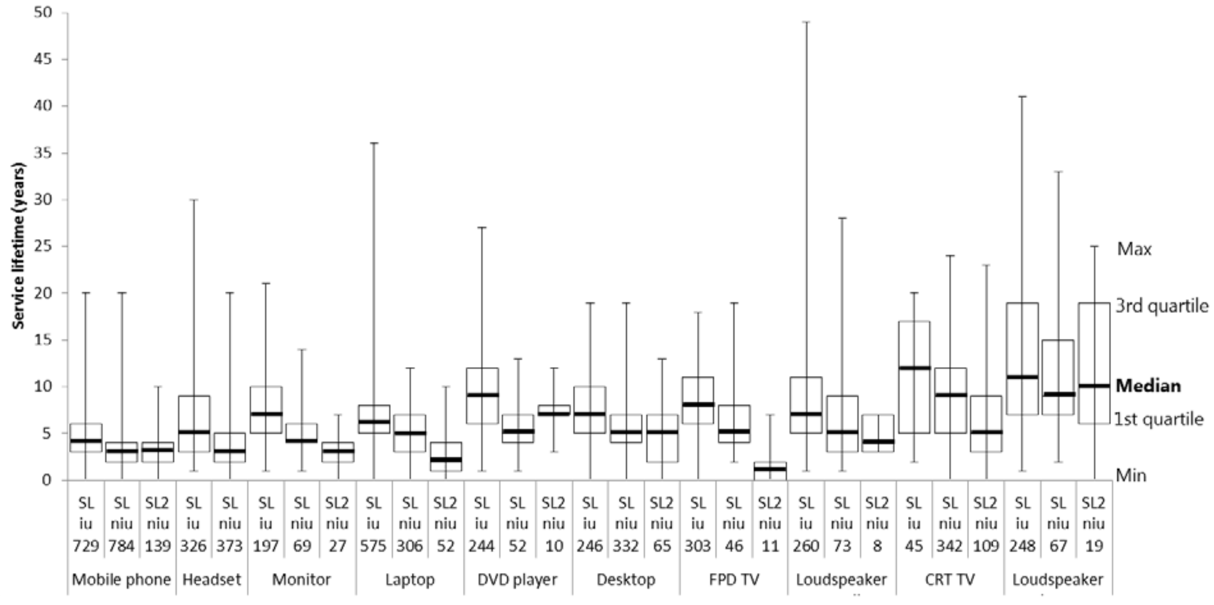

Figure 1: Comparison of the box plots of the service lifetime for 10 different electronic device types. SL iu: service lifetime of devices in use, SL niu: service lifetime of devices no longer in in use, i.e., already stored or disposed of, SL2 niu: second service lifetime of devices no longer in use. The number in the third line indicates the sample size.

The median service lifetime of devices still in use, including the estimated years the user intends to continue to use it, varies between 4 years for mobile phones and 12 years for CRT TVs. The average lifetime of devices still in use ranges between 4.3 years for mobile phones and 13.4 years for large loudspeakers. The median service lifetime of devices no longer in use varies between 3 years for mobile phones and headsets and 9 years for CRT TVs and large loudspeakers. The corresponding average service lifetimes are 3.3 years, 3.8 years, 9.2 years and 10.8 years, respectively. The median second service lifetime is equal to or shorter than the median (first) service lifetime, depending of the type of device and with the exception of DVD Players and large loudspeakers. The first and third quartiles as well as the minimum and maximum values illustrate the often large variance of the data. For most device types, the service lifetime of devices still in use shows the highest variance. An overview of average values including standard deviations and standard errors of the average can be found in Table S14 and S15 of the SI1.

According to the results presented above, users declare intended service lifetimes that are higher than the service lifetimes of the products of the same type they used in the past, by 20% for laptops up to 80% for DVD players. The temporal analysis of the service lifetime has revealed either stable or decreasing service lifetimes for all device types (see below). If the intended service lifetimes declared by the respondents were taken for granted, this would thus imply a trend reversal, which doesn't seem very likely. In several studies users were explicitly asked for the expected and the measured lifetime of various consumer durables, including EE. Cooper and Mayers (2000) found that for mobile phones in the United Kingdom the expected service lifetime exceeds the measured service lifetime by 50%. In Brazil, users expect TVs to last 40%, computers 70% and mobile phones 80% longer than the service lifetime of their previously disposed devices (Echegaray 2014). Similar findings were made in a study on the lifetime of mobile phones in the US (Wilhelm, Yankov, and Magee 2011). In an Austrian study, the authors distinguished between desired, expected and actually measured service lifetime. They found that the expected lifetime is substantially lower compared to the desired lifetime, and the discrepancy between the desired and the actually measured lifetime amounts from 170% to 330% (Wieser and Tröger 2015). All these discrepancies show that longer lifetimes are expected by many users, but not achieved. The reasons may include fast innovation cycles, wear and tear, low product quality, or poor reparability. We thus regard the data for devices no longer in use as more reliable and use only this data for further analysis.

Mobile phones and headsets clearly show the shortest median and average service lifetimes. CRT TVs and large loudspeakers show the longest service lifetimes. The service lifetime of mobile phones is often connected to mobile phone contracts (J.D. Power and associates 2007), which in Switzerland normally last two years. This finding can be confirmed by the histogram of the service lifetime of mobile phones, with its mode at two years. Headsets are often included in mobile phone packages, which may explain that they have similar lifetimes as mobile phones. CRT TVs and large loudspeakers are both durable products that are rather replaced due to technical upgrade than failure. Using Fisher's classification of products (Fisher 1997), CRT TVs and large loudspeakers can be regarded as functional products, whereas the remaining device types are rather innovative products.

<heading level 3> Histograms of service lifetime

Figure 2 shows the normalized histograms of the service lifetime of devices already stored or disposed of, for 10 electronic device types over all available sales years. The service lifetime is not normally distributed based on the Shapiro-Wilk test, but positively skewed. Headsets and mobile phones exhibit similar (and the narrowest) service lifetime distributions. The service lifetimes of desktops and laptops are also similarly distributed. CRT TVs and large Loudspeakers show the longest service lifetimes and the widest distributions. The positively skewed distributions show that for all device types, a small number of devices remain in use for a multiple of the average or median service lifetime. One potential explanation for this observation is that all devices of a given type could in principle be used for such a long time, as it seems to be technically feasible. However, as our survey did not investigate the reasons for obsolescence of devices, we have no positive evidence so far that most devices were replaced before failure.

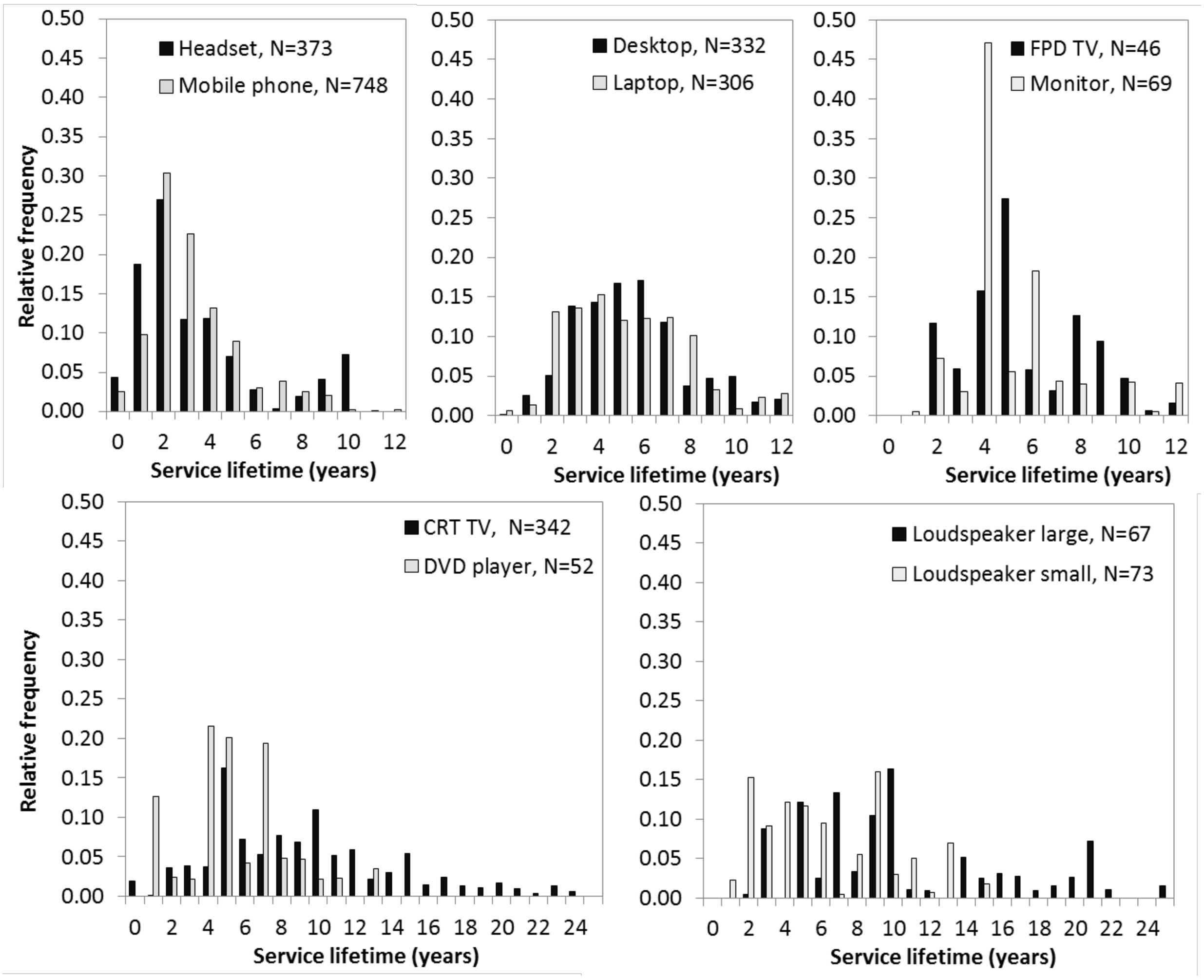

Figure 2: Normalized histograms of the service lifetime of devices no longer in use for 10 electronic device types. N denotes the sample size.

<heading level 3> Temporal change of service lifetime

Although various studies emphasize that the product lifetime may decrease significantly over time (Babbitt et al. 2009; Echegaray 2014; Murakami et al. 2010; Oguchi et al. 2010; Prakash et al. 2015; Sabbaghi et al. 2015; Wang et al. 2013), the cumulative histograms resulting from the analysis of the change over time of the service lifetime show no significant trend for the temporal change for desktops, laptops, FPD TVs and mobile phones. The service lifetimes of monitors, large and small loudspeakers and DVD players show a slight decrease, the more recently the devices were sold. For CRT TVs, after 10 years, a decrease of the further service lifetime as well as of the variance can be observed. Figure 3 shows two examples of the temporal change of the service lifetime. The remaining cumulative histograms are provided in Figures S6 – S9 in the SI1. Reasons for the decrease of product lifetime mentioned in literature, such as faster innovation cycles, falling prices (Prakash et al. 2015), increasingly sophisticated advertisement or the desire for social inclusion (Wieser and Tröger 2015) might have less influence than expected. It could therefore be justified to assume constant lifetimes for certain device types in a dynamic MFA model.

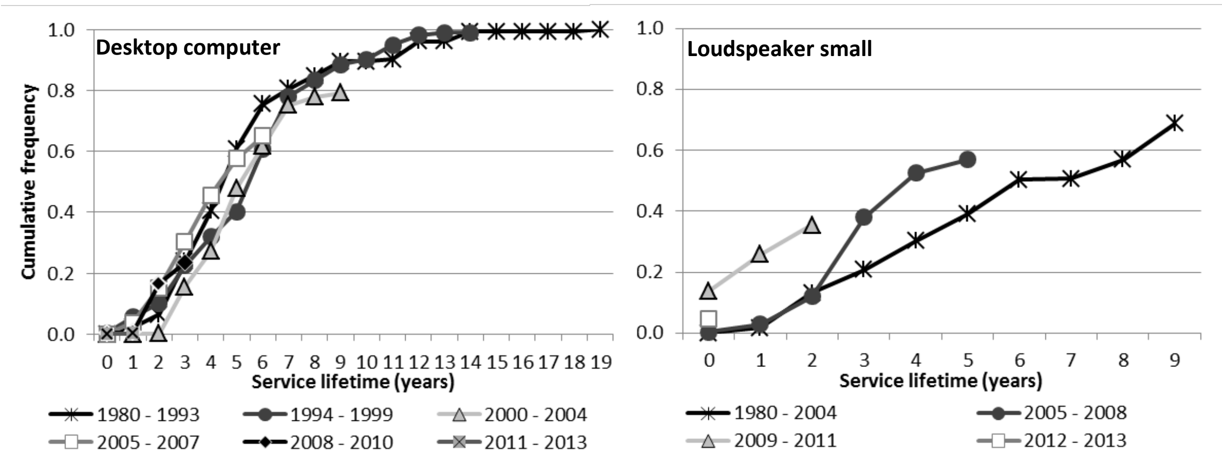

Figure 3: Example of the analysis of the temporal change of the service lifetime of a) desktop computers and b) small loudspeakers. Each line represents a sales years group of devices, i.e., the set of devices sold in the time period indicated in the legend.

<heading level 2> Storage time

<heading level 3> Median and average storage time

The box plots of the storage time and the second storage time are shown in Figure 4. Each box plot is based on data over all available sales years.

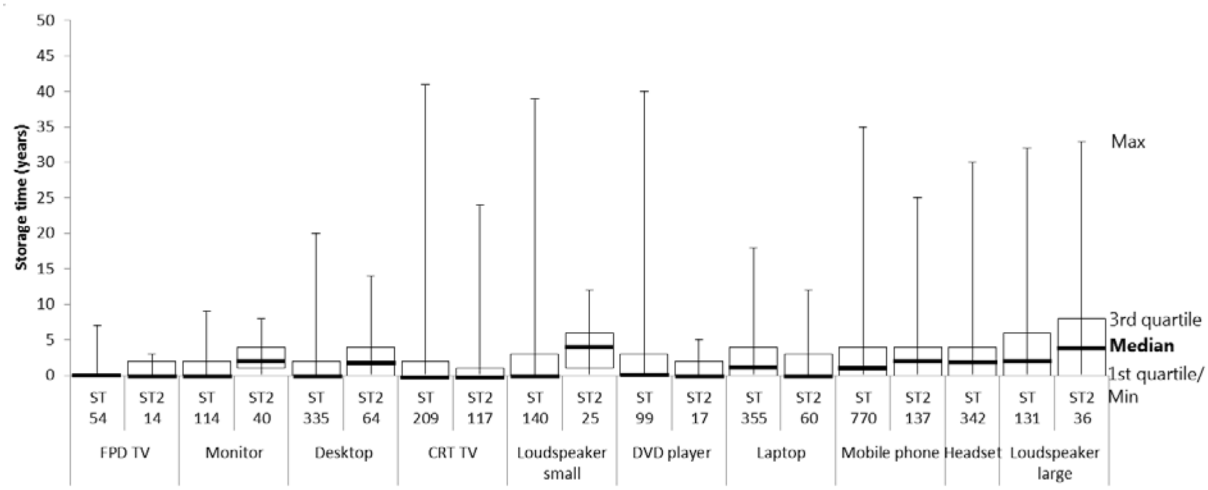

Figure 4: Comparison of box plots of the storage time for 10 different electronic device types. ST: storage time, ST2: second storage time. The number in the second line indi-

cates the sample size.

The median storage time, including devices with 0 storage time, is 0 years for most device types. Laptops and mobile phones have a median storage time of 1 year, headsets and large loudspeakers of 2 years. The average storage time ranges from 0.8 years for FPD TVs to 3.6 years for large loudspeakers. For FPD TVs, CRT TVs, Laptops and DVD players, the median second storage time is similar to or smaller than the median storage time. For all other device types, the median second storage time is larger by at least one year. With a few exceptions, the maximum storage time exceeds 10 years for most device types, which illustrates the large variance of the storage time. An overview of average values can be found in Table S16 and S17 of the SI1.

The variation of the average storage time among device types is smaller than that of the service lifetime, with most device types having an average storage time of 1.5 to 2.8 years. Compared to the average service lifetime, the average storage time is similar for mobile phones and headsets, about a factor 6 to 7 smaller for CRT and FPD TVs and a factor 2 to 3 smaller for the remaining device types. Small devices such as mobile phones and headsets are thus stored for a longer time than large devices such as TVs, compared to the time they are actively used. Remy and Huang (2015) also found that the storage time is highly influenced by the personal attachment to a device. This could explain why laptops are longer stored than, for example, small loudspeakers.

<heading level 3> Histograms of storage time

The normalized histograms of the storage time show similar distributions for most device types (Figure 5), indicating again a smaller variation of the storage time among device types, compared to the service lifetime. The share of devices that are not stored at all ranges from 30% for headsets up to 75% for FPD TVs.

<heading level 3> Temporal change of storage time

The analysis of the temporal change of the storage time illustrates that for most device types, more devices are stored, the more recently the devices are originally sold. Their storage time, however, is often shorter and the variance of the data is smaller. Exceptions are large and small loudspeakers, where more recently sold devices are less stored and have shorter storage times than devices with earlier sales years. Explanations for these observations are difficult to find. Evidence could only be provided by a survey that investigates more into the reasoning behind the users' decisions. The temporal change of the storage time is depicted in Figures S10 – S14 in the SI1.

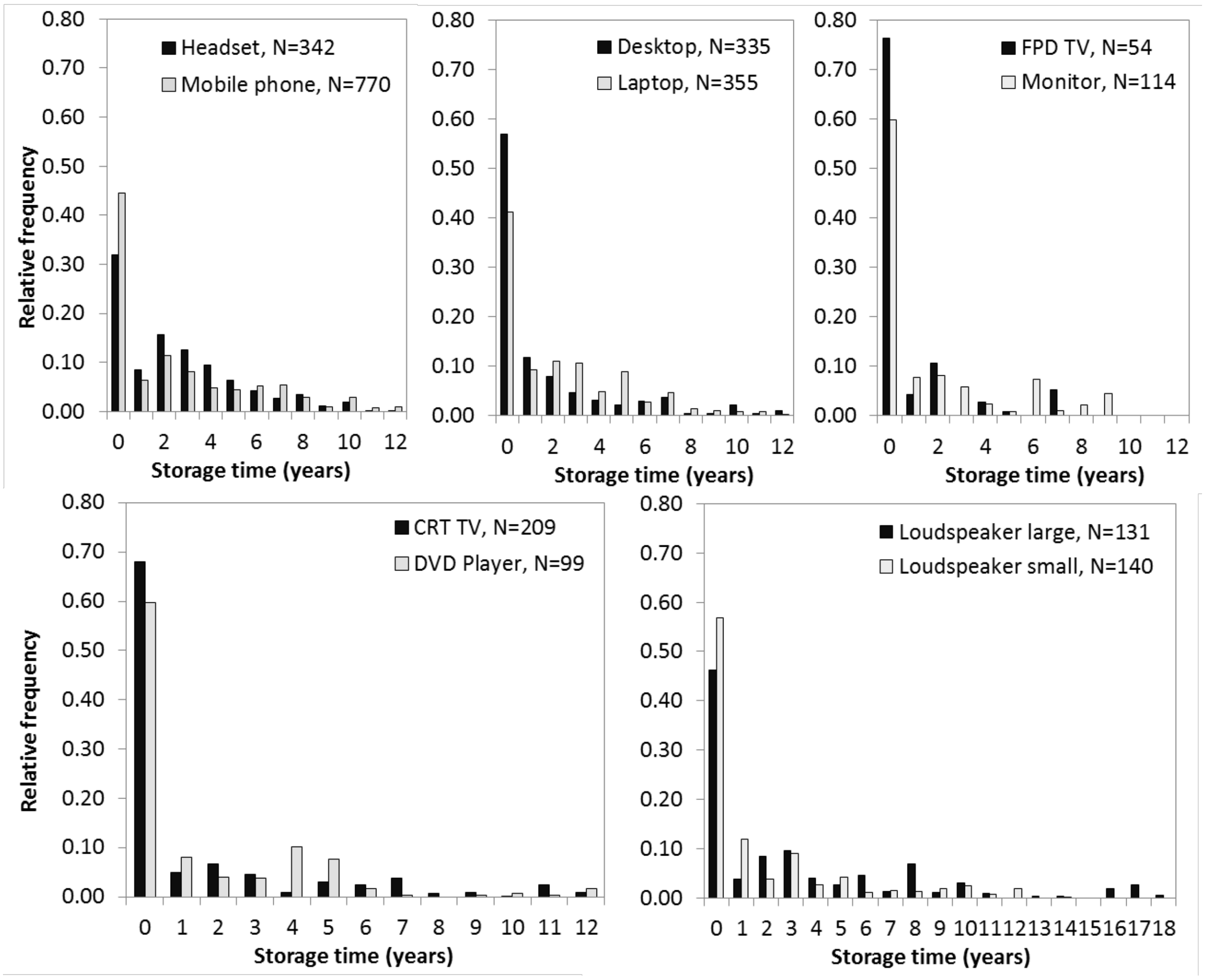

Figure 5: Normalized histograms of the storage time for 10 electronic device types. N denotes the sample size.

<heading level 2> Reuse, storage and disposal pathways

The transfer coefficients representing the different disposal pathways of the considered device types are listed in Table 2. The rate of reuse directly after active use is highest for FDP TVs (30%) and Monitors (20%). Headsets are the least likely to be directly reused with a rate of less than 1%. The share of devices that are stored after their first active use is highest for headsets with 70%. The lowest storage rates can be clearly attributed to CRT TVs and FPD TVs with 30%. Collection rates directly after first use are highest for CRT TVs (55%) and DVD players (42%). After first storage, reuse rates are higher for most device types than directly after active use. However, most devices are brought to the collection system. Exceptions are FPD TVs, whose reuse rates after first storage are higher than the collection rate.

Second-hand devices show similar or even higher storage rates for most device types compared to new devices, ranging from 28% for CRT TVs up to 83% for monitors. Collection rates directly after second use are highest again for CRT TVs (58%) and DVD players (47%), but also high for laptops (44%). After the storage of second-hand devices, again most devices are brought to the collection system. However, for some device types, still 18% to 40% of devices are reused as third-hand devices.

If a device is reused, its average service lifetime is extended by at least 30%. Taking into account the reuse rates up to 30% after the first active use (or up to 80% after the first storage), reuse can thus play a significant role in service lifetime extension.

The transfer coefficients from active use of new devices to storage show that headsets and mobile phones, but also laptops, are more often stored than, for example, desktops, monitors or TVs. This confirms again that size plays a role in storage decisions. The high storage rates after second use may indicate that users of second-hand devices still consider a third use for their devices and therefore rather store them instead of disposing of them immediately. As most devices are brought to the collection scheme after storage, the question arises why they were stored in the first place. The reason for storage was not explicitly sampled by our survey. In their comments, however, participants mention several reasons: usage as replacement devices, data storage, spare part storage, toys for kids, storage due to nostalgic reasons.

Table 2: Transfer coefficients representing the different disposal pathways of the 10 device types.

From	To	Desktop	Laptop	Monitor	Mobile phone	Headset	CRT TV	FPD TV	Loudspeaker small	Loudspeaker large	DVD player
Active use	Storage	0.43	0.62	0.44	0.58	0.70	0.31	0.27	0.52	0.51	0.47
	Active use 2*	0.11	0.12	0.21	0.15	0.002	0.07	0.28	0.02	0.07	0.09
	Donation	0.03	0.02	0.01	0.01	-	0.01	0.02	0.00	0.01	0.00
	Collection	0.39	0.19	0.33	0.22	0.18	0.55	0.25	0.23	0.35	0.42
	Municipal waste	0.01	0.01	-	0.00	0.08	0.01	0.00	0.20	0.02	0.02
	Unknown	0.03	0.04	0.01	0.04	0.04	0.05	0.18	0.02	0.04	0.00
Storage	Active use 2*	0.09	0.26	0.11	0.24	0.13	0.21	0.80	0.30	0.16	0.29
	Donation	0.02	0.03	0.07	0.06	-	0.02	-	-	0.04	-
	Collection	0.82	0.67	0.68	0.59	0.51	0.73	0.10	0.38	0.69	0.63
	Municipal waste	0.00	-	0.03	0.02	0.30	-	0.10	0.27	0.07	0.08
	Unknown	0.06	0.04	0.11	0.09	0.07	0.04	-	0.05	0.04	-
Active use 2*	Storage 2**	0.63	0.40	0.83	0.69	-	0.28	0.53	0.81	0.65	0.45
	Active use 3	0.05	0.08	0.05	0.14	-	0.12	0.10	0.01	0.15	0.08
	Donation	0.02	0.08	-	0.01	-	0.02	0.03	-	0.02	-
	Collection	0.26	0.44	0.11	0.14	-	0.58	0.26	0.18	0.18	0.47
	Municipal waste	-	-	-	0.00	-	0.00	0.06	-	-	-
	Unknown	0.04	-	-	0.02	-	0.01	0.01	-	-	-
Storage 2**	Active use 3***	0.38	0.34	0.20	0.18	-	0.21	-	-	0.40	-
	Donation	0.07	-	0.14	0.10	-	0.10	-	-	-	-
	Collection	0.51	0.53	0.62	0.54	-	0.62	-	1.00	0.60	1.00
	Municipal waste	0.04	-	-	0.10	-	0.04	-	-	-	-
	Unknown	-	0.13	0.03	0.07	-	0.04	-	-	-	-

- : no data available
*Active use 2: active use of second-hand devices
**Storage 2: storage of second-hand devices
***Active use 3: active use of third hand devices
CRT TV: cathode ray tube television
FPD TV: Flat panel display television

The disposal pathways 'donation', 'municipal waste' an 'unknown' do not play a significant role. Only headsets and small loudspeakers show a high disposal rate to the municipal waste directly after the active use as well as after storage.

<heading level 2> Comparison to existing literature

The comparison of our results to those of similar studies in literature should be interpreted with some caution due to different regional and temporal scopes. Moreover, most studies either focus on service lifetime or total lifetime, which in many cases includes possible storage time. To make comparisons with total lifetime, we thus sum up our service lifetime (of devices no longer in use) and storage time. Figure 6 shows our calculated total lifetime as an average over all available sales years, compared to available data from literature. Although our results contain participants' estimates of the expected storage time, they correspond well to existing data. An additional figure and a table with results from existing literature can be found in the SI1.

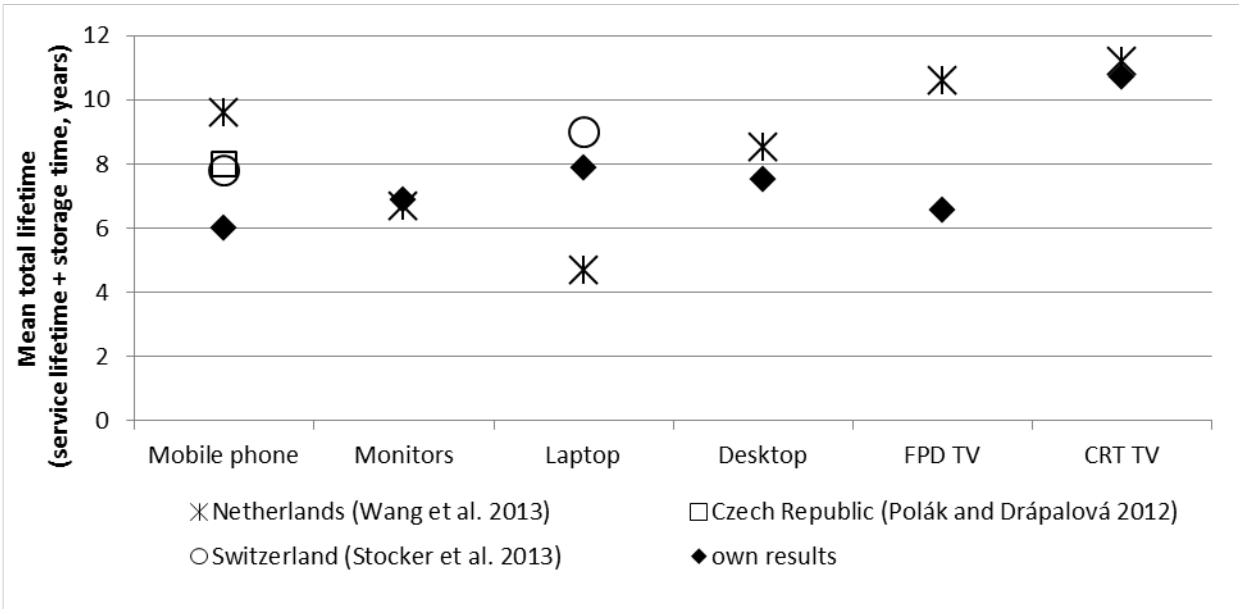

Figure 6: Comparison of our calculated total lifetime (on average over all available sales years) to average total lifetimes from existing literature.

<heading level 1> Limitations and uncertainty

The data on the service lifetime, storage time and disposal pathways were obtained from an online survey and complementary interviews. Survey participants indicated in which year they bought, put to storage or disposed of their devices. Thus, the uncertainty of their information is a maximum of plus or minus one year, depending on when exactly during the year a device was bought etc. Furthermore, as participants were asked not only about present devices, but also on the use, storage and disposal of past devices, the data may partly base on subjective estimates. The collection of data from online surveys has the advantage of fast data access and low resource requirements. The drawbacks are, however, that data quality is difficult to monitor and under-coverage and self-selection, among others factors, may lead to biased data, compared to a truly random sample of respondents of a given population (Bethlehem 2009). The introduction of weighting factors based on the 30 age-gender-education groups partly corrects the bias in our case; however, the weighting can also increase data uncertainty, for example by increasing already questionably high peaks in the survey results.

The number of observations for the second service lifetime and second storage time is quite low for most device types, so the uncertainty of these results is high. In order to avoid biased data due to right censoring, for some evaluations we had to omit data for more recent sales years of each device type sample, which decreases the sample size. Furthermore, as far as temporal trends in the service lifetime and storage time can be observed, the aggregation of all sales years increases the variance in the box-plots and histograms.

However, despite data uncertainty, our research provides an extensive data collection that can be used as a basis for improved future research. The microdata provided are valid for the Swiss context only if the proposed weighting adjustments are applied. The data could be used as a reference for other countries, provided that consumption and use patterns of EE are similar to Switzerland, and appropriate weighting adjustments are applied. For further data evaluation issues such as data uncertainty, overestimation of the remaining lifetime of devices in use, right censoring of data on devices no longer in use, or rough estimates of remaining storage time should be taken into account.

<heading level 1> Conclusion and Outlook

Our results provide new and important insights on product lifetimes and the trigger events to transfer devices between active use, storage and disposal, despite the methodological limitations of our approach as discussed above. Our study is a first step towards a better understanding of the current stocks and flows of EE and improved forecasts of future stocks and flows. It also helps to identify knowledge gaps and potential for future research.

Our results suggest that the assumption of constant service lifetimes of EE over sales years, which is underlying many models in use, is a possible simplification for some device types. The distribution shape of the service lifetime varies significantly among device types and is often not normally distributed. Due to the lack of data, many MFAs of EE apply average service lifetime data. We thus recommend taking into account, if ever possible, device-type dependent and, if applicable, time variant distribution models to treat service lifetime of EE in MFAs adequately.

The storage time is a significant variable when considering the product lifetime of EE. Storage slows down the waste generation as well as the flows to the collection schemes and therefore increases the stock of material resources in households. This is substantiated by our observation that, depending on the device type, 27% to 70% of new devices and 28% to 83% of second-hand devices are stored after their active use and the average storage time accounts for 13% up to 80% of the service lifetime. If storage is more adequately considered in future MFA studies in the electronics sector, it will be possible to reduce the uncertainty about material resources in storage stocks at private households and about the delay of recycling streams.

The analysis of disposal pathways has shown that considerable quantities of devices are reused, which happens either directly after active use (which can be the first or second use) or after storage. The resource savings potentials connected to these pathways to reuse were not addressed in this study but could be the subject of future research.

The quantitative survey did not investigate the reasons for replacing a device, choosing a certain disposal pathway, keeping a device in storage, etc. Such information about the reasoning behind user decisions, however, would facilitate the interpretation of the existing quantitative data and is therefore considered an important area of future research.

Subsequent to this study, we intend to determine current and future return of indium, neodymium and gold contained in EE in Switzerland, based on past and assumed or extrapolated future sales flows of the different device types.

<heading level 1> Acknowledgments

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