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A comparative assessment of WEEE collection in an urban and rural context: Case study on desktop computers in Belgium

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ABSTRACT

In order to comply with the targeted collection rates set by new European waste management regulations, a better knowledge of Waste Electrical and Electronic Equipment (WEEE) collection flows is needed. This paper highlights the importance of considering the regional spatial context to develop an appropriate waste collection strategy. Through material flow analysis, we compare the collection flows of end-of-life desktop computers in two neighbouring regions and link the differences of collection rates with spatial ones. The Brussels Capital Region (BCR), an urban area, and the Walloon Region (WR), a mixed urban-rural area with a predominance of rural areas, are chosen as case studies. The quantities and collection flows of end-of-life desktop computers are estimated by combining statistics and reporting data. Globally, in the WR, 70.99% of end-of-life desktop computers are collected in accordance with the WEEE Directive while only 32.98% are in the BCR. This difference may be related to spatial context. For instance, the high population density increases the built-up areas and limits space for waste collection infrastructures. As a consequence, in the BCR, only 22.29% of end-of-life desktop computers from households are captured by compliant collection channels against 84.80% in the WR. The collection from businesses still needs to be developed in both regions but also suffers from this lack of infrastructures. While the reliability assessment of our estimates emphasizes a lack of data regarding non-compliant collection channels, our results underline the need to take into account the regional spatial context in setting up the collection of WEEE.

1. Introduction

As indicated by the last Global E-waste Monitor (Baldé et al., 2017), the annual quantity of Waste Electrical and Electronic Equipment (WEEE) is growing each year from 3 to 4% and is expected to exceed 50 Mt in 2020. To manage this constant waste growth in Europe, the WEEE Directive (2012/19/EU) has been recast and the targeted collection and recycling rates have been increased (European Parliament, Council of the European Union, 2012). As a result, in 2019, 85% of the weight of WEEE produced or 65% of the weight of electronic equipment put on the market in the previous three years will have to be collected and properly treated (targeted recycling rates from 55 to 80% depending on the type of WEEE). Whilst, except for photovoltaic panels, recycling rates reported in Eurostat complies with the WEEE Directive, the collection remains the bottleneck of the WEEE end-of-life value chain (Eurostat, 2018a).

To tackle this problem, collection rates need to be increased based on a better understanding of WEEE flows in the various collection channels. Whereas recycling activities often take place at national and international levels, the collection is closely tied to the local context. The appropriate level of analysis is thus a regional assessment of collected WEEE flows. As Leigh et al. (2007) and, more recently, Bahers and Kim (2018) pointed out, to date there is a gap of analysis at the regional level, with many studies focussing on national or continental scales (e.g. Duygan and Meylan, 2015; Huisman et al., 2012; Huisman and Baldé, 2013; Parajuly et al., 2017). In addition, a European study on municipal waste highlighted that regional recycling rates can vary up to 40% from national ones due to regional specificities (Montevecchi and Reisinger, 2014). Such specificities (e.g. space constraints, variation in waste composition, …) could often be linked to the rural or urban character of different regions. Thereby, the regional assessment of WEEE collection flows is overdue, even more when there is a regional disparity of urban and rural areas.

In Belgium, Recupel is the organization in charge of the conventional management of WEEE. This organization has been set up by manufacturers and importers to comply with the take-back obligation, also known as extended producer responsibility. The collection network of Recupel is made up of four collection channels: 1) container parks, 2)

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retail stores, 3) reuse centres and 4) private operators. WEEE collected through this network are sorted in six categories depending upon specific treatments and depollution steps. Desktop computers are collected together with small appliances (e.g. vacuum cleaners, irons, …) as well as information and communication technologies (ICT) equipment, screens excluded, in the category “other”. Each year, Recupel has to report its collection data to regional agencies (OWD, 2014; Recupel, 2013). Besides Recupel, alternative operators are also involved in the collection of WEEE. These operators are on the one hand legitimate operators - approved for the treatment of WEEE but not part of the network of Recupel - and, on the other hand, illegal operators, which often export WEEE illegally. According to Eurostat data for 2013, the overall collection rate of WEEE in Belgium is close to the European Union average of around 40% of the weight of electronic equipment put on the market in the previous three years (Eurostat, 2018a). This shows that the collection of Belgian WEEE needs to be improved. Indeed, according to several more recent studies, over half of European and Belgian WEEE is managed via non-compliant networks (e.g. incineration, illegal exports, landfill, …) (Huisman et al., 2015; Huisman and Baldé, 2013).

As already pointed out by Leigh et al. (2007) in their literature review, end-of-life computers are often taken as case study for flow assessments of WEEE. Indeed, computers are a consumer good with increasing penetration rate in the market: in 2013, 81% (+2% from 2012) of Europeans have access to a computer (Eurostat, 2018c) and 57% (+1% from 2012) of European employees use computers (Eurostat, 2018e). Desktop computers were chosen for the case study because their end-of-life involves a wide variety of stakeholders (households, businesses, reuse centres, recycling operators, exporters, …). In addition, Steubing et al. (2010) state that desktop computers can be seen as trace equipment for ICT. In this work, the term ‘desktop computer’ refers only to computer system unit (i.e. computer case with motherboard, power supply unit and disk drives). Computing input devices (keyboards, mouse devices, …) and screens are excluded from our assessment, respectively because they could vary from one user to another and require a specific treatment (European Parliament, Council of the European Union, 2012). The term ‘computer’, used alone, refers to a mix of desktop computers and laptops.

Local waste flows are often evaluated at the scale of cities through assessments of urban metabolism, as the several examples given by Hoekman and Blottnitz (2017) point out. However, some regional assessments were conducted, such as for the distribution of end-of-life computers in the Atlanta metropolitan area (Leigh et al., 2007), the collection of WEEE in Galicia (Mar-Ortiz et al., 2011) or the treatment chain of WEEE in the Midi-Pyrénées region (Bahers and Kim, 2018). These assessments mainly focus on a single area of study. Material flow analysis (MFA), mentioned by Bahers and Kim (2018) as well as Allesch and Brunner (2017) as an appropriate tool to assess waste management systems, is commonly used in order to assess waste flows. Moreover, a literature review by Moriguchi and Hashimoto (2016) has shown several examples of the use of MFA in order to support the management and the recycling of WEEE. Overall, flow assessments of computers are often conducted at the national level in order to estimate the upcoming end-of-life flows and to adjust waste treatment infrastructures accordingly (Dwivedy and Mittal, 2010; Kang and Schoenung, 2006; Rahmani et al., 2014; Steubing et al., 2010). A case study carried out by Yoshida et al. (2009) compared the flows of end-of-life computers collected through different collection channels for two reference years in order to highlight the impact of a new regulation on WEEE management. None of these studies simultaneously takes into account the quantity of end-of-life computers, the various collection channels for these computers and the regional variation of the collection.

The main contribution of our study is the comparison of WEEE collection between two neighbouring regions with similar waste management and distinct spatial context. The spatial context refers to spatial aspects like population density, urban-rural typology or employment density. By assessing the several collection channels at a regional level, this comparison highlights the impact of the spatial context on waste collection and the necessity to consider this context to develop an appropriate waste management strategy. The quantities and collection flows were studied for the selected reference year 2013.

2. Material and methods

Two Belgian regions were chosen as case studies: the Brussels Capital Region (BCR) and the Walloon Region (WR). According to the urban-rural regional typology defined by Eurostat, the former is an urban area while the latter is a mixed urban-rural area (Eurostat, 2018d). Indeed, the WR has a predominance of rural areas (60% of rural areas, 30% of semi-urban areas and 10% of urban areas) with 40% of the population living in urban areas (35% in semi-urban areas and 25% in rural areas). The comparison of the WEEE collection in these two regions is performed using a MFA.

The quantities and collection flows of end-of-life desktop computers are estimated by applying a three-step methodology that combines statistics and reporting data. Firstly, the stock of desktop computers in-use in households and businesses is estimated by combining statistics on households and businesses with ICT statistics. The differentiation between households and businesses is important as the collection channel followed by WEEE may vary according to their origin. Secondly, the quantity of end-of-life desktop computers generated are estimated by linking the estimate of in-use desktop computers with their average lifetime and mass. Finally, the regional distribution of end-of-life desktop computers in the different collection channels is established by merging end-of-life estimates with collection data and available market studies.

2.1. Desktop computers used in households and businesses

As described by Zoeteman et al. (2010), three types of methods are usually applied to estimate WEEE flows: consumption and use methods, market supply methods and old-for-new methods. The two latter types are based on PRODCOM data (i.e. statistics on the production of manufactured goods) which are only available at national level (Council of the European Communities, 1991). Only the former type (consumption and use methods) is thus applicable at the regional scale. The methodology applied in this paper, combining statistics on households and businesses with ICT statistics, belongs to this type.

2.1.1. Evaluation for households

In the WR, the Walloon Telecommunications Agency (AWT) carries out annual statistical surveys on the use of ICT by households and businesses. The number of computers in households is available in the statistics (AdN, 2015). By combining this value with the market share of desktop computers in households, the annual stock of desktop computers in Walloon households is obtained.

Unlike in the WR, where the AWT provides very comprehensive data on the use of ICT by households, its equivalent in the BCR (Brussels Institute for Statistics and Analysis – IBSA) is limited to the percentage of businesses and households with one or more computers. These data are not sufficient to make similar estimates as for the WR. Despite the fact that these are very different regions in terms of population density and employment to population ratio, the penetration rates of computers in households (Statbel, 2015) as well as in businesses (Statbel, 2016a) follow the same increasing or decreasing trends. The data for the WR are therefore extrapolated to the BCR. The quantity of computers in the Brussels households is estimated, starting from the values obtained for the WR, in proportion to the number of Brussels households (IBSA and Statbel, 2017). The share of desktop computers in households is considered identical to that of Walloon households. These assumptions make it possible to estimate the number of desktop computers in households in the BCR. Fig. 1 (a) summarises the principle followed for

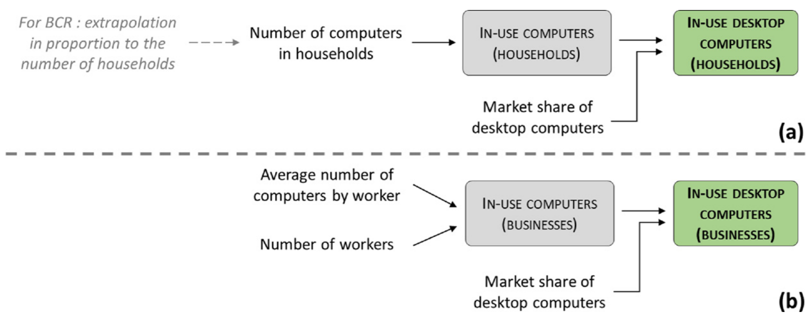

Fig. 1. estimation principle for in-use desktop computers (a) in households; (b) for businesses.

our estimates. The detailed calculation is available in Table A1 of appendix A.

2.1.2. Evaluation for businesses

Unlike for households, no data are published on the number of computers used by businesses in the WR. Nevertheless, the AWT provides data on the average number of computers per worker (AWT, 2014). By combining this data with the number of private, public and self-employed workers (ONSS, 2013), the total amount of computers can be estimated. By combining these values with the market share of desktop computers in businesses, the number of desktop computers in businesses is obtained for the WR.

The data for the WR were extended to Brussels businesses taking into account the presence in the BCR of the European institutions whose employees are not included in the statistics of the Belgian social security office because the majority of them are not subject to the social security requirements of Belgian employees. The number of workers in the European institutions is available in the annual Human Resources reports of the European Commission (DG Human Resources and Security, 2014). These workers are associated with the private sector. The share of desktop computers in Brussels businesses is considered identical to that of WR. These assumptions make it possible to estimate the number of desktop computers in businesses in the BCR. Fig. 1 (b) summarises the principle followed for our estimates. The detailed calculation is available in Table A1 of appendix A.

2.2. Quantity of end-of-life desktop computers in households and businesses

The estimate of computer stocks based on ICT statistics does not allow to know the year of placing on the market of the computer reaching its end of life. It is therefore not possible to relate the quantities obtained either to a specific lifetime or mass, as usually done when estimating WEEE flows (Parajuly et al., 2017). The quantity of desktop computers renewed each year is estimated, considering the following average lifetimes: three and a half years for private companies and European institutions, five years for the self-employed, six years for public enterprises and eight and a half years for households (Baldé et al., 2015; RDC Environnement, 2008).

The mass of end-of-life desktop computers is estimated according to the mass evolution of desktop computers provided by Baldé et al. (2015). For each place of use (private, public, …), the average mass over the lifetime of the desktop computer arriving at the end of life is calculated. For example, for a desktop computer in the public, the average mass on the 6 years before end of life are used. The Table 1 gives the average masses used for 2013. On this basis, the mass of end-of-life desktop computers from the diverse places of use are obtained for the BCR and the WR.

Table 1
Average masses of desktop computers used for 2013.

Place of use	Private	Self-employed	Public	Households
Average mass [kg/unit]	8.80	8.85	8.88	8.95

For further calculations, end-of-life desktop computers are gathered in two groups: end-of-life desktop computers from businesses and end-of-life desktop computers from households. To that end, end-of-life desktop computers from self-employed workers are split between the two groups according to the statistics of the Belgian institute for the social security of the self-employed regarding the share of workers between economic sectors (INASTI, 2016): only end-of-life desktop computers from the industry sector (30% for the BCR and 20% for WR) are allocated to the group from businesses. The remaining share of end-of-life desktop computers from self-employed workers (70% for the BCR and 80% for the WR) are allocated to the group from households.

Fig. 2 illustrates the principle followed for our estimates. The detailed calculation is available in Table A2 of appendix A.

2.3. Regional distribution of end-of-life desktop computers in the different collection channels

As previously mentioned, the origin of a WEEE may influence the collection channel followed. In particular, the potential for reuse of a desktop computer depends on its previous lifetime, which is related to the location of use (i.e. household or business). Desktop computers used in businesses have a lower lifetime and thus a higher potential for reuse (RDC Environnement, 2008): they are mostly collected by operators in reuse channels. Some collection channels, often illegal, are not sufficiently documented to determine whether desktop computers are coming from households or businesses.

In this research, the collection of end-of-life desktop computers is aggregated in four groups of collection channels: the compliant channels for recycling, the official reuse channels, the Belgian non-compliant channels and the non-compliant channels outside Belgium. The first group consists of conventional collection channels of Recupel as well as some exports to the Netherlands. The conventional channels are documented by reports of regional agencies while exports to Netherlands have been studied in a Belgian market study (Huisman and Baldé, 2013). The second group gathers compliant reuse operators like brokers or social organizations. These operators have been the subject of an economic and environmental study (RDC Environnement, 2008). The third group consists of WEEE disposed of with municipal and similar waste as well as WEEE found in shredder processes. This group has been studied in the Belgian market study (Huisman and Baldé, 2013). The last group includes all non-compliant collection leading to an illegal export of waste. The main data regarding these channels come from a European study on WEEE flows (Huisman et al., 2015). The gap between the estimations of the quantities of end-of-life desktop computers and those collected in the four groups of collection channels will be gathered in a “unknown” channel.

2.3.1. Compliant channels for recycling

In Belgium, the conventional collection of WEEE is managed by Recupel. In this work, container parks, retail stores and reuse centres

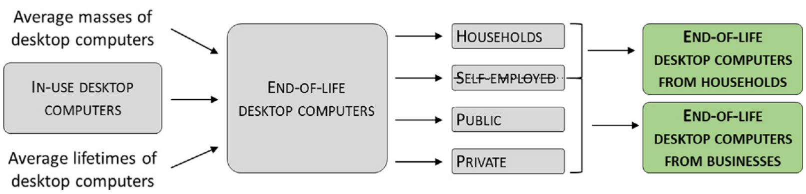

Fig. 2. estimation principle for end-of-life desktop computers.

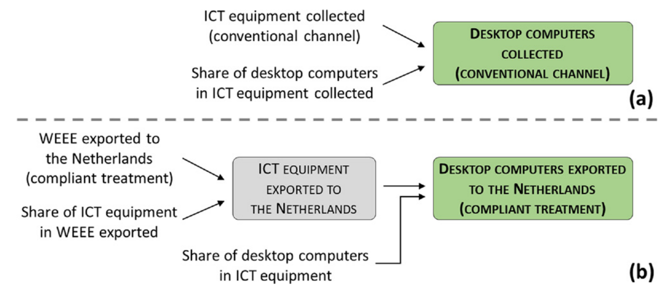

Fig. 3. estimation principle for desktop computers (a) collected by conventional channel; (b) exported to the Netherlands.

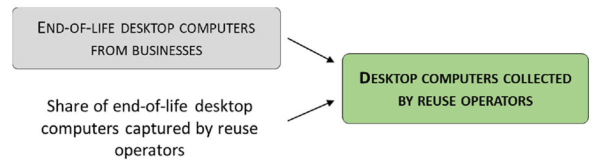

Fig. 4. estimation principle for desktop computers collected by reuse operators.

are considered to be collection channels dedicated to households. Private operators are considered to be collection channels dedicated to businesses. The collection results reported by Recupel to regional agencies are the main official source of data related to the collection of WEEE. These collection results are given according to the classification of Recupel previously described as well as to the EU classification. The quantity of ICT equipment collected from households is thus known for the two regions (OWD, 2014; Recupel, 2013). No specific data for Belgium are available on the share of desktop computers in the ICT equipment collected. Data from a German study of 2007 are used (Chancerel, 2010). As the generation of WEEE linearly depends on gross domestic product (GDP) (Kumar et al., 2017) and the GDP per capita of Germany and Belgium are close (less than 4% of difference) from 2007 to 2013 (Eurostat, 2018b), this approximation is considered as acceptable. However, the temporal and geographical mismatch will be taken into account in our reliability assessment. Fig. 3(a) illustrates the principle followed to estimate the quantities of desktop computers collected in the conventional collection channel. The detailed calculation is available in Table A3 of appendix A.

The study of the Belgian WEEE market in 2011 (Huisman and Baldé, 2013) mentions an export of WEEE to the Netherlands where they are treated in compliance with the WEEE Directive. Due to missing data, the shares of ICT equipment in "other" WEEE and of desktop computers in ICT equipment are considered equivalent to those of private operators in the conventional collection channel. The quantities of desktop computers collected through this channel are estimated. This estimate does not allow to distinguish whether desktop computers come from households or businesses. Fig. 3(b) illustrates the principle followed to estimate the quantities of desktop computers exported to the Netherlands. The detailed calculation is available in Table A3 of appendix A.

2.3.2. Official reuse channels

As desktop computers from households have a longer lifetime, minimizing their potential for reuse, the official reuse channels only concern computers from businesses. Even though no direct collection of data are available for this collection channel, the quantity of desktop computers going through this channel is estimated by using the share of desktop computers captured by reuse operators (RDC Environnement, 2008). Fig. 4 illustrates the principle followed to estimate the quantities of desktop computers collected by official reuse channels. The detailed calculation is available in Table A3 of appendix A.

2.3.3. Belgian non-compliant channels

The collection results for municipal and similar waste are annually reported in the BCR (Bruxelles-Propreté, 2014) and the WR (SPW - DGO3, 2013) and statistics are available for the proportion of WEEE in municipal waste and similar waste from businesses. No data are available for Belgium on the share of desktop computers in the WEEE collected with municipal and similar waste. Data from a study of WEEE flows in the Netherlands in 2011 are used (Huisman et al., 2012). Although the GDP per capita in the Netherlands is higher (+10% in 2012) than in Belgium (Eurostat, 2018b), this study was selected because it was the most recent estimate for end-of-life desktop computers in a neighbouring country of Belgium. In addition, the study of the Belgian WEEE market in 2011 also used some data from Dutch studies (Huisman and Baldé, 2013). As for the use of German data, the temporal and geographical mismatch will be taken into account in our reliability assessment. Fig. 5(a) illustrates the principle followed to estimate the quantities of desktop computers collected with municipal and similar waste. The detailed calculation is available in Table A3 of appendix A.

The study of the Belgian WEEE market in 2011 (Huisman and Baldé, 2013) and its estimated evolution of WEEE provides an estimate of the quantity of "other" WEEE (equivalent to the fraction "other" of Recupel) in pre-shredder material. Due to missing data, the share of ICT equipment in "other" WEEE and the share of desktop computers in the ICT equipment are considered equivalent to the one of private operators in the conventional collection channel. This estimate does not allow to distinguish whether desktop computers come from households or businesses. Fig. 5(b) illustrates the principle followed to estimate the quantities of desktop computers in Belgian pre-shredder material. The detailed calculation is available in Table A3 of appendix A.

2.3.4. Non-compliant channels outside Belgium

Some WEEE are also exported for crushing, in particular to France, the Netherlands and Germany (Huisman and Baldé, 2013). Following the same assumptions as for desktop computers in Belgian pre-shredder material, the study of the Belgian WEEE market of 2011 makes it possible to estimate the quantity of desktop computers following this channel, but does not allow to distinguish whether desktop computers come from households or businesses. Fig. 6(a) illustrates the principle followed to estimate the quantities of desktop computers in exported pre-shredder material. The detailed calculation is available in Table A3 of appendix A.

The study on European WEEE flows (Huisman et al., 2015) estimates the proportion of WEEE exported to Africa. The global quantity of WEEE produced in 2013 in the BCR and the WR is estimated thanks to the WEEE Market study (Huisman and Baldé, 2013) and Recupel data (Recupel, 2013). The share of "other" WEEE in exported WEEE is taken from the Belgian market study (Huisman and Baldé, 2013). Due to missing data, the share of ICT equipment in "other" WEEE is taken from a Dutch WEEE flows study (Huisman et al., 2012) and the share of desktop computers in ICT equipment considered equivalent to the one

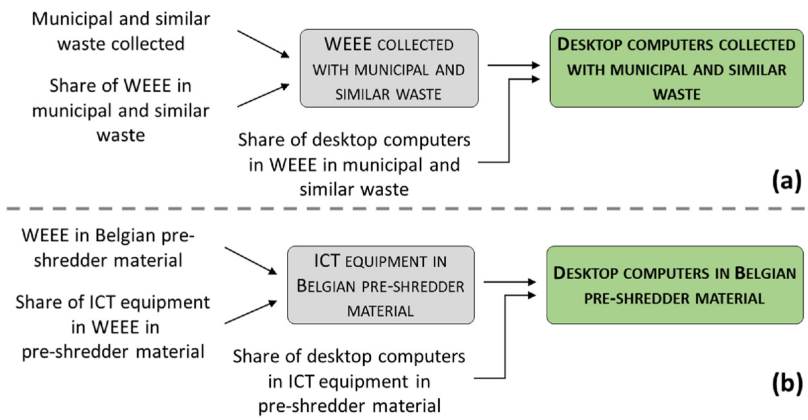

Fig. 5. estimation principle for desktop computers (a) collected with municipal and similar waste; (b) in Belgian pre-shredder material.

used for the non-conventional channel (shredding). The temporal and geographical mismatch of these data will be taken into account in our reliability assessment. The Dutch WEEE flows study (Huisman et al., 2012) estimates the share of exported computers from businesses. Based on the market shares of computers from households and businesses in the BCR and the WR, the share of exported computers from the BCR can be estimated. Fig. 6(b) illustrates the principle followed to estimate the quantity of desktop computers exported from the BCR and the WR to Africa. The detailed calculation is available in Table A3 of appendix A.

The European study also mentions a proportion of WEEE exported to Asia among which a certain part is ICT equipment. Due to a lack of data, we use the same assumptions than those for illegal export to Africa in order to estimates the quantities of computers exported from the BCR and the WR to Asia. The detailed calculation is available in Table A3 of appendix A.

2.3.5. Gap of collection data

In addition to the aforementioned collection channels, other end-of-life systems exist. They are much less documented but, by combining a study of WEEE in Europe (Huisman et al., 2015) with the Belgian market study (Huisman and Baldé, 2013), two additional collection channels described below have been identified and quantified.

The first additional channel consists of a supplementary export to Africa and belongs to the group of official reuse channels. Indeed, the European study on WEEE flows estimates the proportion of WEEE legally exported from Europe (Huisman et al., 2015). Due to a lack of data, the same share of desktop computers as that used for illegal export to Africa is used in order to estimates the quantities of desktop computers exported. The quantity of WEEE exported to Africa by the reuse channels is considered legally exported and is deducted from the quantity obtained here. Fig. 7(a) illustrates the principle followed to estimate the supplementary export of desktop computers to Africa. The detailed calculation is available in Table A3 of appendix A.

The second additional channel consists of a supplementary shredding of desktop computers and belongs to the group of non-compliant channels outside Belgium. The European study on WEEE flows estimates the proportion of WEEE that are shredded (Huisman et al., 2015). The study of the Belgian WEEE market in 2011 (Huisman and Baldé, 2013) estimates the share of "other" WEEE found in WEEE found in pre-shredder material. Considering this share and by using the same hypothesis than for WEEE found in pre-shredder material in Belgium, the additional quantity of desktop computers found in pre-shredder material is estimated. Fig. 7 (b) illustrates the estimation principle. The detailed calculation is available in Table A3 of appendix A.

2.4. Reliability assessment of estimates

As our assessment combines several sources of data, ranging from direct data to average statistics, a reliability assessment was conducted in order to discuss the estimates obtained for the different collection channels. This reliability assessment is based on a method known as

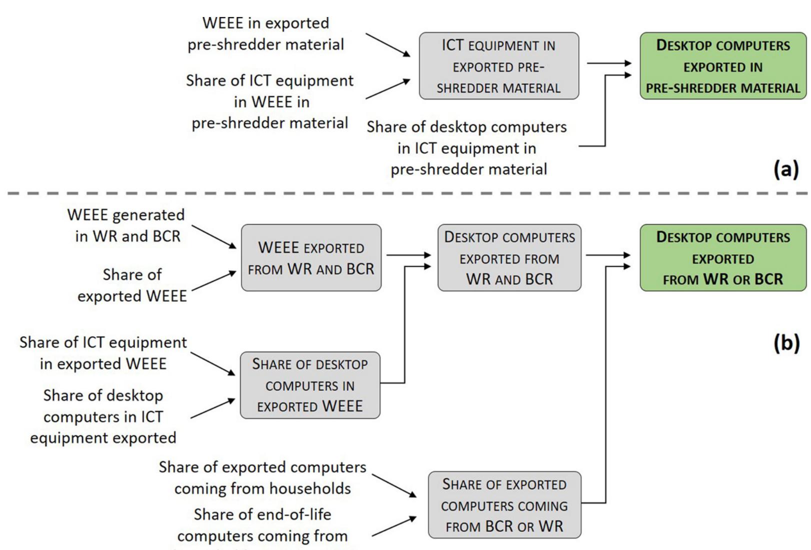

Fig. 6. estimation principle for desktop computers (a) in exported pre-shredder material; (b) exported to Africa or Asia.

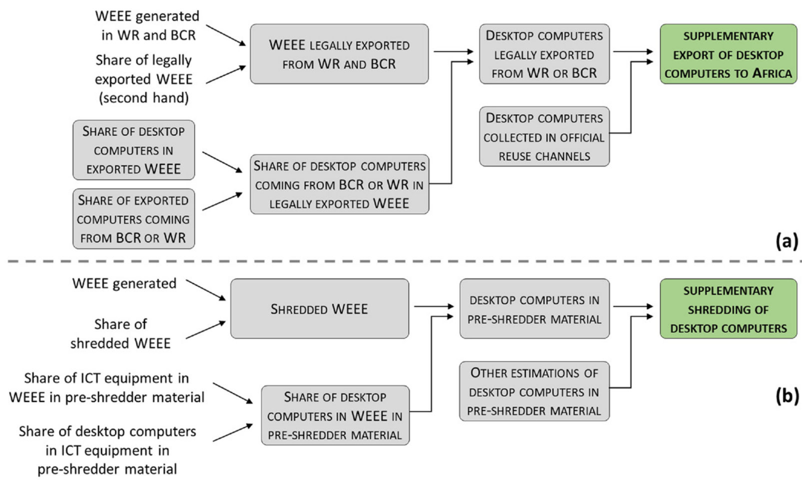

Fig. 7. estimation principle for supplementary (a) export of desktop computers to Africa; (b) shredding of desktop computers.

Pedigree matrix approach and proposed by Weidema and Wesnæs (1996). This method is conventionally used to assess uncertainties in environmental life cycle assessment. A similar reliability assessment was performed by Hoekman and Blottnitz (2017) in order to discuss the relative quality of different data sources of a MFA.

The Pedigree matrix approach consists in a semi-quantitative evaluation of five data quality indicators (reliability, completeness, temporal correlation, geographical correlation, and technological correlation). We granted a score of 1 to 5 to each of the indicators to represent the quality of data regarding each indicator (Table 2): the higher the scores, the higher the level of uncertainty. For instance, estimations based on data from a German or Dutch study will receive a geographical correlation score of 3. A global score of uncertainty (1 to 5) is granted on the basis of the average of the five indicators.

3. Results

3.1. In-use and end-of-life desktop computers

According to the assumptions described above, in 2013, households and businesses in the BCR and the WR owned just over 2.5 million desktop computers. The results obtained for end-of-life desktop computers in 2013 are presented in Table 3.

In order to validate our estimate for 2013, we apply our methodology on data from 2007 and we compare our results with those of the German study carried out by Chancerel (2010). This study was selected because it was the most recent estimate for end-of-life desktop computers in a European country. The comparison shows a higher value (0.79 kg/inh) for the WR and the BCR than for Germany (0.49 to 0.61 kg/inh). This result could be explained by the fact that the third Belgian region, the Flemish Region, with a profile closer to the WR than the BCR, is not take into account in our estimate (Eurostat, 2018d). The quantity of end-of-life desktop computers per inhabitant for the whole of Belgium should therefore be lower. On this basis, the estimate obtained is considered as acceptable.

3.2. Collection

3.2.1. Compliant channels for recycling

Through these four collection channels, Recupel collected in 2013 respectively 531 t and 3 868 t of ICT equipment in the BCR (49% from households and 51% from businesses) and in the WR (78% from households and 22% from businesses). Among the ICT equipment collected, 31% are desktop computers (Chancerel, 2010). On this basis, the amount of end-of-life desktop computers collected by Recupel and coming from households is 1 025 t for French-speaking Belgium (92% of which come from the WR and 8% from the BCR). The amount coming from businesses stands at 348 t for French-speaking Belgium, shared between 24% for the BCR and 76% for the WR.

The Belgian market study (Huisman and Baldé, 2013) mentions an export of “other” WEEE to the Netherlands estimated at 0.11 kg/inh. Due to a lack of specific data, we suppose that 34% from this flow are ICT equipment (Recupel, 2013) made up of around 31% of desktop computers (Chancerel, 2010). The quantity of desktop computers exported and compliantly treated in the Netherlands is estimated at 41 t for the WR and 13 t for the BCR.

Table 4 summarizes the quantities of desktop computers from the WR and the BCR collected in the compliant channels for recycling.

3.2.2. Official reuse channels

Second-hand actors are also very active for this flow as, due to their shorter lifetime, desktop computers from businesses have significant potential for reuse. According to the most recent study found on this subject (RDC Environnement, 2008), the reuse sector, made up of social and charity organizations as well as private operators, collects 20% of desktop computers with potential for reuse, i.e. coming from businesses. As the quantity of end-of-life desktop computer from businesses was estimated at 2 227 t (62% in the WR and 38% in the BCR), 450 t of desktop computer are collected in the official reuse channels. Among these computers, 45% are legally exported in Europe (118 t from the WR and 73 t from the BCR) or in Africa (4 t from the WR and 3 t from the BCR) as second hand appliances, 40% cannot be repaired and are recycled (112 t from the WR and 69 t from the BCR) and 15% are reused in Belgium (40 t from the WR and 25 t from the BCR).

The European study on WEEE flows estimates that 2% of WEEE in Europe are legally exported (Huisman et al., 2015). Overall, 18 t of desktop computers are thus exported to Africa. By deducing the quantity of WEEE exported to Africa by the reuse channels, we considered that around 11 t are additionally legally exported (4 t from the WR and 7 t from the BCR).

Table 5 summarizes the quantities of desktop computers from the WR and the BCR collected in the official reuse channels.

3.2.3. Belgian non-compliant channels

In the BCR, WEEE accounted for 0.23% of municipal waste in 2011 (ARCADIS, 2012). In the WR, for the years 2009–2010, WEEE accounted for 0.3% of municipal waste (RDC Environnement, 2010). In Belgium, a study of the WEEE market of 2011 (Huisman and Baldé, 2013) considers 0.6% of WEEE in similar waste from businesses. In absence of more recent data, these values are used. According to the WEEE flows in the Netherlands in 2011 (Huisman et al., 2012), a share of 4% of desktop computers is considered. In 2013, 207 451 t and 422

Table 2
data quality indicators, inspired by Weidema and Wesnæs (1996).

Score	1	2	3	4	5
Reliability	Verified* data	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert);	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered	Representative data from > 50% of the sites relevant for the market considered	Representative data from only some sites (< < 50%) relevant for the market considered	Representative data from only one site relevant for the market considered	Representativeness Unknown or incomplete data
Temporal correlation	Less than 3 years of difference to our reference year	Less than 6 years of difference to our reference year	Less than 10 years of difference to our reference year	Less than 15 years of difference to our reference year	Age of data unknown or more than 15 years of difference to our reference year
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, OR from similar area	Data from area with slightly similar production conditions	Data from unknown area
Technological correlation	Data from enterprises, processes and materials under study	Data from and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

* by on-site checking, by recalculation, through mass balances or cross-checks with other sources.

Table 3
quantities of end-of-life computers from households and businesses in 2013.

	Households		Businesses		Total	
	t	kg/inh	t	kg/inh	t	kg/inh
BCR	365	0.32	851	0.74	1 215	1.10
WR	1 113	0.31	1 377	0.39	2 490	0.70
BCR and WR	1 478	0.31	2 227	0.47	3 705	0.79

Table 4
quantities collected in the compliant channels for recycling.

Channels	quantities collected [t]			
	Brussels Capital Region		*Walloon Region*	
	Households	*Businesses*	*Households*	*Businesses*
Conventional channel	81	84	944	264
Private recyclers (export)	13		41	

Table 5
quantities collected in the official reuse channels.

Channels	quantities collected [t]			
	Brussels Capital Region		*Walloon Region*	
	Households	*Businesses*	*Households*	*Businesses*
Second-hand actors (reuse in BE)	–	25	–	40
Second-hand actors (export for reuse in EU)	–	73	–	118
Second-hand actors (export for reuse in Africa)	–	3	–	4
Second-hand actors (recycling)	–	69	–	112
Additional export to Africa	–	7	–	4

256 t of municipal waste as well as 208 166 t and 105 564 t of similar waste were collected respectively in the BCR (Bruxelles-Propreté, 2014) and in the WR (SPW - DGO3, 2013). Thus, in the BCR and the WR respectively 19 t and 51 t of desktop computers are collected with municipal waste. Similarly, 50 t and 25 t of desktop computers are collected with similar waste from businesses.

"Other" WEEE found in pre-shredder Belgian material represent 0.31 kg/inh (Huisman and Baldé, 2013). Due to a lack of specific data, the same assumptions as for the export of waste to the Netherlands are used for the share of ICT equipment. The share of desktop computer (18%) is taken from a German study. Thus, the quantity of desktop computers in the Belgian pre-shredder material is estimated at 66 t for the WR and 22 t for the BCR.

Table 6 summarizes the quantities of desktop computers from the WR and the BCR collected in Belgian non-compliant channels.

3.2.4. Non-compliant channels outside Belgium

The Belgian market study (Huisman and Baldé, 2013) mentions an

Table 6
quantities collected in the Belgian non-compliant channels.

Channels	quantities collected [t]			
	Brussels Capital Region		*Walloon Region*	
	Households	*Businesses*	*Households*	*Businesses*
Municipal and similar waste	19	50	51	25
Scrap dealers (pre-shredder material)	22		66	

export of "other" WEEE to neighbouring countries (Netherlands, France and Germany) around 0.27 kg/inh. Due to a lack of specific data, we use the same assumptions than those for desktop computers found in Belgian pre-shredder material. The quantities of desktop computers in the exported pre-shredder material are estimated at 60 t for the WR and 19 t for the BCR.

The European study on WEEE flows estimates that 14% of WEEE are exported to Africa (Huisman et al., 2015). Among these WEEE, 10% are "other" WEEE (Huisman and Baldé, 2013) among which 40% are ICT equipment (Huisman et al., 2012). The global quantity of WEEE generated in 2013 in the BCR and the WR is estimated around 120 kt, among which 16 kt are exported to Africa. From these exported WEEE, 116 t are desktop computers. According to the Dutch WEEE flows study (Huisman et al., 2012), among these exported computers, 37% come from households and 63% from businesses. Based on the market shares of desktop computers from households and businesses in the BCR and the WR, it is considered that 46% of the desktop computers exported come from the WR (20 t from households and 33 t from businesses) and 54% from the BCR (23 t from households and 40 t from businesses). Based on the study on European WEEE flows (Huisman et al., 2015), we considered that 70% of these computers are reused.

The European study on WEEE flows estimates that 8% of WEEE are exported to Asia, among which a little over 20% are ICT equipment (Huisman et al., 2015). Thus, the quantity of desktop computers exported to Asia is estimated at around 183 t for the WR (67 t from households and 116 t from businesses) and 219 t for the BCR (80 t from households and 139 t from businesses).

The European study on WEEE flows estimates that 33% of WEEE are shredded (Huisman et al., 2015). Considering that 20% of WEEE found in pre-shredder material are "other" WEEE, the total quantity of desktop computers found in pre-shredder residue is estimated to 365 t and 118 t respectively for the WR and the BCR. There is therefore a complementary grinding of 239 t for the WR and 78 t for the BCR.

Table 7 summarizes the quantities of desktop computers from the WR and the BCR collected in non-compliant channels outside Belgium.

3.3. Synthesis

Based on estimations made in sections 3.1 and 3.2, Table 8 presents the repartition of end-of-life desktop computers for the two regions in the various collection channels. Fig. 8 illustrates this comparison. The detailed calculations for estimations are available in appendix A (Table A1: in-use estimations; Table A2: stock estimations; Table A3: collection estimations).

Different trends can be observed between desktop computers from households and those from businesses. On one side, the collection of the former is highly influenced by the context. In the WR, 84.80% of end-of-life desktop computers from households are captured by compliant collection channels, mainly through the conventional collection channels. In the BCR, this collection channel is less effective: only 22.29% of desktop computers from households are collected. On the other side, trends for the collection of desktop computers from businesses are similar for both regions. In the WR, 19.16% of this flow are collected through the conventional collection channels while 20.29% are captured by official reuse channels. In the BCR, the collection is also low: 9.92% are collected through the conventional collection channels and 20.89% through the reuse one. Due to less effective conventional channels, in the BCR, the quantity of desktop computers going through illegal export channels is higher (31.32%) than in the WR (21.45%). Belgian non-compliant channels are low in the two regions (respectively 7.45% in the BCR and 5.72% in the WR).

Table 7
quantities collected in the non-compliant channels outside Belgium.

Channels	quantities collected [t]			
	Brussels Capital Region		Walloon Region	
	Households	Businesses	Households	Businesses
Scrap dealers (pre-shredder material)	19		60	
Export to Africa (reuse)	4	40	4	33
Export to Africa (waste)	19	–	16	–
Export to Asia	80	139	67	116
Scrap dealers (additional pre-shredder material)	78		239	

Table 8
share of desktop computers collected in the several collection channels for the BCR and the WR.

Channels	quantities collected [t]			
	Brussels Capital Region		Walloon Region	
	Households	Businesses	Households	Businesses
Compliant channels for recycling				
Conventional channel	6.69%	6.95%	37.91%	10.59%
Private recyclers (export)	1.08%		1.63%	
Official reuse channels				
Second-hand actors (reuse in BE)	–	2.06%	–	1.62%
Second-hand actors (export for reuse in EU)	–	6.02%	–	4.76%
Second-hand actors (export for reuse in Africa)	–	0.21%	–	0.17%
Second-hand actors (recycling)	–	5.71%	–	4.51%
Additional export to Africa	–	0.60%	–	0.16%
Non-compliant channels (BE)				
Municipal and similar waste	1.57%	4.11%	2.04%	1.02%
Scrap dealers (pre-shredder material)	1.77%		2.67%	
Non-compliant channels outside Belgium				
Scrap dealers (pre-shredder material)	1.59%		2.39%	
Export to Africa (reuse)	0.35%	3.32%	0.14%	1.34%
Export to Africa (waste)	1.57%	–	0.64%	–
Export to Asia	6.64%	11.48%	2.69%	4.64%
Scrap dealers (additional pre-shredder material)	6.38%		9.61%	
Total :	**68.08%** (*)		**88.52%** *	
Unknown	31.92%(**)		11.48%**	

* 100% = all end of life desktop computers from households and businesses in BCR or WR.

** Percentages may not always total 100% due to rounding error.

Additionally, despite the different studies and data cross-checked to establish this distribution between the several collection channels (among others: Huisman et al., 2015, 2012; Huisman and Baldé, 2013; Monier et al., 2013; OWD, 2014; RDC Environnement, 2008; Recupel, 2013), both in the BCR and the WR, the collection channels followed by a part of end-of-life desktop computers is still unknown (respectively 31.92% and 11.48% in the BCR and the WR). This gap between the estimates of end-of-life desktop computers and those of collection channels can be explained according to two major hypotheses. Firstly, estimates of illegal exports are poorly documented and may be underestimated, mainly for the BCR, where traders' activity is more important (Seum and Hermann, 2010). Secondly, taken into account that end-of-life desktop computers are not necessarily sent directly to a collection channel, they can be stored or resold without going through end-of-life channels (e.g. resale between individuals, resale to an employee of the company, …).

In the WR, 70.99% of end-of-life desktop computers are processed in accordance with the WEEE Directive (i.e. reuse or compliant recycling), with 9.25% of reuse. In the BCR, this rate drops to 32.98%, with 12.55% of reuse.

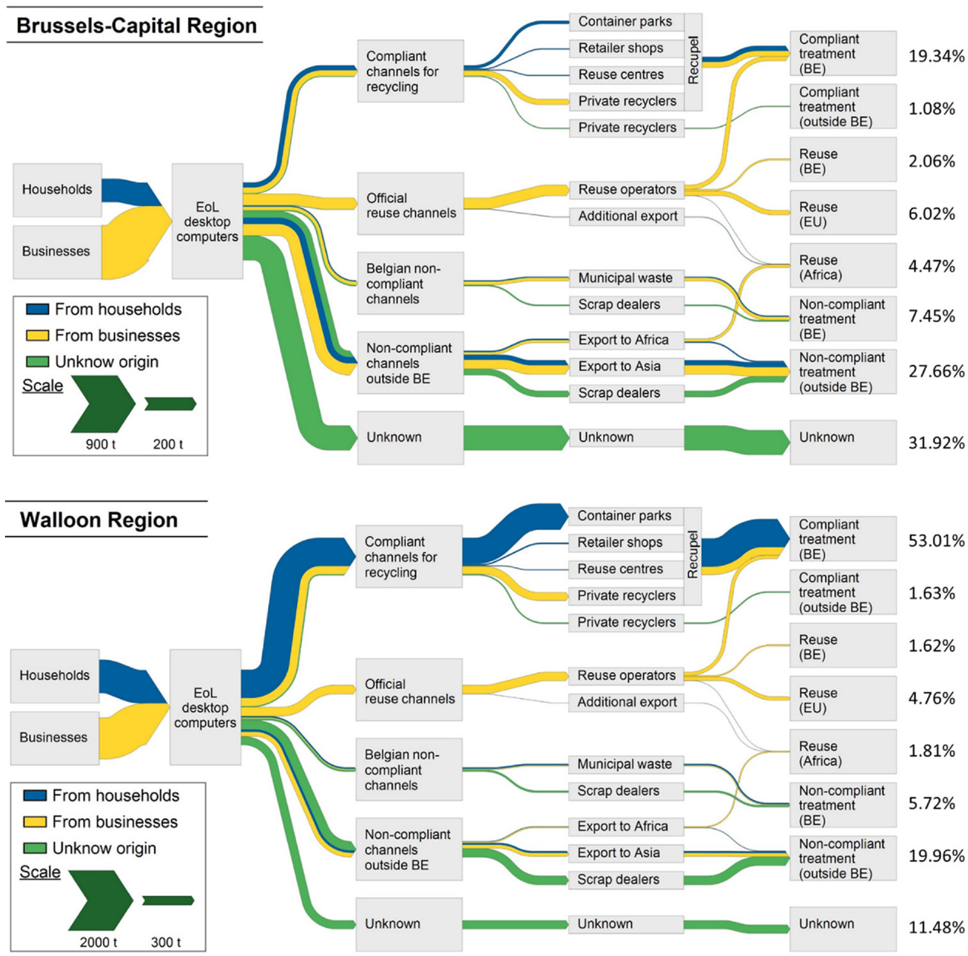

Fig. 8. Distribution of collections in the WR and the BCR.

4. Discussion

4.1. Potential impacts of spatial context on collection results

As stated in the previous section, the collection results vary among the two regions. By overlapping the results of our comparative MFA with spatial effects on waste collection already pointed out in other studies, this section provides an understanding of these regional variations in waste collection.

The population density is higher in the BCR (7155 in./km^2 in 2013), an urban area, than in the WR (212 in./km^2), a mixed urban-rural area (Statbel, 2017, 2016b). This high population density results in a high proportion of built-up areas (67.10% in the BCR compared with 13.03% in the WR) so that the possibilities to dedicate space for waste management infrastructures are limited (Statbel, 2017). Indeed, there are only 2 container parks in the BCR against 215 in the WR in 2013. As it was already pointed out by researchers (Montevecchi and Reisinger, 2014; Thomas and Sharp, 2013), a lack of container parks could lead to poor collection rates. The collection in container parks, one of the main compliant collection channels for WEEE from households, is thus much more efficient in the WR. As a consequence, the share of end-of-life desktop computers from households collected through the conventional collection channels is higher in the WR (84.80%) than in the BCR (22.29%).

The high population density of the BCR also affects the collection of WEEE from businesses. The lack of space for waste management infrastructures also reduces the number of private recyclers (2 in the BCR, against 18 in the WR in 2013) which are the main compliant collection channels for businesses. The high employment density in the BCR (4429 full-time equivalent (FTE) per km^2 against 77 FTE/km^2 in the WR) emphasizes this lack of collection points. Thus, the share of end-of-life desktop computers from businesses collected by the official collection channels is less important in the BCR (9.92%) than in the WR (19.19%). This issue of collection in an urban area probably exists also in larger Walloon cities, such as Liège or Charleroi, but it appears less because of the preponderance of rural areas in the WR.

In addition to the weak infrastructure in the urban areas described above, the high population and employment densities attract a large number of stakeholders. For instance, in the BCR, 18 compliant collectors are recognised by the authorities (one collector for 9 km^2), against 54 for the WR (one collector for 312 km^2) (IBGE, 2018; OWD, 2018). The number of non-compliant collectors cannot be determined as they are not indexed by authorities. The coexistence of theses multiple stakeholders leads to a competition which is not in favour of the compliant channels, as some competing actors pay (scrap dealers, illegal traders, …) in exchange for collecting WEEE (RDC Environnement, 2008). This partly explains why the collection rates of non-compliant and unknown channels are higher in the BCR than in the WR.

Some social aspects, that can sometimes be related to the spatial context, could influence the collection of WEEE. For instance, a study on the implication of households in the collection of waste showed that, in rural areas, the move towards container parks is more anchored in the habits of people. Bringing WEEE towards the container park is thus not seen as a constraint (Saphores et al., 2006). This behaviour of citizens in rural areas provides an additional understanding of the higher collection rate in the conventional collection channels for the WR. However, as there is no general consensus among social aspects that

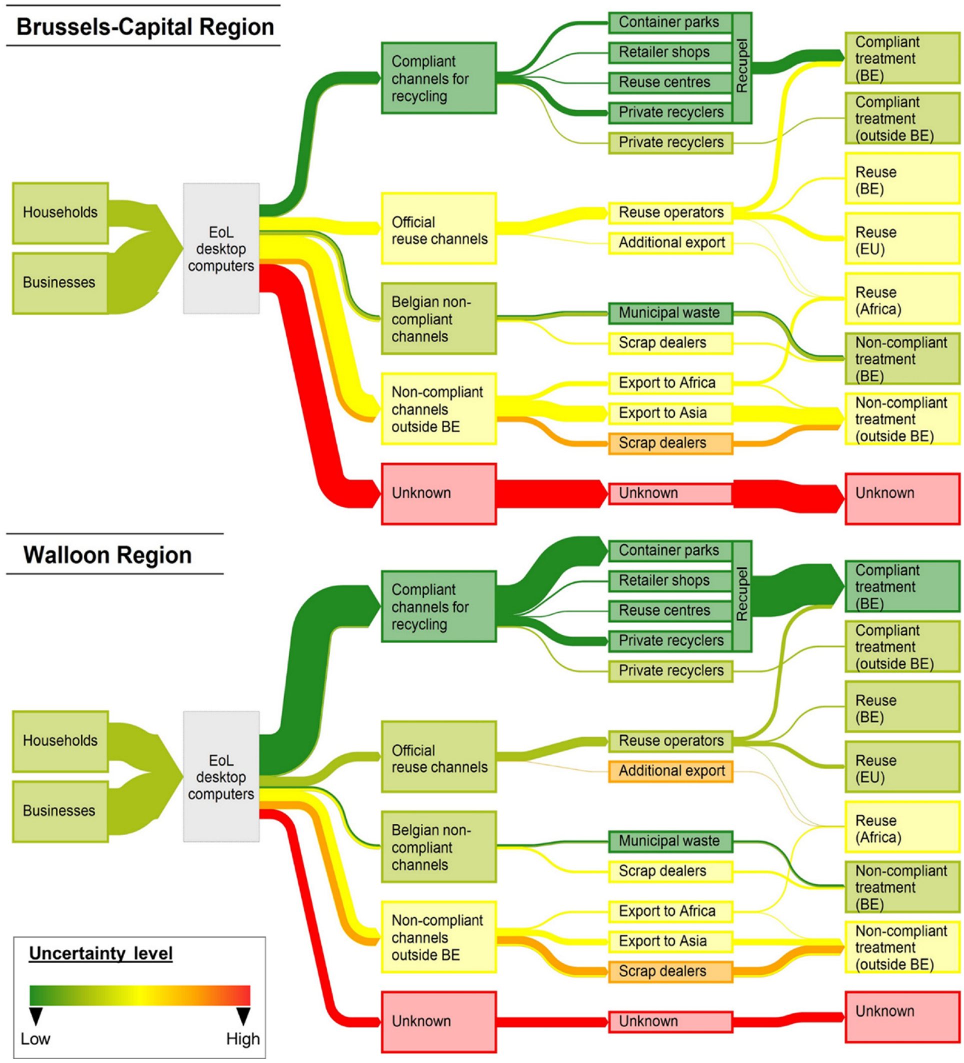

Fig. 9. reliability assessment of estimates.

directly affect waste collection rates as well as among interdependence of these aspects (Thomas and Sharp, 2013), the lack of data on the recycling behaviours in the BCR and in the WR prevents any further assumptions.

4.2. Reliability assessment of estimates

Our reliability assessment was conducted in accordance with the methodology set out above. Fig. 9 shows global score of uncertainty for the different collection channels. The detailed quality indicators used are available in appendix B (Table B1 and Table B2).

Overall, uncertainty levels obtained are similar for the BCR and the WR, except for the official reuse channels. Indeed, in the WR, a specific study was conducted on Walloon stakeholders of the reuse market, resulting in a lower uncertainty level. In other collection channels, lower uncertainty levels are reached by more documented channels, like Recupel or municipal and similar waste collection, where collection data are available. Conclusions related to compliant collection channels could thus be considered as reliable. In contrast, conclusions based on estimates for illegal export channels or unknown collections should be taken with caution. Due to the mass distribution between the collection channels, the regional distribution of the BCR obtains the higher global uncertainty level.

To improve the reliability of estimates, two options were pointed out. On one side, regarding the end-of-life estimates, the availability of statistics on the use of desktop computers in households and businesses allows to reach a relatively low uncertainty level. However, as Araújo et al. (2012) explained, the type of method used (i.e. consumption and use method) shall, in principle, not be used for a product like desktop computers because this type of product is subject to technological variations. To improve the estimates of end-of-life desktop computers, a market supply method or old-for-new method should be applied. These methods require regional sales data, which are still missing. The improvement of regional end-of-life estimates is thus dependent on the availability of such data. On the other side, regarding the estimates for the collection channels, the potential for improvement concerns mainly non-compliant channels. At first sight, the improvement of data related to these channels may seem irrelevant since they should disappear due to the gradual toughening of legislations. Nevertheless, these channels are persistent and a better documentation on them could help to implement appropriate actions.

4.3. Improvement of the collection

As previously mentioned, in 2019, 85% of WEEE will have to be collected and properly treated in Europe (European Parliament and Council of the European Union, 2012). In the light of the regional distribution of end-of-life desktop computers between the several collection channels, an improvement of the collection is urgently needed in order to reach the targeted collection rate, especially in the BCR where compliant collection flows are considerably low. Based on our regional assessment, this improvement should consist of two parts. Firstly, a better understanding of the collection channels for desktop computers from businesses is required. Indeed, whether in the BCR or in the WR, these computers are still too weakly collected through compliant channels. Moreover, the collection channels followed by the non-compliantly collected desktop computers are not well identified. As this flow has a high potential for reuse, the improvements should be done in a way that promotes the official reuse channels. Secondly, specifically for the BCR, the collection from households should be improved. This flow has no potential for reuse and should thus directly be sent to recycling channels. As the Brussels urban context has an undeniable influence on the collection results, transposition into an urban area of a model similar to that applied in the WR would be inappropriate. As pointed out by Nowakowski and Mrówczyńska (2018), the development of collection channels of WEEE in an urban area should take into account urban constrains like parking difficulties, limited space for containers, …

More broadly, to organize the collection in a way that takes into account the local context, waste management systems should evolve. So far, the collection of WEEE has been implemented by pursuing a top-down approach: regional policies arise mainly from national or European decisions. In contrast, the involvement of citizens and businesses as well as the inclusion of geographical characteristics require a switch to a bottom-up approach. Nowadays, a growing body of studies highlights the importance of taking into account the consumer's perspective as well as the spatial context (Bahers and Kim, 2018; Nowakowski and Mrówczyńska, 2018), but there is still a lack of practical application. In this regard, geographic information system spatial analysis could help to develop integrated waste management system adapted to regional spatial contexts (Khan et al., 2018; Leigh et al., 2007).

Finally, results from regional MFA can be used in combination with life cycle assessment in order to improve the environmental impacts related to the collection and the treatment of WEEE. As pointed out by Laner and Rechberger (2016), this combination provides a consistent decision support in waste management. In particular, a global life cycle assessment of the different collection channels could highlight the environmental hotspots. On this basis, priority measures can be defined in order to improve the environmental footprint of WEEE management.

5. Conclusions

This paper compares the collection flows of end-of life desktop computers in two neighbouring regions with different urban-rural typologies in order to highlight the importance of considering this context to develop an appropriate waste management strategy. Our comparative MFA of an urban area, the BCR, with a mixed urban-rural, the WR, shows that the collection from households is impacted by the regional spatial context. Indeed, the lack of collection infrastructures in urban area, limited in particular by the high population density and proportion of built-up areas, as well as the habits of people to move towards container parks, which is less anchored than in rural areas, could partly explain that the conventional collection of WEEE is less efficient in the BCR (22.29%) than in the WR (84.80%). Besides the weak development of the compliant collection from businesses (respectively 60.55% and 69.23% in the BCR and the WR have non-compliant or unknown collection channels), this collection is also affected by a lack of infrastructures. As a consequence, the share of end-of-life desktop computers from businesses collected by conventional collection channels is also less important in the BCR (9.92%) than in the WR (19.16%). The results support the need to take into account the regional spatial context in setting up the collection of WEEE.

Our assessment faces two main limitations. Firstly, if some collection channels, like the compliant channels for recycling and the official reuse channels, are sufficiently documented, other collection channels suffer from a lack of data. Our semi-quantitative reliability assessment highlights that this lack generates a higher uncertainty level for urban regions where compliant collection channels are less effective. Secondly, there is a gap between the estimates of end-of-life desktop computers and those of collection channels. This gap may be caused by an underestimation of illegal exports that are poorly documented as well as by the non-inclusion of stocks in our estimates. To improve the reliability of our MFA, the estimate of end-of-life desktop computer could be validated through a traditional market supply method as the one developed by Baldé et al. (2015). This type of method requires sales data, which are still missing at regional scale The improvement of regional end-of-life estimates is thus dependent on the availability of such data. In addition, further improvements in the data related to non-compliant channels and collection of WEEE from businesses are needed. These data will allow a better estimate of the collection rates of these channels and help to implement appropriate actions.

To comply with the WEEE Directive, 85% of WEEE should be collected for recycling or prepared for reuse by 2019. In the WR, 70.99% of end-of-life desktop computers are processed in accordance with the WEEE Directive, with 9.25% of reuse. In the BCR, this rate drops to 32.98%, with 12.55% of reuse. Based on our regional assessment, in addition to the aforementioned improvement of the collection from businesses, specifically for the BCR, the collection from households should be improved. This flow has no potential for reuse and should thus directly be sent to recycling channels. As the Brussels urban context has an undeniable influence on the collection results, transposition into an urban area of a model similar to that applied in the WR would be inappropriate. More broadly, to organize the collection in a way that takes into account the local context, waste management systems should evolve. So far, the collection of WEEE has been implemented by pursuing a top-down approach: regional policies arise mainly from national or European decisions. In contrast, the involvement of citizens and businesses as well as the inclusion of geographical characteristics require a switch to a bottom-up approach.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.11.008.

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