Assessing the life cycle environmental impacts of bulky waste management in Brussels

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Abstract
This study investigates the circular economy potential of bulky waste management in Brussels and the life cycle-based environmental impacts of different bulky waste management systems. The latter was formulated in two alternative circular economy (CE) scenarios that were assessed in comparison with a reference scenario describing the current situation. The first CE scenario developed aims to improve the treatment of bulky waste. And, the second CE scenario targets to improve the collection with increasing the separate collection on bulky waste material with a reuse and recycling potentials.
The environmental impacts of these three scenarios were analysed using a life cycle assessment (LCA) and following a material-based approach. An attributional LCA modelling was applied, aiming at comparing the impacts of different scenarios as a result of changes in the treatment options performed in each scenario. The changes consider for each scenario the reorientation of bulky waste from incineration to recycling and from recycling to preparation for reuse, including the requirements for collection and transport.
The results show that the improvement of treatment of bulky waste has displayed a better environmental performance than the current situation, and that the implementation of separate collection – which has particularly increased the preparation for reuse rate, has yielded to a significantly better environmental performance than all scenarios. The results have also shown that if the preparation for reuse shows the highest environmental credits insofar as the produced second-hand substitutes an alternate one, these credits can decrease when there is no substitution.
Keywords: circular economy, life cycle assessment, bulky waste, reuse, recycling

1. Introduction

Circular Economy (CE) builds upon several approaches that emphasize on waste management and resource valorisation patterns. One of these approaches follows the principle: "*the smaller the resource circulation (activity-wise and geographically) the more profitable and resource efficient*"[1]. Whilst activity-wise, refers to "*don't repair what is not broken, don't remanufacture what can be repaired, don't recycle what can be remanufactured*", geographically indicates "*the small loops (reuse, repair and remanufacture) are best done locally or regionally*" [1]. The identification of waste materials and products that have a key potential in CE has been subject to several discussions. For instance, in Brussels, bulky waste has been targeted as one of the priority flows within the regional programme of circular economy [2]. Bulky waste generated in Brussels, as in many other cities and regions, constitutes a heterogenic spectrum of large objects or products made of different materials such as wood, plastic, glass, steel, textile, etc.
The bulky waste stream is considered as 'feedstock' for preparation for reuse and recycling to produce second-hand and recycled products respectively, when separate collection of different types and/or of different materials in bulky waste is performed upstream [2], [3]. This perspective is in line with CE since reuse and recycling promote resource efficiency and contribute in reducing environmental pressure [4]–[6]. However, bulky waste is often damaged during the collection due to non-adequate collection equipment, reducing its reuse potential. Furthermore, when the collection is mixed, i.e. non-recyclable, recyclable and potentially reusable materials are collected together, the bulky waste stream is usually destined to landfill, which accordingly represent a 'loss' of resources [3]. Thus, even though the CE potential is present, i.e. separate collection, preparation for reuse and (local) recycling potentials, it is under-exploited.
Exploiting the CE potential in waste management requires to consider different options of waste management, that should be assessed from an environmental point of view. Life cycle assessment (LCA) is recognised as the most appropriate to assess the environmental impacts of waste management options [7], [8].
The assessment of environmental performance of bulky waste management options has been less widely studied in the literature. First, the number of studies that have applied a life cycle-based method is limited; only Castellani et al., 2015 and Fisher et al., 2011 have assessed the environmental performance of bulky waste based on LCA. Often, as it is the case in [10], authors discussed the environmental impacts based on a quantitative analysis of generation, collection and treatment. Second, most studies have applied a product approach i.e. focusing on a type of bulky waste product (e.g. sofas and dining tables [9]), instead of a material approach which allows to keep track of the materials that composed the bulky waste stream. Lastly, no study has considered the effects of different types of collection in the assessment of the environmental performance.
This study investigates i) the CE potential of bulky waste management in Brussels and ii) the life cycle-based environmental impacts of different bulky waste management systems. The different management systems of bulky waste include their requirements in terms of collection, transport and treatment.

Due to the nature of bulky waste – as a heterogenic pool of materials, we opted for a material-based approach. The case study is conducted in Brussels, with city-specific primary data on bulky waste collection, treatment and composition.

2. Materials and methods

2.1. Case study description, data on bulky waste collection, composition and treatment

In order to assess different management options of bulky waste, it is important to analyse the current situation in terms of collection, waste composition and treatment, as well as in terms of its potential for a more circular management system.

In Brussels, bulky waste is collected by two main actors: public actors and social economy organizations (SEOs). After the collection, bulky waste is transported to public civic amenity sites (CAS) or SEOs' centres, respectively, where citizens can also bring their bulky waste.

We categorise the types of collection in: separate and mixed (henceforth classical). The former indicates the collection of only items with a reuse potential. Thus, a sorting occurs at source to collect what can be (prepared to be) reused/resold. The latter refers to the collection of all items without any sorting at source. Public actors perform only the classical collection, that includes the collection on the demand of citizens and curb side collection. The SEOs perform both types of collection (curb side collection excluded). Beside SEO initiatives, we find several decentralized operating initiatives in Brussels such as bring banks, private exchanges (e.g. gifts, donations, online sales, etc.) and second-hand markets where bulky items are not considered as waste. Such initiatives are not monitored and quantitative data on their activities are unavailable, if not, inaccessible. Due to this data limitation, these activities are excluded from the scope of the quantitative analysis in this study.

Table 1 shows the total amount of bulky waste that is collected in Brussels in 2014, by each collector and according to each collection mode. Table 2 presents the group of materials that compose the bulky per collector and per collection type.

At CAS, the bulky waste collected by public actors or brought by citizens is separated according to the nature of their materials (e.g. a broken wood table goes to the wood container). The data on the amount collected and the material composition (always in weight) of this fraction was provided by public actors and is included in the amount in Table 1 and Table 2. This fraction is mainly sent for recycling. Besides, there are also containers for mixed bulky waste, wherein items that cannot be sent to recycling are put and then sent to incineration with energy recovery. Only the total amount collected of this fraction is available. However, the data on its material composition is missing for Brussels, but available for Flanders, another Belgian region. We have thus estimated the material composition of this mixed fraction collected in Brussels using as proxy the material composition of the mixed fraction collected in Flanders for 2011 [11]. However, within that material composition, items that could not be classified in any material group were grouped as residual. And due to lack of specific data or appropriate proxy material group for this residual fraction, the latter was excluded from the quantitative analysis in this study. This fraction that is not included in Table 1 and Table 2 amounts 7,447 tons and corresponds to 18% of total bulky waste collected.

Table 1 Bulky waste collection

Tons, 2014	Public actors	SEOs	Total
Classical collection	19,845	179	20,024
Citizen deposit at CAS or SEOs centres	13,145	357	13,502
Separate collection	0	1,238	1,238
Total	32,990	1,774	34,764

Table 2 Average material composition (by weight) of bulky waste collected by public actors and SEOs

Material group	Public actors	SEOs	
	Classical	Source-separated	Classical
Iron	14.5	3.8	9.2
Aluminium	8.3	2.5	6.2
Polyvinyl chloride	5.6	4.8	3.8
Polypropylene	4.5	3.8	3.1
Polyethylene	1.1	1.0	0.8
Wood	61.8	64.3	61.5
Glass	2.1	8.1	7.7
Ceramics	2.1	11.8	7.7

Table 3 shows the treatment rates of bulky waste collected in Brussels per actor (total = 100%) and Table 4 provides the treatment rates per material, per actor and per collection mode. The total rates per table yields to 100%.

The data was provided by publics actors and SEOs. More than half of bulky waste, including the residual fraction, is incinerated in Brussels, almost 44% is sent to recycling[1], representing the fractions sorted at CAS. The sorted fractions present at CAS are handled by private companies and sent for recycling out of Brussels. Furthermore, preparation for reuse shows the lowest rate and is performed only by SEOs. However, it is the most widely performed valorisation by SEOs.

Table 3 Treatment rates of bulky waste collected in Brussels

In %	Preparation for reuse	Recycling	Incineration
Public actors	0.0	37.8	57.1
SEOs	2.4	2.1	0.6

Table 4 Treatment rates for the reference scenario

(%)	Public actors		SEOs					
	Recycling	Incineration	Preparation for reuse		Recycling		Incineration	
			SC*	CC*	SC	CC	SC	CC
Iron	9.56	4.18	0.09	0.01	0.04	0.13	0.00	0.00
Aluminium	6.37	1.52	0.06	0.01	0.03	0.09	0.00	0.00
Polyvinyl chloride	0.29	5.07	0.09	0.01	0.00	0.01	0.08	0.04
Polypropylene	0.23	4.05	0.07	0.00	0.00	0.01	0.07	0.03
Polyethylene	0.06	1.01	0.02	0.00	0.00	0.00	0.02	0.01
Wood	20.10	38.50	1.57	0.09	0.72	0.85	0.00	0.00
Glass	0.51	1.45	0.15	0.01	0.01	0.09	0.12	0.01
Inert	0.69	1.30	0.23	0.01	0.02	0.09	0.17	0.01

*SC: separate collection; CC: classical collection (that includes the citizen deposit)

2.2. Bulky waste circular economy scenarios

Among the different types of scenarios (see [12]), we have chosen the "What-if scenario" type for this study. Indeed, "*What-if scenarios* respond to the question: What will happen, on the condition of some specified events?" [12]. This approach is known and recognised in the context of LCA scenarios development and analysis [13], [14]. Considering this approach, the underlying principle is that the bulky waste management scenarios represent different changes or events that can be implemented in the waste collection and treatment options. And, the environmental effects associated these changes are assessed.

The reference scenario corresponds to the current bulky waste management system that has been described in section 2.1 and is compared with two alternative scenarios. The **circular economy scenario 1** focuses on improving the treatment performance of bulky waste in Brussels. And the aim of the **circular economy scenario 2** is to improve the collection schemes and rates to foster the valorisation of bulky waste. Table 5 allows comparing the collection and treatment rates of the different scenarios. The sum of collection and treatment rates per scenario equals 100% respectively.

On the one hand, it has been estimated that 10% of the collected bulky waste in Brussels can be sent to preparation for reuse [15], yielding to 3,476 tons. Currently, only 846 tons of the bulky items are reused with preparation in Brussels. This indicates that there is still more than 75% of the collected bulky waste that could be refurbished but are 'loss' in other treatment mode. Furthermore, there is still a considerable amount of recyclable materials in the bulky waste that is incinerated, for instance wood, metal and other recyclable materials [3], [11], [16]. These fractions mainly correspond to the mixed bulky waste and can be redirected to recycling (i.e. material-specific container) rather than incineration, insofar as advanced sorting operations at CAS are carried out. This scenario thus promotes: 1) the integration of the SEOs in the valorisation chain after the collection by public actors. Indeed, the collaboration between public actors and SEOs, enhances SEOs to access CAS (where bulky waste is centralized) and perform a manual sorting to capture items that have the potential to be reused. 2) the recirculation of flows within the regional boundaries through the deviation of flows that are currently sent to recycling, towards preparation for reuse channels; and the deviation of flows collected by public actors that currently sent to incineration, towards recycling channels. Table 5 thus shows that with the CE scenario 1, the preparation for reuse and recycling rates have increased of almost 5% and 23% respectively, to the detriment of the incineration.

On the other hand, the aim of the **circular economy scenario 2** is to improve the collection schemes and rates to foster the valorisation of bulky waste. This scenario thus targets to capture more flows in terms of higher quality by public actors and SEOs. It has been estimated that 14,654 tons of bulky waste could be separately collected [16]. Currently, only 1,238 tons are separately collected, indicating that 13,416 tons of bulky waste are under-exploited and end in less adequate collection channels, reducing their valorisation potentials. This amount could be captured with a separate collection mode. Although, public actors are the most important collectors in terms of collected quantity, they do not perform this collection mode. In this scenario, we assume that public actors implement the separate collection mode and that SEOs increase their separate collection. Table 5 shows that the separate collection rate highly increases of 38% while capturing the 13,416 tons of bulky waste (that are under-exploited) with the

[1] By default, 'recycling' or 'recycled' refer to treatment performed at dismantling, shredding and sorting facilities. Thus 'sent to recycling' corresponds to 'sent to dismantling, shredding and sorting facilities'.

separate collection mode. Furthermore, it shows the preparation for reuse rate has increased of almost 20% to the detriment of recycling and incineration. This highlights the positive effects of separate collection on the preparation for reuse rate. Further details on the scenario description are provided as supplementary information.

Table 5 Collection and treatment rates of scenarios

%, 2014	**Reference scenario**		**Scenario 1: improved treatment**		**Scenario 2: Improved collection**	
Collection rates	Public actors	SEOs	Public actors	SEOs	Public actors	SEOs
Classical collection	56.6	0.6	56.6	0.6	36.5	0.5
Citizen deposit	37.5	1.2	37.5	1.2	19.8	1.0
Separate collection	0.0	4.1	0.0	4.1	28.9	13.2
Treatment rates						
Preparation for reuse	0.0	2.4	0.0	7.3	0.0	27.1
Recycling	37.8	2.1	58.8	3.9	37.9	11.1
Incineration	57.1	0.6	28.5	1.5	18.4	5.5

2.3. Life cycle scenario assessment

Life cycle assessment (LCA) is an environmental management tool for assessing environmental aspects and potential impacts associated with a product, process, or service. LCA follows a cradle-to-grave approach, considering the full life cycle of the product. It is regulated by ISO standards 14040 and 14044. Moreover, LCA methodology is a powerful tool for decision making and for the End of Life option (EoL), allowing for the identification of hotspots associated with a specific waste management policy and the eventual implementation of focused strategies to reduce environmental impacts [17].

The **aim** of this study is to evaluate the life cycle-based environmental impacts of different bulky waste management systems including their requirements on different types of collection and transport.

The different bulky waste management systems are translated into life cycle scenarios and represented Figure 1.

As shown in Figure 1, the **system boundaries** encompass the entire bulky waste chain from collection to end-of-life treatment (bin-to-grave system boundary). It thus includes the: i) waste collection, distinguishing different collection models, ii) transport to CAS and/or reuse centres by collectors or citizens, iii) manual sorting and selection at CAS or reuse centres, iv) transport to treatment options and v) treatment options that include: preparation for reuse, recycling and incineration with energy recovery.

The reference flow is the collection of 34,764 tons of bulky waste in Brussels in 2014 (see Table 1) and the **functional unit** is the treatment of 1 ton of bulky waste collected.

In this study, we apply an **attributional LCA** modelling which aims at comparing the impacts of different scenarios as a result of changes performed in each scenario.

This modelling applied in this study focuses on the changes that are induced by the reorientation of bulky waste from incineration to recycling, and from recycling to preparation for reuse (both affecting the treatment processes and the treatment of by-products) and by the increase of the separate collection type (that mainly affects the transport).

For each alternative scenario, we model the reorientation from incineration to recycling by considering i) the avoided impacts of the incineration and the avoided production of recovered electricity, corresponding to the amount to be incinerated, and ii) the induced impacts of the recycling and the avoided production of primary raw materials, corresponding to the amount to be recycled.

As for the reorientation from recycling to preparation for reuse, for each alternative scenario we model i) the avoided impacts of the recycling and the reduced production of primary raw materials corresponding to the amount to be recycled, and ii) the induced impacts of preparation for reuse and the use of first-hand products corresponding to the amount to be prepared for reuse.

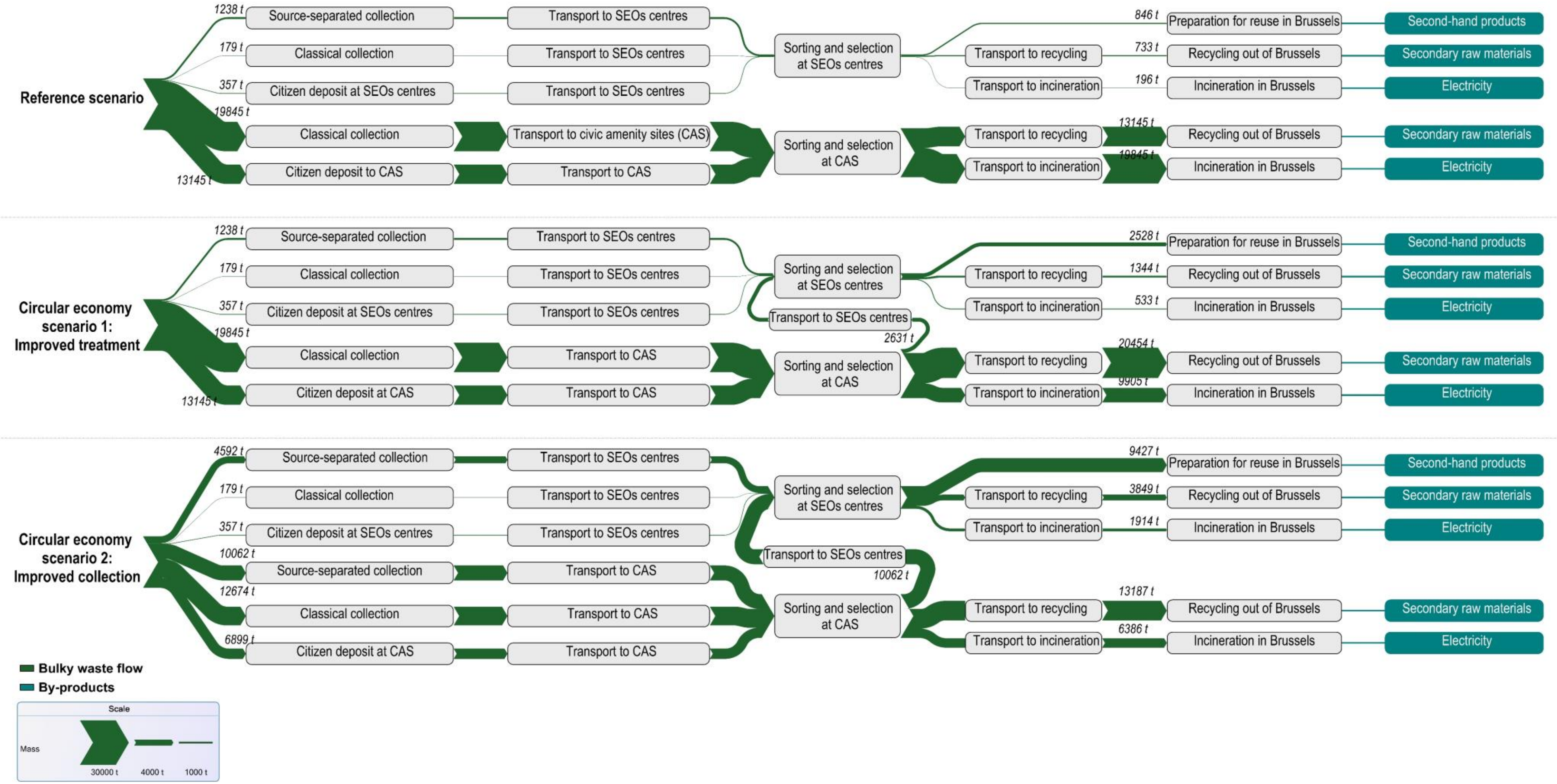


Figure 1 Bulky waste circular economy scenarios for LCA

2.4. Life cycle inventory data

2.4.1. Collection and treatment transport

Table 6 shows the average transport distance for the different collection types and to the different treatment options. The preparation for reuse takes place at SEOs centres, where second-hand products are sold. The data on transport distance has been estimated based on data provided by collectors. The data on truck and fuel consumption were taken from [18] and representative transport processes were taken from EcoInvent 3.5 database.

Table 6 Distance for collection and treatment types per ton of bulky waste

Collection and treatment types	Truck	Distance (km/t)
Separate collection to SEOs centres	Lorry 3.5 to 7.5 t	6.7
Classical collection to SEOs centres	Lorry 3.5 to 7.5 t	10
Deposit by citizens to SEOs centres	Passenger car	26.7
Separate collection to CAS	Lorry 21 t	7.3
Classical collection to CAS	Lorry 21 t	7.3
Deposit by citizens to CAS	Passenger car	26.7
From CAS to SEOs centres	Lorry 3.5 to 7.5 t	3.3
From SEOs centres to recycling	Lorry 16 to 32 t	47.8
From SEOs centres to incineration	Lorry 21 t	1.2
From CAS to recycling	Lorry 16 to 32 t	47.1
From CAS to incineration	Lorry 21 t	1.3

2.4.2. Sorting and selection

Bulky waste sorting and selection take place at SEOs centres and CAS. This activity concerns the functionality testing of bulky items and identification of the bulky items with and without a reuse potential. Items with a reuse potential are the ones that can be sent to preparation for reuse. This test consists of visual inspection of items and is manually performed. In the CE scenarios 1 and 2, items with a reuse potential from the selection occurring at CAS are redirected to SEOs centres. It is assumed that the environmental impacts of this manual sorting and selection and visual inspection are negligible, and thus not accounted in this analysis.

2.4.3. Treatments of bulky waste

The environmental impacts of the **incineration** of materials in bulky waste for each scenario were modelled using data available in EcoInvent 3.5. The incinerator in Brussels is an energy recovery plant that treats municipal solid waste, with production of electricity, with fly ash extraction. The amount of electricity that is recovered from each specific material was calculated based on the energy content of these materials and the efficiency of the incinerator in Brussels. In the modelling, we have assumed that the electricity produced by the incinerator displaces the same quantity of electricity according to the electricity mix of Belgium constituted of hydro (1%), oil (2%), wind (42%) and natural gas (56%), as mentioned in the EcoInvent 3.5. The bottom ash from the facility is valorised in the road construction as secondary raw material, substituting gravel.

For the modelling of the environmental impacts of the recycling, data about emissions, energy consumption and material flow for both the production starting from waste materials (i.e. secondary production) and the production starting from virgin raw materials (i.e. primary or virgin production) have been initially gathered from EcoInvent 3.5. This data was adjusted by literature data presented in the following.

For metal scrap, the recycling process includes that metal scrap is first sent for sorting and preparation through mechanical shredding, separation, cleaning and drying, with a material loss of 10% for iron [19] and 4.8% for aluminium [20]. Then, the recovered iron and aluminium scraps are sent to a furnace for melting to produce respectively secondary iron and secondary aluminium [21]. 9.8% and 3% of material loss during the reprocessing were considered respectively for iron and aluminium [19], [20]. The secondary iron and aluminium produced were assumed to respectively substitute primary materials namely pig iron and aluminium ingot [19], [20] as proposed by the EcoInvent attributional modelling. We also considered that there is no material quality loss during the reprocessing corresponding to substitution ratio of 1:1 [19], [20].

As for plastics, the recycling process consists of a mechanical reprocessing during which the plastics are first shredded and granulated to produce flakes that are then cleaned, dried and extruded [21]. We accounted material losses during the recycling process of each plastic type: 40% for PVC, 12% for PP and 21% for PE [5]; we also considered the material quality loss that represents around 10%, corresponding to a substitution ratio of 1:0.9 [5]. The produced secondary plastic pellets of PVC, PP and PE were assumed to substitute the production of primary plastics granulates of PVC, PP and PE, respectively [21].

The wood found in bulky waste is a mix of wood of category A and B[2] [21]. It was therefore assumed that such material would be used in the production of secondary particle board, one of the largest end market for recovered wood in the Belgium [21]. The preparation phase consists of chipping and mechanically sorting to reclaim the wood fibres prior to drying. The recovered waste wood fibres are used in the production of secondary fibreboard. And the recycled fibreboard containing recovered fibres were assumed to substitute for virgin fibreboard produced using virgin wood [6]. A material loss of 13.5% was accounted during the preparation and of 5% during the reprocessing phase [5], but we consider no material quality loss, i.e. substitution ratio of 1:1 [5].
Lastly, the recycling process of glass, here assumed similar to the one of ceramics waste, starts with preparation and sorting at a recovery facility, where the glass is sorted, crushed to produce respectively glass. A material loss of 6.1% was accounted [6]. The cullet is then sent to a remelting facility for the production of secondary glass that was assumed to substitute a primary flat glass, with 1% of material loss accounted [6]. Likewise, secondary ceramics were assumed to substitute ceramic product. We considered no material quality loss, i.e. the substitution ratio is 1:1 for glass and ceramics recycling process.
In this study, **preparation for reuse** means according to the European Waste Framework Directive "*checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing*" [22]. This study excludes the bulky items that are not waste (i.e. not collected) and are used again (e.g. via donations or online sales) for the same or different purpose for which they were conceived.
Modelling the environmental burdens of preparation for reuse implies to include the cleaning or repairing recovery operations processes for each bulky waste products. However, given the versality of bulky waste products and the absence of information which preparation for reuse process is carried out and for which bulky items, the environmental impacts of these processes are assumed to be 0.5% of those to produce materials composing the bulky waste products. This assumption is further discussed in the sensitivity analysis in section 3.3.1.
The environmental credits are those from the avoided processes that would have been required to make the product or the materials from virgin materials. The only by-product of any preparation for reuse process is a second-hand product that may substitute a new product. In the absence of empirical data on the propensity of an item to replace an alternate one for Brussels, we first set the substitution rate to 1 for the analysis. Subsequently, we discuss this assumption through a sensitivity analysis in section 3.3.2 wherein the substitution rate varies in this range [0; 1]. With this coverage, we ensure to cover all the possible changes creates when the preparation for reuse is performed in scenarios.

2.5. Life cycle impact assessment

The Life Cycle Impact Assessment was conducted using the method ReCiPe2016 [23] that was executed with the Software SimaPro (Pré Consultants, The Netherlands). ReCiPe2016 method translates emissions and resource extractions from the life cycle inventories into environmental impacts categories, at midpoint and endpoint levels. The midpoint level cover 17 impact categories and the endpoint, 3 impact categories focusing on damages on human health, ecosystems and resources availability. Damages on human health is assessed using the concept of "disability-adjusted life years" (DALY) for a person, that accounts for years of life lost and years of life disabled due to for example a disease. The damages on ecosystems are measured in loss of species over area and time. They are measured in potentially disappeared fraction of species (PDF) $\times$ m^2 $\times$ year for terrestrial ecosystems and in PDF $\times$ m^3 $\times$ year for freshwater and marine ecosystems. Lastly, the damages on resource availability are expressed in US dollars ($) and account for the increase of the cost of a commodity due to the extraction of a mineral or fossil resource [24]. These endpoint impact categories are used to present the results in the following section.
The method distinguishes three set of perspectives for the impact assessment namely: Individualist, Hierarchist and Egalitarian and we use in this study the Hierarchist perspective. The latter seeks for a consensus between the Egalitarian and Individualist perspectives. Plus, it includes long term emissions over a 100-year timeframe and is based on the most common policy principles [24].

3. Results and discussion

3.1. Environmental impacts of bulky waste treatment options

The results of the life cycle environmental impacts of the treatment options of 1 ton of bulky waste are shown in Figure 2, Figure 3 and Figure 4. Positive values indicate the environmental burdens whereas the negative values indicate the environmental benefits. The sum of both values yields the net balance of impacts. The results are presented using the endpoints impacts categories on human health, on ecosystems and on resources, as described in section 2.5.
Figure 2 shows the environmental impacts of the incineration with energy recovery and ash extraction of 1 ton of bulky waste. The damages on human health and on ecosystems are mainly in majority created by the municipal waste incineration processes (in red in Figure 2) that is the main contributor with almost 80 of the impacts. As for

[2] category A refers to untreated and non-impregnated solid wood. They are mainly crates and pallets (industrial packaging) but also rafters, dunnage and formwork; Category B is treated wood but not impregnated. It can be painted or varnished wood, laminated or agglomerated panels from furniture, doors and frames[21].

the damages on resources, quicklime and the waste collection are the main contributors. However, the electricity recovered, next to the substitution of gravel, is the main contributor to credits, for all the impacts categories and foremost for impact category on resources. The results thus display a negative net impact, representing a credit, for damages on the resources and a positive net impact for the two other impact categories.

Figure 3 shows the environmental impacts of the recycling of 1 ton of bulky waste. The impacts show the contribution of the recycling process, waste collection and the avoided production of virgin raw materials. The results show that the credits surpass the burdens indicating a negative net impact, that is a benefit. The credits originate from the avoided virgin raw material production at 71% for damages on human health, 60% on for damages on ecosystems and 64% for damages on the resources. The waste collection has a very low contribution (between 0.7% and 2.5%). Table 7 presents the contribution of the recycling process of each material in the bulky waste, in net impacts. It shows that when considering all the impacts categories, the recycling of aluminium contributes the most (36% in average) to the environmental impacts the recycling of 1 ton of bulky waste, followed by the recycling of wood (14% in average); whereas the less contributor is the recycling of glass (2.5% in average).

Figure 4 shows the environmental impacts of the preparation for reuse of 1 ton of bulky waste. As for the case of recycling, the credits exceed the burdens, yielding to a negative net impact. However, this result is based on the assumption taken on the environmental impacts of the preparation for reuse process in section 2.4.3 that will be discussed in section 3.3.1.

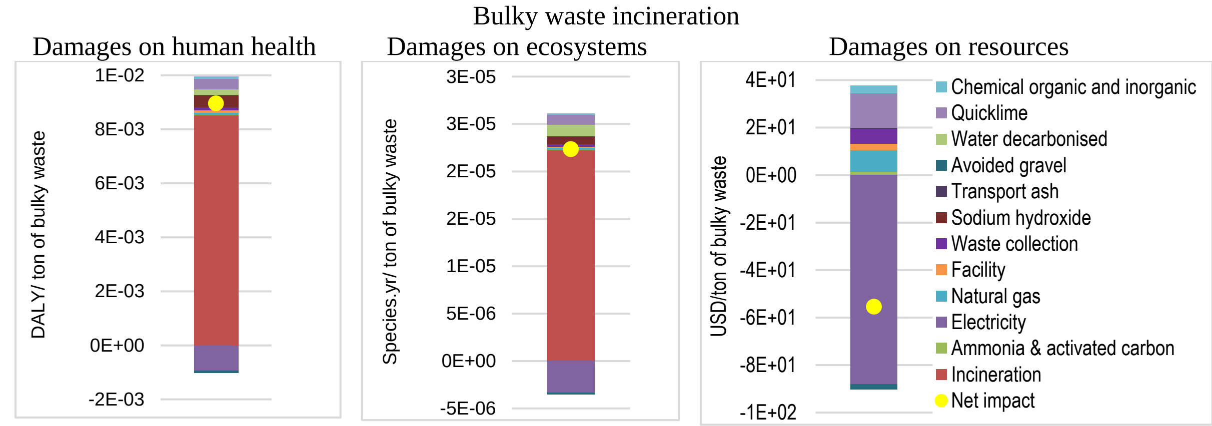


Figure 2 Environmental impacts of the incineration of 1 ton of bulky waste

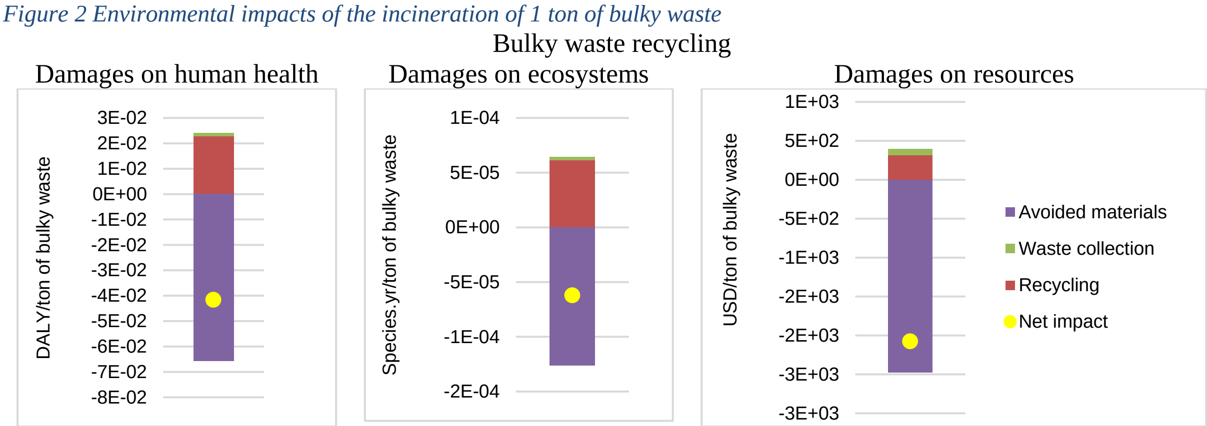


Figure 3 Environmental impacts of the recycling of 1 ton of bulky waste

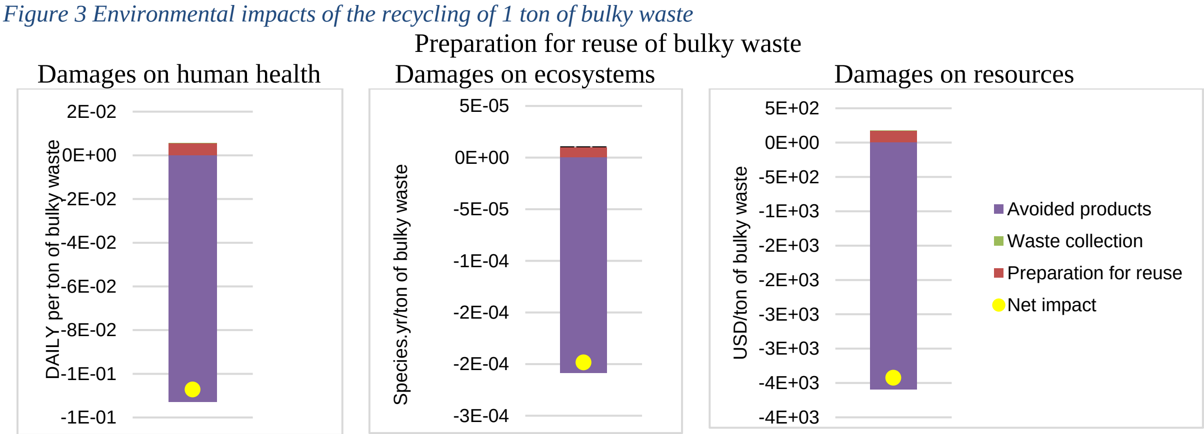


Figure 4 Environmental impacts of the preparation for reuse of 1 ton of bulky waste

Table 7 Contribution analysis (in net impact) of the recycling of materials in the bulky waste

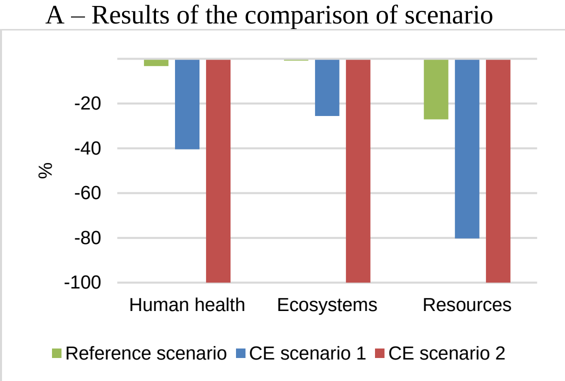
	Human health (DALY)	Ecosystems (species.yr)	Resources (USD)
Aluminum	-2.64E-02	-2.50E-05	-6.11E+02
Iron	3.44E-03	-3.39E-06	-6.73E+01
PVC	-2.22E-03	-6.59E-06	-2.39E+02
PP	-2.77E-03	-6.95E-06	-5.62E+02
PE	-2.68E-03	-7.22E-06	-4.98E+02
Wood	-1.03E-02	-1.30E-05	-1.01E+02
Glass	-1.36E-03	-2.42E-06	-3.34E+01
Ceramics	-5.68E-04	-3.02E-07	-4.10E+01

3.2. Environmental impacts of scenarios: comparative results

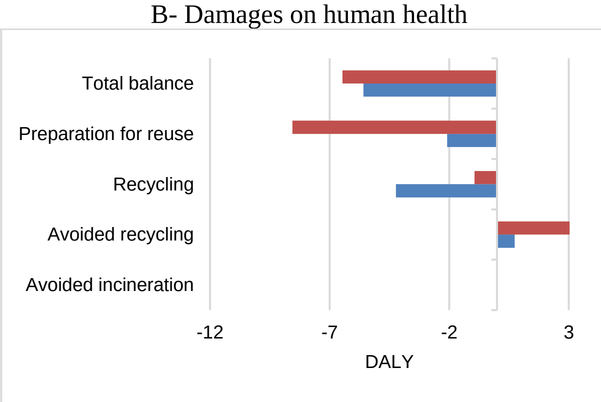
This section presents the results of the comparison of the environmental impacts of scenarios. They correspond to the impacts due to the changes shown in Figure 1. The changes include the redirection of bulky waste to new treatment option, resulting in avoiding the former treatment process. Figure 5 A illustrates and compares the overall environmental impacts of scenarios per impact category. The overall environmental impacts per scenario equal the total bulky waste distributed over the different treatment of that scenario (in Figure 1) and multiplied by the impact intensity of each corresponding treatment (in Figure 2, Figure 3 and Figure 4). For instance, the environmental impacts of the reference scenario consider: 846 t (Figure 1) × the impacts of preparation for reuse (Figure 4) + 13,878 t (Figure 1) × the impacts of recycling (Figure 3) + 20,041 t (Figure 1) × the impacts of incineration (Figure 2).

Figure 5 A indicates clearly how the preparation for reuse, fostered by the separate collection significantly improve the environmental performance of bulky waste management in Brussels. The underlying facts of Figure 5 A are elucidated in Figure 5 B-D, which are, per impact category, the net impacts originating from the changes in the CE scenario 1 and 2. The changes are: the avoidance of incineration when redirecting bulky waste to recycling and the avoidance of recycling when redirecting bulky waste to the preparation for reuse. The main trend shown by the results is that, for all the impacts categories, the credits generated by the 'new'/substituting treatment processes are high enough to surpass the burden of the avoided treatments, so as to generate a negative net impact. Even though avoiding incineration allows to reduce very low impacts on human health, and ecosystems, its environmental credit according to the impact on resource is lost and the credits of new treatment process, the recycling, are higher, creating a negative net impact balance. Further, avoiding recycling constitutes a loss of an environmental credit for all impact categories, but the credits of the preparation for reuse substituting the treatment process are the highest for all the impact categories. The total balance shows the significant contribution of recycling and preparation for reuse, fostered by the separate collection, to the reduction of the damages on each impact category.

A – Results of the comparison of scenario



B- Damages on human health



C- Damages on ecosystems

D – Damages on resources

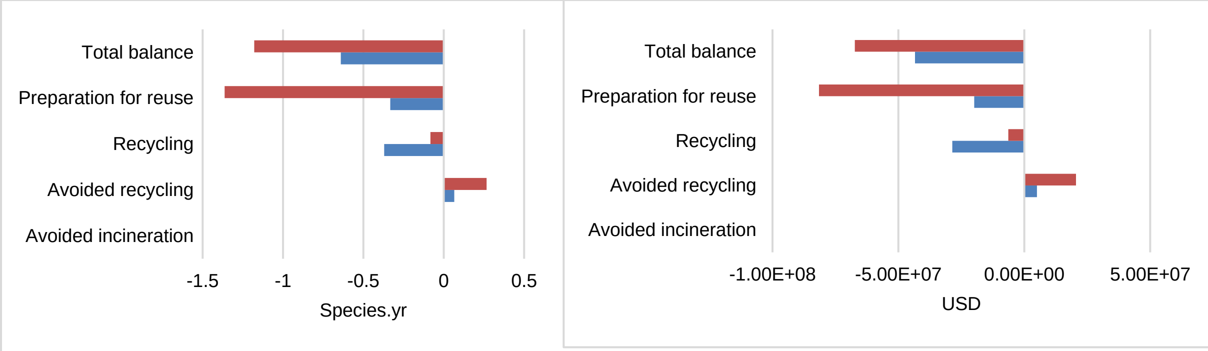


Figure 5 Comparative results of environmental impacts of scenarios

3.3. Sensitivity analysis of the results on the environmental performance

The environmental assessment of products or materials is generally affected by uncertainties typical of LCAs, such as system boundary definitions, the quality and representativeness of the inventory data, the availability of primary data versus secondary data, and the selection of the impact categories, etc. In this study, we mainly focus on the considerations taken concerning the environmental impacts of preparation for reuse and the functionality of second-hand products.

3.3.1. Sensitivity analysis on environmental impacts of preparation for reuse

The processes during the preparation for reuse can change depending on the status of the bulky items (materials or products). The same type of material or product could require a minor intervention in some circumstances and major ones in others (e.g. refurbishment or remanufacturing). Because of current uncertainties, it is preferable to set a certain range of variation of the impacts of the preparation for reuse process. In the analysis of circular economy scenarios (section 0), we set the potential environmental impact of preparation for reuse of a material amounted to $p_0 = 0.5\%$ of the total environmental impact of the production of that material. We thus performed a sensitivity analysis of the results, assuming the potential environmental impact of preparation for reuse of a material varies from $p_1 = 0.1\%$ to $p_2 = 1\%$ (see Table 8). Values higher than 10% are excluded, since if bulky products require major repairs, they are generally not adequate for the prepared for reuse channel.

Table 8 shows the variations of the overall environmental impacts of scenarios when considering different preparation for reuse processes between the baseline situation ($p_0 = 0.5\%$) with each of the alternative cases ($p_1 = 0.1\%$) and ($p_2 = 1\%$). It indeed confirms that they are more environmental benefits when less preparation for reuse processes are performed ($p_1 = 0.1\%$) and more in contrast ($p_2 = 1\%$). And even though there is a cumulative positive effect of these benefits in scenarios 1 and 2 compared to the reference scenario, Table 8 reports in general very low variations of the overall impacts of the scenarios in different preparation for reuse processes. This sensitivity analysis confirms the considerations discussed and demonstrates to a certain extent that the environmental performance of bulky waste management scenarios is lightly influenced by the assumptions related to the environmental impacts of the preparation for reuse.

Table 8 Environmental performance of bulky waste management scenarios with different preparation for reuse processes

Reference scenario		Baseline $p_0 = 0.5\%$	$p_1 = 0.1\%$	Variation (%)	$p_2 = 1\%$	Variation (%)
Human health	DALY	-2.11E-01	-2.14E-01	-1.5	-2.07E-01	1.6
Ecosystems	species.yr	-9.18E-03	-9.38E-03	-2.1	-8.97E-03	2.4
Resources	USD	-1.82E+09	-1.84E+09	-1.1	-1.80E+09	1.3
Scenario 1						
Human health	DALY	-2.61E+02	-2.67E+02	-2.3	-2.54E+02	2.6
Ecosystems	species.yr	-6.40E-01	-6.56E-01	-2.4	-6.23E-01	2.7
Resources	USD	-4.34E+07	-4.41E+07	-1.5	-4.27E+07	1.6
Scenario 2						
Human health	DALY	-6.46E+00	-6.63E+00	-2.5	-6.29E+00	2.8
Ecosystems	species.yr	-1.18E+00	-1.21E+00	-2.7	-1.14E+00	3.1
Resources	USD	-6.73E+07	-6.83E+07	-1.5	-6.59E+07	2.1

3.3.2. Sensitivity analysis on the substitution rate of second-hand products

In section 0, we have assumed that the environmental benefits of reusing second-hand products consider that the production of new materials or components is avoided. However, the propensity to replace new products depends on a range of factors that include the condition of the product as well as the needs of the person in receipt of the reused item. In different circumstances, purchase of a second-hand item may not necessarily replace a new one. It can happen that it replaces nothing at all (i.e. it is an additional item, and if the person purchasing the item could

not buy it as reused, they would not buy a new item). To consider these aspects, we hence carried out a sensitivity analysis of the results, assuming the substitution rate for the preparation for reuse (initially $s_0 = 1$) varies in this range [0; 1], taking the values $s_1 = 0.75$ and $s_2 = 0$, as shown in Table 9.
The results obviously show that the overall environmental impacts of scenarios decrease when the second-hand product tends not to replace an alternate one. These sensitivity analysis stresses and confirms that although the separated collection and the preparation for reuse for reuse through scenario 2 display good environmental performance, whenever a second-hand product does not displace an alternate one, this environmental performance can significantly decrease.

Table 9 Environmental performance of bulky waste management scenarios with different substitution rates

Reference scenario		Baseline $s_0 = 1$	$s_1 = 0.75$	Variation (%)	$s_2 = 0$	Variation (%)
Human health	DALY	-2.11E-01	-1.90E-01	11	-1.49E-01	41
Ecosystems	species.yr	-9.18E-03	-7.98E-03	15	-5.47E-03	68
Resources	USD	-1.82E+09	-1.70E+09	7	-1.32E+09	38
Scenario 1						
Human health	DALY	-2.61E+02	-2.37E+02	10	-1.65E+02	58
Ecosystems	species.yr	-6.40E-01	-5.52E-01	16	-2.91E-01	120
Resources	USD	-4.34E+07	-4.10E+07	6	-3.31E+07	31
Scenario 2						
Human health	DALY	-6.46E+00	-5.93E+00	9	-3.78E+00	71
Ecosystems	species.yr	-1.18E+00	-1.02E+00	16	-5.20E-01	127
Resources	USD	-6.73E+07	-6.23E+07	8	-5.06E+07	33

4. Conclusion and outlook

The analysis of the CE potential of bulky waste management has shown the positive effects of i) the redirection of potentially reusable bulky items to SEOs centres on the treatment rates and ii) the increase of the separate collection mode on the treatment rates. Moreover, the environmental performance of the different bulky waste management scenarios has been investigated using the LCA method. The investigation resulted in that the improvement of treatment rates has shown a better environmental performance than the current situation, and that the implementation of separate collection – which has indirectly increased the treatment rates, has yielded to a significantly better environmental performance than all scenarios.
This study is very timely, especially since 1) the interest in the circular economy potential of Brussels is growing, 2) preparation for reuse is becoming an effective way of maintaining a product's economic value for longer, and 3) Brussels start to see circular economy (and preparation for reuse) potentials in the multi-materials bulky waste streams. And, this is particularly relevant as it means that such a study can feed circular economy policies.
From this point of view, this study has contributed in showing that environmental benefits can significantly increase when the separate collection is performed. And this can be done with the integration of more SEOs and the informal sector in the preparation for reuse and of the local recycling chains. This could be strengthened by the developments of legal and financial mechanisms, as well as training of workers, that will be integrated in the regional public policies.
Although our work can be of value, we believe that future efforts should focus attention on several aspects. This study can be improved by capturing the variations of the treatment options efficiency, which has been assumed constant, when the collection schemes change. Lastly, this study has focused on the environmental performance, while social (e.g. job creation) and economic aspects (e.g. external cost) are relevant to enrich the sustainability assessment of bulky waste management scenarios.

References

[1] W. R. Stahel, “Policy for material efficiency--sustainable taxation as a departure from the throwaway society,” *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.*, vol. 371, no. 1986, pp. 20110567–20110567, Jan. 2013.

[2] PREC, “Programme régionale en economie circulaire 2016-2020- Mobiliser les ressources et minimiser les richesses perdues : Pour une économie régionale innovante,” 2016.

[3] URBANREC, “Definition of the starting situation in URBANREC regions - Deliverable report D1.1,” Aug. 2017.

[4] V. Castellani, S. Sala, and N. Mirabella, “Beyond the throwaway society: A life cycle-based assessment of the environmental benefit of reuse,” *Integr. Environ. Assess. Manag.*, vol. 11, no. 3, pp. 373–382, Jul. 2015.

[5] L. Rigamonti, M. Grosso, and M. C. Sunseri, “Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems,” *Int. J. Life Cycle Assess.*, vol. 14, no. 5, pp. 411–419, Jul. 2009.

[6] D. A. Turner, I. D. Williams, and S. Kemp, “Greenhouse gas emission factors for recycling of source-segregated waste materials,” *Resour. Conserv. Recycl.*, vol. 105, pp. 186–197, Dec. 2015.

[7] V. Elia, M. G. Gnoni, and F. Tornese, “Measuring circular economy strategies through index methods: A critical analysis,” *J. Clean. Prod.*, vol. 142, pp. 2741–2751, Jan. 2017.

[8] A. Laurent *et al.*, “Review of LCA studies of solid waste management systems – Part I: Lessons learned and perspectives,” *Waste Manag.*, vol. 34, no. 3, pp. 573–588, Mar. 2014.

[9] K. Fisher, K. James, and P. Maddox, “Benefits of Reuse Case Study: Domestic Furniture,” WRAP and ERM Ltd, Nov. 2011.

[10] C. Alexander, A. Curran, C. Smaje, and I. Williams, “Evaluation of bulky waste and reuse schemes in England,” *Proc. Inst. Civ. Eng. - Waste Resour. Manag.*, vol. 162, no. 3, pp. 141–150, Aug. 2009.

[11] OVAM, Ecorem, Febem, Coberec, and Komosie, “Sorteeranalyse grofvuil en analyse grofvuilinzameling,” 2011.

[12] L. Börjeson, M. Höjer, K.-H. Dreborg, T. Ekvall, and G. Finnveden, “Scenario types and techniques: Towards a user’s guide,” *Futures*, vol. 38, no. 7, pp. 723–739, Sep. 2006.

[13] M. Höjer *et al.*, “Scenarios in selected tools for environmental systems analysis,” *J. Clean. Prod.*, vol. 16, no. 18, pp. 1958–1970, Dec. 2008.

[14] H.-L. Pesonen *et al.*, “Framework for scenario development in LCA,” *Int. J. Life Cycle Assess.*, vol. 5, no. 1, p. 21, Jan. 2000.

[15] Ressources and Avis-Opinion, “Le réemploi et la préparation au réemploi dans le futur Programme Régional d’Économie Circulaire (PREC) en Région de Bruxelles-Capitale,” 2015.

[16] T. Ewbank, “« La nature et la part du réutilisable » Identification de la part et de la nature des déchets encombrants amenés en PàC ou collectés en PàP et susceptibles d’être réutilisés,” Jun. 2017.

[17] M. Pini, P. Neri, and A. M. Ferrari, “Environmental Performance of Waste Management in an Italian Region: How LCI Modelling Framework could Influence the Results,” *Procedia CIRP*, vol. 69, pp. 956–961, Jan. 2018.

[18] RDC Environnement, “Évaluation des bénéfices environnementaux, économiques et sociaux de différents scénarios de réutilisation des déchets par les entreprises d’économie sociale,” Juillet 2008.

[19] R. Remus, M. A. A. Monsonet, S. Roudier, and L. D. Sancho, “Best Available Techniques (BAT)Reference Document for Iron and Steel Production Industrial Emissions Directive 2010/75/EU Integrated Pollution Prevention and Control,” 2013.

[20] European Aluminium, “Environmental Profile Report Life-Cycle inventory data for aluminium production and transformation processes in Europe,” Feb. 2018.

[21] Recydata, “Monitoring des quantités de déchets industriels générés dans la Région de Bruxelles-Capitale en 2010, 2011 et 2012 et de leurs modes de traitement,” 2014.

[22] EC, “Directive 2008/104/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance),” in *Core EU Legislation*, London: Macmillan Education UK, 2008, pp. 426–429.

[23] M. A. J. Huijbregts *et al.*, “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level,” *Int. J. Life Cycle Assess.*, vol. 22, no. 2, pp. 138–147, Feb. 2017.

[24] M. Goedkoop, R. Heijungs, and M. Huijbregts, “ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level,” p. 132, 2009.

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Supplementary information

1. Treatment rates per material, per actor, per collection mode

The total rates per actor and per collection mode yields to 100%.

%, 2014	**Reference scenario**		**Scenario 1: improved treatment**		**Scenario 2: Improved collection**	
Collection rates	Public actors	SEOs	Public actors	SEOs	Public actors	SEOs
Classical collection	56.6%	0.6%	56.6%	0.6%	36.5%	0.5%
Citizen deposit	37.5%	1.2%	37.5%	1.2%	19.8%	1.0%
Separate collection	0.0%	4.1%	0.0%	4.1%	28.9%	13.2%
Treatment rates						
Preparation for reuse	0.0%	2.4%	0.0%	7.3%	0.0%	27.1%
Recycling	37.8%	2.1%	58.8%	3.9%	37.9%	11.1%
Incineration	57.1%	0.6%	28.5%	1.5%	18.4%	5.5%

%, 2014	**Reference scenario**		**Scenario 1: improved treatment**		**Scenario 2: Improved collection**	
Collection rates	Public actors	SEOs	Public actors	SEOs	Public actors	SEOs
Classical collection	$C_{PA,CC} * C_T^{-1}$	$C_{SEO,CC} * C_T^{-1}$	$C_{PA,CC1} * C_T^{-1}$	$C_{SEO,CC1} * C_T^{-1}$	$C_{PA,CC2} * C_T^{-1}$	$C_{SEO,CC2} * C_T^{-1}$
Citizen deposit	$C_{PA,CD} * C_T^{-1}$	$C_{SEO,CD} * C_T^{-1}$	$C_{PA,CD1} * C_T^{-1}$	$C_{SEO,CD1} * C_T^{-1}$	$C_{PA,CD2} * C_T^{-1}$	$C_{SEO,CD2} * C_T^{-1}$
Separate collection	$C_{PA,SC} * C_T^{-1}$	$C_{SEO,SC} * C_T^{-1}$	$C_{PA,SC1} * C_T^{-1}$	$C_{SEO,SC1} * C_T^{-1}$	$C_{PA,SC2} * C_T^{-1}$	$C_{SEO,SC2} * C_T^{-1}$
Treatment rates						
Preparation for reuse	-	$T_{SEO,PFR} * C_T^{-1}$	-	$T_{SEO,PFR1} * C_T^{-1}$	-	$T_{SEO,PFR2} * C_T^{-1}$
Recycling	$T_{PA,REC} * C_T^{-1}$	$T_{SEO,REC} * C_T^{-1}$	$T_{PA,REC1} * C_T^{-1}$	$T_{SEO,REC1} * C_T^{-1}$	$T_{PA,REC2} * C_T^{-1}$	$T_{SEO,REC2} * C_T^{-1}$
Incineration	$T_{PA,INC} * C_T^{-1}$	$T_{SEO,INC} * C_T^{-1}$	$T_{PA,INC1} * C_T^{-1}$	$T_{SEO,INC1} * C_T^{-1}$	$T_{PA,INC2} * C_T^{-1}$	$T_{SEO,INC2} * C_T^{-1}$
Landfill	$T_{PA,LAN} * C_T^{-1}$	-	$T_{PA,LAN1} * C_T^{-1}$	-	$T_{PA,LAN2} * C_T^{-1}$	-

Symbol	Description	Data	Reference
	Reference scenario		
$C_{SEO,CC}$	Amount collected in classical collection by SEOs	206 t	Waste statistics
$C_{SEO,CD}$	Amount collected at SEO centres by citizen deposit	412 t	Waste statistics
$C_{SEO,SC}$	Amount collected in separate collection by SEOs	1,443 t	Waste statistics
$C_{PA,CC}$	Amount collected in classical collection by public actors (PA)	24,970 t	Waste statistics
$C_{PA,CD}$	Amount collected at civic amenity sites (CAS) by citizen deposit	10,672 t	Waste statistics
$C_{SEO,CCT}$	Total amount of classical collection and collection at SEO centres by citizen deposit	619 t	$C_{SEO,CCT} = C_{SEO,CC} + C_{SEO,CD}$
C_{SEO}	Total amount collected by SEOs	2,062 t	$C_{SEO} = C_{SEO,CC} + C_{SEO,CD} + C_{SEO,SC}$
C_{PA}	Total amount collected by PA	35,642 t	$C_{PA} = C_{PA,CC} + C_{PA,CD}$
C_T	Total amount collected by PA and SEOs	37,704 t	$C_T = C_{PA} + C_{SEO}$
$T_{SEO,CC,PFR}$	Amount collected (classical collection + citizen deposit) by SEO and prepared for reuse	62 t	Waste statistics
$T_{SEO,SC,PFR}$	Amount separately collected by SEO and prepared for reuse	927 t	Waste statistics
$T_{SEO,CC,REC}$	Amount collected (classical collection + citizen deposit) by SEO and sent to recycling	515 t	Waste statistics
$T_{SEO,SC,REC}$	Amount separately collected by SEO and sent to recycling	341 t	Waste statistics
$T_{SEO,CC,INC}$	Amount collected (classical collection + citizen deposit) by SEO and incinerated	42 t	Waste statistics
$T_{SEO,SC,INC}$	Amount separately collected by SEO and incinerated	175 t	Waste statistics
$T_{PA,REC}$	Amount collected by PA and sent to recycling	15,318 t	Waste statistics
$T_{PA,INC}$	Amount collected by PA and incinerated	20,324 t	Waste statistics
$T_{SEO,PFR}$	Total amount collected by SEO and prepared for reuse	988 t	$T_{SEO,PFR} = T_{SEO,CC,PFR} + T_{SEO,SC,PFR}$
$T_{SEO,REC}$	Total amount collected by SEO and sent to recycling	856 t	$T_{SEO,REC} = T_{SEO,CC,REC} + T_{SEO,SC,REC}$
$T_{SEO,INC}$	Total amount collected by SEO and incinerated	217 t	$T_{SEO,INC} = T_{SEO,CC,INC} + T_{SEO,SC,INC}$
	Circular economy potential		
P_{SC}	Potential of separate collection	12.47 kg/an/inh	(Ewbank, 2017)
$POP_{Br,2014}$	Number of inhabitants in Brussels in 2014	1,175,173 inh	(Hermia, 2015)
P_{PFR}	Potential of reuse	10%	(Ressources and Avis-Opinion, 2015)
D_{L-I}	Potential of deviation of waste from landfill to incineration	50%	(URBANREC, 2017)
C_{SC}	Amount that can be separately collected in total	14,654 t	$C_{SSC} = P_{SC} * POP_{Br,2014} * 10^{-3}$
C_{SC+}	Amount of separate collection to be additionally captured	13,211 t	$C_{SC+} = C_{SC} - C_{SEO,SC}$
C_{PFR}	Amount that can be prepared for reuse	3,770 t	$C_{PFR} = C_T * P_{PFR}$
$T_{REC-PFR}$	Amount that can be redirected from recycling to preparation for reuse	2,782 t	$T_{REC-PFR} = C_{PFR} - (T_{SEO,CC,PFR} + T_{SEO,CC,PFR})$
$T_{INC-REC}$	Amount that can be redirected from incineration to recycling	9,441 t	$T_{INC-REC} = C_{SC} - C_{SEO,SC} - C_{PFR}$
$P_{PA,SC}$	Proportion of the potential of separate collection captured by PA	90%	Own assumption
$P_{SEO,SC}$	Proportion of the potential of separate collection captured by SEO	10%	Own assumption
	Scenario 1		
$C_{SEO,CC1}$	Amount collected in classical collection by SEOs	206 t	$C_{SEO,CC1} = C_{SEO,CC}$
$C_{SEO,CD1}$	Amount collected at SEO centres by citizen deposit	412 t	$C_{SEO,CD1} = C_{SEO,CD}$
$C_{SEO,SC1}$	Amount collected in separate collection by SEOs	1,443 t	$C_{SEO,SC1} = C_{SEO,SC}$
$C_{PA,CC1}$	Amount collected in classical collection by public actors (PA)	15,318 t	$C_{PA,CC1} = C_{PA,CC}$
$C_{PA,CD1}$	Amount collected at civic amenity sites (CAS) by citizen deposit	20,324 t	$C_{PA,CD1} = C_{PA,CD}$
$C_{SEO,CCT1}$	Total amount of classical collection and collection at SEO centres by citizen deposit	619 t	$C_{SEO,CCT1} = C_{SEO,CCT}$
$T_{SEO,CC,PFR1}$	Amount collected (classical collection + citizen deposit) by SEO and prepared for reuse	62 t	$T_{SEO,CC,PFR1} = T_{SEO,CC,PFR}$

$T_{SEO,SC,PFR1}$	Amount separately collected by SEO and prepared for reuse	3,004 t	$T_{SEO,SC,PFR1} = T_{SEO,SC,PFR} + T_{REC-PFR} * T_{SEO,SC,PFR} * C_{SEO,SC}{}^{-1}$
$T_{SEO,CC,REC1}$	Amount collected (classical collection + citizen deposit) by SEO and sent to recycling	515 t	$T_{SEO,CC,REC1} = T_{SEO,CC,REC}$
$T_{SEO,SC,REC1}$	Amount separately collected by SEO and sent to recycling	1,107 t	$T_{SEO,SC,REC1} = T_{SEO,SC,REC} + T_{REC-PFR} * T_{SEO,SC,REC} * C_{SEO,SC}{}^{-1}$
$T_{SEO,CC,INC1}$	Amount collected (classical collection + citizen deposit) by SEO and incinerated	42 t	$T_{PA,CC,INC1} = T_{PA,CC,INC}$
$T_{SEO,SC,INC1}$	Amount separately collected by SEO and incinerated	568 t	$T_{PA,SC,INC1} = T_{PA,SC,INC} + T_{REC-PFR} * T_{PA,SC,INC1} * C_{SEO,SC}{}^{-1}$
$T_{PA,REC1}$	Amount collected by PA and sent to recycling	20,256 t	$T_{PA,REC1} = T_{PA,REC} - T_{REC-PFR} + T_{INC-REC}$
$T_{PA,INC1}$	Amount collected by PA and incinerated	12,604 t	$T_{PA,INC1} = T_{PA,INC} - T_{INC-REC} + T_{LAN-INC}$
$T_{PA,LAN1}$	Amount collected by PA and sent landfilled	781 t	$T_{PA,LAN1} = T_{PA,LAN} - T_{LAN-INC}$
$T_{SEO,PFR1}$	Total amount collected by SEO and prepared for reuse, including redirections of waste	3,066 t	$T_{SEO,PFR1} = T_{SEO,CC,PFR1} + T_{SEO,SC,PFR1}$
$T_{SEO,REC1}$	Total amount collected by SEO and sent to recycling	1,622 t	$T_{SEO,REC1} = T_{SEO,CC,REC1} + T_{SEO,SC,REC1}$
$T_{SEO,INC1}$	Total amount collected by SEO and incinerated	610 t	$T_{SEO,INC1} = T_{SEO,CC,INC1} + T_{SEO,SC,INC1}$
	Scenario 2		
$C_{SEO,CC2}$	Amount collected in classical collection by SEOs	206 t	$C_{SEO,CC2} = C_{SEO,CC}$
$C_{SEO,CD2}$	Amount collected at SEO centres by citizen deposit	412 t	$C_{SEO,CD2} = C_{SEO,CD}$
$C_{SEO,SC2}$	Amount collected in separate collection by SEOs	2,764 t	$C_{SEO,SC2} = C_{SEO,SC} + C_{SC+} * P_{SEO,SC}$
$C_{PA,SC2}$	Amount collected in separate collection by PA	11,890 t	$C_{PA,SC2} = C_{SC+} * P_{PA,SC}$
$C_{PA,CC2}$	Amount collected in classical collection by public actors (PA)	16,199 t	$C_{PA,CC2} = C_{PA,CC} - C_{PA,SC2} * C_{PA,CC} * C_{PA}{}^{-1} - C_{SC+} * P_{SEO,SC} * C_{SEO,CC} * C_{SEO,CCT}{}^{-1}$
$C_{PA,CD2}$	Amount collected at civic amenity sites (CAS) by citizen deposit	6,231 t	$C_{PA,CD2} = C_{PA,CD} - C_{PA,SC2} * C_{PA,CD} * C_{PA}{}^{-1} - C_{SC+} * P_{SEO,SC} * C_{SEO,CD} * C_{SEO,CCT}{}^{-1}$
C_{SEO2}	Total amount collected by SEOs	3,383 t	$C_{SEO2} = C_{SEO,CC2} + C_{SEO,CD2} + C_{SEO,SC2}$
C_{PA2}	Total amount collected by PA	34,321 t	$C_{PA2} = C_{PA,SC2} + C_{PA,CC2} + C_{PA,CD2}$
$T_{SEO,CC,PFR2}$	Amount collected (classical collection + citizen deposit) by SEO and prepared for reuse	62 t	$T_{SEO,CC,PFR2} = T_{SEO,CC,PFR}$
$T_{SEO,SC,PFR2}$	Amount separately collected by SEO and prepared for reuse	9,408 t	$T_{SEO,SC,PFR2} = T_{SEO,SC,PFR} + C_{PA,SC2} * T_{SEO,SC,PFR} * C_{SEO,SC}{}^{-1}$
$T_{SEO,CC,REC2}$	Amount collected (classical collection + citizen deposit) by SEO and sent to recycling	515 t	$T_{SEO,CC,REC2} = T_{SEO,CC,REC}$
$T_{SEO,SC,REC2}$	Amount separately collected by SEO and sent to recycling	3,467 t	$T_{SEO,SC,REC2} = T_{SEO,SC,REC} + C_{PA,SC2} * T_{SEO,SC,REC} * C_{SEO,SC}{}^{-1}$
$T_{SEO,CC,INC2}$	Amount collected (classical collection + citizen deposit) by SEO and incinerated	42 t	$T_{PA,CC,INC2} = T_{PA,CC,INC}$
$T_{SEO,SC,INC2}$	Amount separately collected by SEO and incinerated	1,779 t	$T_{PA,SC,INC2} = T_{PA,SC,INC} + C_{PA,SC2} * T_{SEO,SC,INC} * C_{SEO,SC}{}^{-1}$
$T_{PA,REC2}$	Amount collected by PA and sent to recycling	13,827 t	$T_{PA,REC2} = \left(C_{PA,CC2} + C_{PA,CD2}\right) * T_{PA,REC1} * \left(T_{PA,REC1} + T_{PA,INC1} + T_{PA,LAN1}\right)^{-1}$
$T_{PA,INC2}$	Amount collected by PA and incinerated	8,604 t	$T_{PA,INC2} = \left(C_{PA,CC2} + C_{PA,CD2}\right) * T_{PA,INC1} * \left(T_{PA,REC1} + T_{PA,INC1} + T_{PA,LAN1}\right)^{-1}$
$T_{PA,LAN2}$	Amount collected by PA and sent landfilled	570 t	$T_{PA,LAN2} = \left(C_{PA,CC2} + C_{PA,CD2}\right) * T_{PA,LAN1} * \left(T_{PA,REC1} + T_{PA,INC1} + T_{PA,LAN1}\right)^{-1}$
$T_{SEO,PFR2}$	Total amount collected by SEO and prepared for reuse, including redirections of waste	9,470 t	$T_{SEO,PFR2} = T_{SEO,CC,PFR2} + T_{SEO,SC,PFR2}$
$T_{SEO,REC2}$	Total amount collected by SEO and sent to recycling	3,982 t	$T_{SEO,REC2} = T_{SEO,CC,REC2} + T_{SEO,SC,REC2}$
$T_{SEO,INC2}$	Total amount collected by SEO and incinerated	1,821 t	$T_{SEO,INC2} = T_{SEO,CC,INC2} + T_{SEO,SC,INC2}$