Waste Management 114 (2020) 331–340

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies

L. Rigamonti [a,*], S.E. Taelman [b], S. Huysveld [b], S. Sfez [b], K. Ragaert [c], J. Dewulf [b,d]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b] Ghent University, Green Chemistry and Technology, Coupure Links 653, 9000 Ghent, Belgium
[c] Ghent University, Centre for Polymer and Material Technologies, Department of Materials, Textiles and Chemical Engineering, Technologiepark 130, 9052 Zwijnaarde, Belgium
[d] ETH Zürich, Department of Civil, Environmental and Geomatic Engineering, Institute of Science, Technology and Policy, Hauptgebäude Rämistrasse 101, 8092 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 21 November 2019
Revised 7 July 2020
Accepted 7 July 2020

Keywords:
Secondary resources
Substitution
LCA
Substitutability coefficient
Waste management
Recycling

ABSTRACT

Life Cycle Assessment (LCA) is a widespread tool used to guide decision-makers towards optimal strategic choices for sustainable growth. A key aspect of LCA studies of waste management systems where recycling activities are present is to account for resource recovery and the related substitution effects. Although multiple scientific papers assume a 1:1 substitution ratio between similar materials/products, this is often incorrect as the actual ratio is likely to vary. The focus of this paper is on the calculation of the substitutability coefficient for secondary materials based on technical characteristics. A state of the art literature review showed that many different calculation procedures were applied, which led to a wide variety of substitutability coefficients (sometimes provided under different terminology). In this perspective, the objective of this paper is to provide guidelines on the procedure to be followed to calculate the substitutability coefficient for secondary materials, based on technical characteristics. These guidelines are then applied to two waste management case studies, one dealing with bottom ashes from incineration and the other with plastic waste. In total, sixteen technical substitutability coefficients are given for ten secondary materials, based on state of the art and presented case studies. The paper thus represents a step forward in quantifying the substitutability of secondary materials in waste management LCA studies. The guidelines presented may allow other case studies to enrich the list of coefficients, useful for all LCA practitioners in a harmonized way allowing a more correct evaluation of the environmental impacts associated with recycling activities.

1. Introduction

1.1. The multi-functionality of waste management processes

The recovery of useful secondary resources (material or energy) has gained much attention lately at European policy level, which has been translated in directives, frameworks, strategies and reports that contribute to developments towards a circular economy and more resource-efficient Europe. A few examples are the ‘Raw Materials Initiative Communication’ (EC, 2011a), the ‘Roadmap to a Resource Efficient Europe’ (EC, 2011b), the ‘Europe 2020 Flagship Initiative on Resource Efficiency’ (e.g. EC, 2017) and the ambitious ‘Circular Economy Action Plan’ (e.g. EC, 2018). In this context, waste management which was dominated from the start by linear thinking needs to be transformed into a circular model of growth, with the challenge of recovering as much resources as possible from the different waste fractions available. As there are many different treatment options nowadays for certain waste flows, each of them producing their own basket of secondary resources or products, it is crucial to understand the environmental consequences of the different options. Therefore, a quantitative assessment of the potential environmental burdens of the diverse waste management processes is needed to develop a more sustainable economy and society. In this context, Life Cycle Assessment (LCA), a tool commonly used to calculate potential environmental burdens of products or services over their full life cycle, is often applied according to the international standards ISO 14,040 and 14044. In spite of the availability of these standards, it is not always straightforward on how to analyse the environmental impact of multi-functional processes, often existing in waste management systems. It is explained that dividing the burden between the product and the co-product(s) can be done on the basis of disaggregation, allocation or system expansion, and that

* Corresponding author.
E-mail address: lucia.rigamonti@polimi.it (L. Rigamonti).

https://doi.org/10.1016/j.wasman.2020.07.015
0956-053X/

the latter is recommended by the ISO standards when disaggregation is not feasible. This is also translated in the many LCA studies regarding waste management found in literature, as reported by Laurent et al. (2014) who performed a review of 222 LCA studies of solid waste management systems. In order to solve multi-functionality issues, system expansion has been applied in about 75% of the reviewed LCA studies, while allocation has been exclusively used in about 4% of them (Laurent et al., 2014). However, Majeau-Bettez et al. (2017) illustrates that there are multiple sub-categories to be distinguished, models that deal with multi-functionality in one way or another. The authors describe 5 different types: partition allocation, lump-sum allocation, classical system expansion, alternative activity allocation and product substitution allocation.

Apart from multiple approaches to deal with multi-functionality in LCA, also two modelling approaches exist: attributional (ALCA) and consequential (CLCA). The former approach describes the environmentally relevant physical flows to and from all processes, in the life cycle of a product, at one specific moment in time and assumes that the system under study does not affect in a significant way the environmental performance of the background system, which supplies the materials and energy inputs. The latter approach describes how environmental flows change in response to a change in the system, assuming that changes in the system under study do have large effects on the background system (van Zanten et al., 2018). In case of a multi-functional process, most LCA studies in literature associate attributional LCA with partition allocation strategies to divide the environmental impact of the process to the various products, while system expansion and product substitution allocation is often associated with consequential LCA. However, we have to bear in mind that this association is an over-simplification and does not reflect the characteristics of ALCA and CLCA (Taelman et al., 2015; Majeau-Bettez et al., 2017).

When the LCA analysist wants to apply the approach called "product substitution allocation", also known as "system expansion with substitution" or "avoided burden method" (EC-JRC, 2010; Finnveden et al., 2009), he/she has to identify and model mono-functional processes external to the system under study, which yield products or functions that are equivalent to those of the co-products of the considered multi-functional process. These inventories are commonly subtracted from the inventory of the original multi-functional process in order to estimate the inventory associated with the co-function of interest (Pelletier et al., 2015). This approach has mostly been used for systems where a co-product can replace one or more other products, e.g. recovery of material or energy from waste (EC-JRC, 2010). However, quantifying the extent to which products are functionally equivalent and intersubstitutable is a difficult task. Though, it is important to fairly quantify the comparability of (co–)products as it might influence the interpretation of the LCA results to a great extent.

1.2. The substitutability of recycled materials: Calculation approaches

As energy produced from waste streams can be substituted by comparable energy sources on a 1-to-1 energetic basis, it is less obvious for secondary materials. When the LCA practitioner has identified the actual replaced products by e.g. market analysis, the quantification of the amount of the replaced product needs to be done bearing in mind that the recycled material might be subjected to a decrease in quality ('downcycling'). This may happen due to a number of reasons, such as the worsening of mechanical characteristics during recycling, the cross-contamination with other materials during collection and sorting, or the build-up of chemicals used at the materials production stage (Rigamonti et al., 2018; Hahladakis and Iacovidou, 2018). It is also possible, but less likely, that the recycled material is used in a way it is of more value than the virgin material (e.g. by replacing a highly polluted material, by giving it a better purpose) (Huysman et al., 2017).

Despite such concerns, in the modelling of recycling, the vast majority of waste management LCA studies have so far assumed that one unit of recycled material substitutes for one unit of virgin material (Gala et al., 2015; Geyer et al., 2015; Yang, 2016; Viau et al., 2020). This might imply an over- or underestimation of the real benefit of the recycling activities (in case of downcycling or upcycling, respectively), potentially leading to wrong conclusions and recommendations (Rigamonti et al., 2009; Lazarevic et al., 2010; van der Harst et al., 2016; Faraca et al., 2019).

In the End-of-Life (EoL) formula (now Circular Footprint Formula) included in the Product Environmental Footprint (PEF) Guide (EC, 2013), a ratio between the quality of the secondary material (Q_S) and the quality of the primary material (Q_P) has been introduced. The *quality ratios* shall be determined at the point of substitution and per application or material. Moreover, their quantification shall be based on economic aspects (i.e. price ratio of secondary compared to primary materials at the point of substitution) or on physical aspects when economic aspects are less relevant. Unfortunately, for this last case, no further indications are given. Although economic parameters such as market prices are proposed by a few authors to assess quality (authors cited in Vadenbo et al., 2016; EC-JRC, 2012; Villalba et al., 2002; Schrijvers et al., 2016b; Zink et al., 2015; Yang, 2016), it should be noted that the use of monetary values has its drawbacks, because of time-dependent fluctuations of the market or when prices are missing or inaccurate. Apart from market-based modelling, also an approach that considers the technical functionality can be followed to calculate substitutability, which represents the relative performance of a recovered resource compared to the end-use–specific set of alternative products and which may supply the same required function(s) (Vadenbo et al., 2016). More in detail, Vadenbo et al. propose a framework to calculate the substitution potential where *substitutability* $\alpha^{rec:disp}$, which is used to designate the degree of functional equivalence between recovered (rec) resources and displaced (disp) alternative resources/products for a specific end use, is determined based on technical functionality and can include additional constraints. The theoretically (from a technical point of view) achievable functionality may in fact be restricted by regulations and/or end user's perception. Physical parameters are independent from changes in the economy, however, they are more rarely applied as is it difficult to determine waste-type specific quality factors based on one or multiple physical parameters relevant in the determination of the functionality (Huysman et al., 2017).

1.3. Technical substitutability coefficients for materials in LCA: state-of-the art

Few authors have attempted to account for a quality factor to deal with substitutability based on technical characteristics, which is different from the 1:1 substitution ratio. For example, Gala et al. (2015) introduced a *quality factor* Q to consider the deterioration of the inherent properties of the materials undergoing the recycling process: they calculated it for paper (Q = 0.83 based on the tensile strength indicator) and HDPE (Q≈0.75, as obtained through laboratory tests). Rigamonti et al. (2009, 2010) used a coefficient called *substitution ratio*. In particular, the well-known concept of a maximum number of cycles that can be afforded by cellulose fibres was applied to paper, for which a substitution ratio equal to 0.83 was calculated. The different mechanical properties (in particular the modulus of elasticity and the longitudinal bending strength) of secondary particle board compared to virgin plywood were instead applied to wood, resulting in a substitution ratio equal to 0.6 (based on volume). The concept of the maximum number of cycles was also applied by Pires et al. (2011) to calculate the *substitution ratio* of multi-layer packaging materials from recycled Polyethylene Terephthalate (PET) used in substitution of a multi-layer packaging from virgin PET: it resulted in a ratio of 0.625. Beigbeder et al. (2013) evaluated the *substitution ratio* for an LCA of recycling of plastics from waste electrical and electronic equipment (WEEE) sorted by near infrared (NIR) automating technology based on tensile tests and impact tests. They concluded that the substitution ratio of the recycled high-impact polystyrene (HIPS) sorted by NIR automating technology can be assumed to be 1 as the recycled HIPS presents mechanical properties very close to virgin one. For acrylonitrile–butadienestyrene (ABS) and ABS/polycarbonate blend (ABS/PC), complementary studies should be carried out to evaluate it accurately. However, substitution ratios should be close to 1 for these polymers as well, because of the low degradation of mechanical properties.

More recently, Schrijvers et al. (2016a) stated that down-cycling can be incorporated by combining the end-of-life recycling rate with a *quality-correction factor* that represents to what extent the inherent properties of the material are lost, using the limiting factor as quality parameter, but no examples are given. Huysman et al. (2017) developed a *quality factor* for plastic waste based on the compatibility between the composing polymers in a mix (the interfacial tension is the only considered physical parameter). The factor has mainly a classification function, i.e. it identifies the most suitable waste treatment option according to the quality of the stream. To account for the difference in recycled versus virgin plastic material needed for an injection moulding application, Huysveld et al. (2019) calculated a *substitution ratio* based on the density difference between both materials. The recycled plastic material, which consisted of a mix of mainly PET, Polypropylene (PP), Polyvinylchloride (PVC) and Polystyrene (PS), had a higher density compared to the virgin material (PP) used for the application. This resulted in a substitution ratio of 0.69. Maga et al. (2019) performed an LCA for different recycling technologies for post-industrial and post-consumer polylactic acid (PLA) waste in Germany. The authors stated that the generated recycled PLA demonstrates a lower quality than virgin PLA-products and they calculated a *correction factor* based on the technical properties tensile strength and molecular weight. In particular, in case of mechanical recycling of PLA waste from lightweight packaging the correction factor represents a price adjusted value by reduction in tensile strength (10%) compared to recyclate from the scenario of mechanical recycling of post-industrial PLA: its value is 51% (that means that 1 kg of recyclate substitutes 0.49 kg of virgin PLA). In case of solvent-based recycling of PLA waste from lightweight packaging the correction factor was calculated based on the loss of molecular weight compared to virgin material and resulted in 15% (i.e. 1 kg of recyclate substitutes 0.85 kg of virgin PLA). Civancik-Uslu et al. (2019) analysed the replacement of eucalyptus wood sheets, which are used to separate loaded pallets to prevent damaging each other during top storage, by plastic compound alternatives composed of virgin PP, recycled PP and mineral fillers. In the modelling, they used a *Q factor* based on the mechanical properties of virgin and recycled materials. More in detail, as the flexural modulus is the most important technical property of the material in the case of plastic sheet application, the calculation of the Q factor is based on this. They measured a flexural modulus of recycled PP as 1005 MPa whereas, according to their market search, they assumed a flexural modulus of virgin PP equal to 1075 MPa: the Q factor was thus estimated as 0.94.

Borghi et al. (2018) introduced three coefficients (Q1, Q2 and M) for the calculation of the amount of natural aggregates displaced by recycled aggregates (RAs) recovered from construction and demolition waste. The Q1 coefficient considers the quality of RAs in terms of "clean composition": if there are impurities such as soil, wood, plastics, etc., Q1 is less than 1. In particular, since the presence of soil in RAs appeared as a limiting factor for the RAs marketability, the assigned value for Q1 was set based on the soil content in RAs and considering the maximum value (15% by mass) set by the Italian legislation. The coefficient Q2 considers the technical characteristics of RAs compared to those of the substituted material in relation to the specific application. In particular, when RAs are used in road construction as unbound materials in the embankment body and sub-base layers, Q2 is assumed equal to 1, since the technical characteristics of the RA are fully comparable with those of the natural raw material. When RAs are used for environmental reclamation and fillings, Q2 corresponds to the ratio between the natural raw material and the RA densities. The M coefficient takes into account for the existence of a market for RAs and is defined as the ratio between the amount of RAs sold and produced in the recycling plant in a time period. The *replacement coefficient*, i.e. the coefficient that quantifies the amount of avoided material, is the product of the three coefficients and in the analysed case study resulted in the range 0.58–0.65 depending on the RA considered. Pantini et al. (2018) used a *replacement coefficient* to calculate the amount of virgin hot mix asphalt (HMA) replaced by cold mix asphalt (CMA) produced from reclaimed asphalt pavement (RAP). The coefficient was calculated considering that road constructors usually increase the thickness of the layer made of CMA by 30–50% compared to the typical value required for traditional HMAs due to the different properties (e.g. poor workability) and mechanical performances of the two types of asphalt. The replacement coefficient between the CMA and the virgin HMA resulted in 0.67. Instead, when RAP is used to produce HMA, the technical properties and lifetime of HMAs containing reclaimed asphalt do not change compared with asphalts only containing virgin materials, and so both aggregates and bitumen in RAP can directly replace their equivalent virgin products in the new mixture at a ratio of 1:1 (Pantini et al., 2018).

Table 1 summarises the technical substitutability coefficients already present in literature.

It can be concluded that technical substitutability coefficient calculations have many forms and are done by using different approaches. Harmonization is necessary to make the results of LCA studies more reliable.

1.4. Aim of the paper

The objective of this paper is to steer a more consistent and correct way of calculating the substitutability of secondary materials in waste management LCA studies. This should result in more accurate environmental sustainability assessments of recycling activities. Based on sections 1.2 and 1.3, it becomes clear that multiple approaches are used for the calculation of such substitutability, resulting in different substitutability coefficients. There is a lack of a common procedure to be followed. Therefore, this paper provides guidelines on the calculation of technical substitutability coefficients for LCA waste management studies, based on the learnings from previous studies. Departing from the framework proposed by Vadenbo et al. (2016), the focus in this paper is on the technical functionality of the materials as a basis for calculating the substitution coefficient. This reflects substitutability to a high extend, without restriction by institutions and / or user's perception. The guidelines are put in practice with two real waste management cases (on bottom ashes from incineration and plastics). Both the findings of the case studies, together with the substitutability coefficients based on technical functionality (sometimes indicated with different terminology) already presented in literature, are included in a summarized table. Obviously this list of

Table 1
Substitutability coefficients based on the technical functionality for some secondary materials: the literature source is indicated in the last column.

Secondary material	Application(s)	Substitutable material(s)	Technical propert(y)(ies) considered to calculate the coefficient	Value of the technical substitutability coefficient	Source
Recycled wood from municipal waste collection	Secondary particle board	Virgin plywood	Thickness to have the same modulus of elasticity and longitudinal bending strength	0.6 m^3 virgin plywood / m^3 secondary particle board	Rigamonti et al., 2010
Recycled paper	N.A.	Virgin paper	Tensile strength	0.83 kg virgin paper / kg recycled paper	Gala et al., 2015
Recycled HDPE	N.A.	Virgin HDPE	N.A. (no explanation of the parameters investigated in the laboratory tests)	0.75 kg virgin HDPE / kg recycled HDPE	Gala et al., 2015
Recycled HIPS	N.A.	Virgin HIPS	Tensile strength and impact strength	1 kg virgin HIPS / kg recycled HIPS	Beigbeder et al., 2013
Recycled plastic mix containing mainly PET, PP, PVC and PS	Injection moulding application	Virgin PP	Density	0.69 kg virgin PP / kg recycled plastic mix	Huysveld et al., 2019
Recycled PLA from solvent-based recycling of PLA waste from lightweight packaging	N.A.	Virgin PLA	Loss of molecular weight compared to virgin material	0.85 virgin PLA / kg recycled PLA	Maga et al., 2019
Recycled PP	Plastic sheet application	Virgin PP	Flexural modulus	0.94 virgin PP / kg recycled PP	Civancik-Uslu et al., 2019
Mixed RA from construction and demolition waste	Unbound material in the embankment body and sub-base layers of roads	Natural raw material (i.e. unprocessed material extracted from quarries) (NA)	Presence of impurities and bearing capacity	0.97 kg NA / kg RA	Borghi et al., 2018
Mixed RA from construction and demolition waste	Unbound material in environmental reclamation and filling activities	Natural raw material (i.e. unprocessed material extracted from quarries)	Presence of impurities and density	0.86 kg NA / kg RA	Borghi et al., 2018
Reclaimed asphalt pavement	Cold mix asphalt (CMA)	Virgin hot mix asphalt (HMA)	Thickness of the layer made of CMA compared to the typical value required for traditional HMAs to have the same field performance	0.67 kg virgin HMA / kg recycled CMA	Pantini et al., 2018
Reclaimed asphalt pavement	Hot mix asphalt (HMA)	Virgin hot mix asphalt (HMA)	Field performance and lifetime	1 kg virgin HMA / kg recycled HMA	Pantini et al., 2018

N.A. = not available.

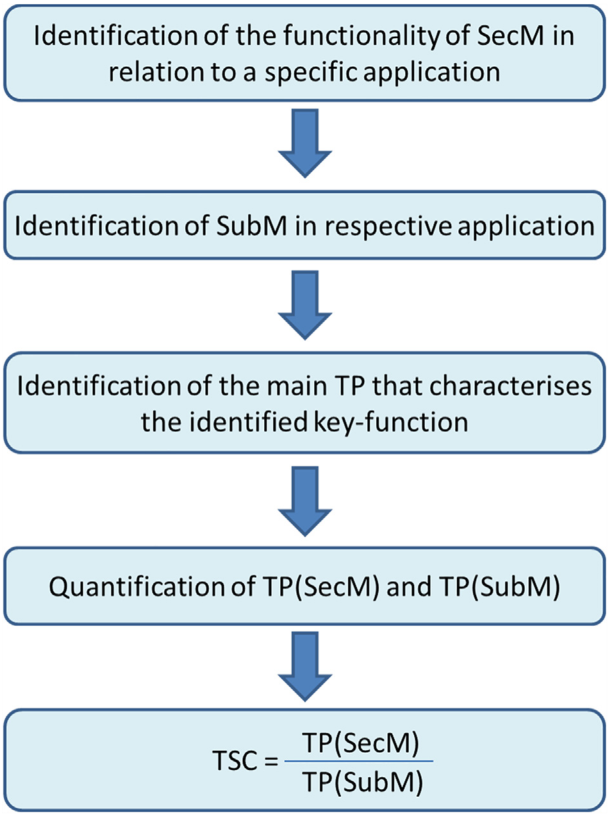

Fig. 1. Proposed procedure to calculate the technical substitutability coefficient TSC (SecM = secondary material; SubM = substitutable material; TP = technical property).

technical substitutability coefficients is not exhaustive but it can be enriched in the future considering the guidelines as proposed in this paper.

2. Material and methods

2.1. Guidelines development

The proposed guidelines are reported in Fig. 1.

The first step consists in the identification of the functionality of the secondary material in relation to a specific application by answering the question: "What is the secondary material (SecM) used for?" The second step is the identification of the substitutable (virgin) material (SubM) in the respective application. The leading question is "What material does the secondary material potentially substitute in that application"?. The following step is the identification of the main technical property (TP) that characterises the identified key-function or that is necessary to fulfil that key-function. The fourth step implies the quantification of this technical property (i.e. technical functionality) both for one unit of the secondary material (TP(SecM)) and one unit of the assumed replaced material (TP(SubM)). Finally, the ratio of the values of the main technical property of the substitutable materials shall be calculated: the resulting value is the technical substitutability coefficient (TSC), as shown in Equation (1):

$$TSC = TP(SecM) / TP(SubM) \tag{1}$$

This procedure will be followed in the two cases studies presented in sub-section 2.2.

2.2. Case studies description

2.2.1. Bottom ashes from incineration of residual household waste

This case study is about the management of municipal solid waste (MSW) from households and small medium enterprises in two neighbouring cities, Ghent and Destelbergen, located in Flanders, Belgium. Through door-to-door collection, the intermunicipal waste management organisation IVAGO collects approximately 29,650 t per year. This waste stream is burned, with energy recuperation, at the incineration plant of IVAGO in Ghent. The incineration process constitutes out of 10 sub-processes, as shown in Fig. 2. First, the collected waste is dumped into a waste bunker (step 1) and mixed by a grapple to obtain a homogeneous input in the feed funnel. The waste is then brought to the furnace (step 2), maintaining a temperature during incineration of approximately 1000 °C for more than two seconds. Fixed carbon and leftovers from the incineration of volatilised components, called bottom ashes (BA), fall by gravity in a water seal where they are cooled down. After incineration of 100 kg residual household waste, 24.5 kg ash stays behind: 20 kg bottom ashes and 4.5 kg flue gas residue and fly ash. The latter fraction is sent to landfill while the bottom ashes contain useful resources. They usually consist out of five different fractions: slag particles, metals, glass residues, ceramics and unburned organic material. According to Rendek et al. (2007), the chemical composition consists mainly out of SiO_2, CaO, Al_2O_3, Fe_2O_3, Na_2O, MgO, total S, total Cl, and unburned

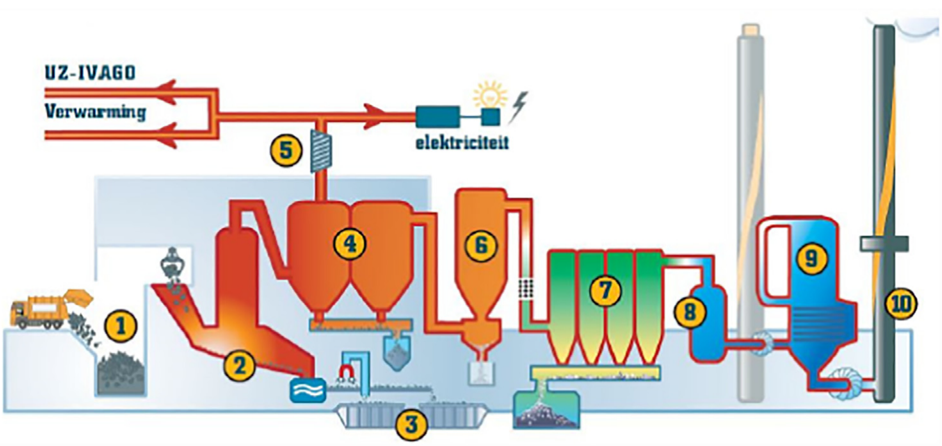

Fig. 2. Scheme of the waste incineration plant at IVAGO (IVAGO, 2008). 1 = waste bunker, 2 = furnace, 3 = separation of ferrous metals from bottom ashes, 4 = boiler, 5 = turbine, 6 = semi-wet washing, 7 = sleeve filters, 8 = wet washing, 9 = DeNOx and 10 = stack.

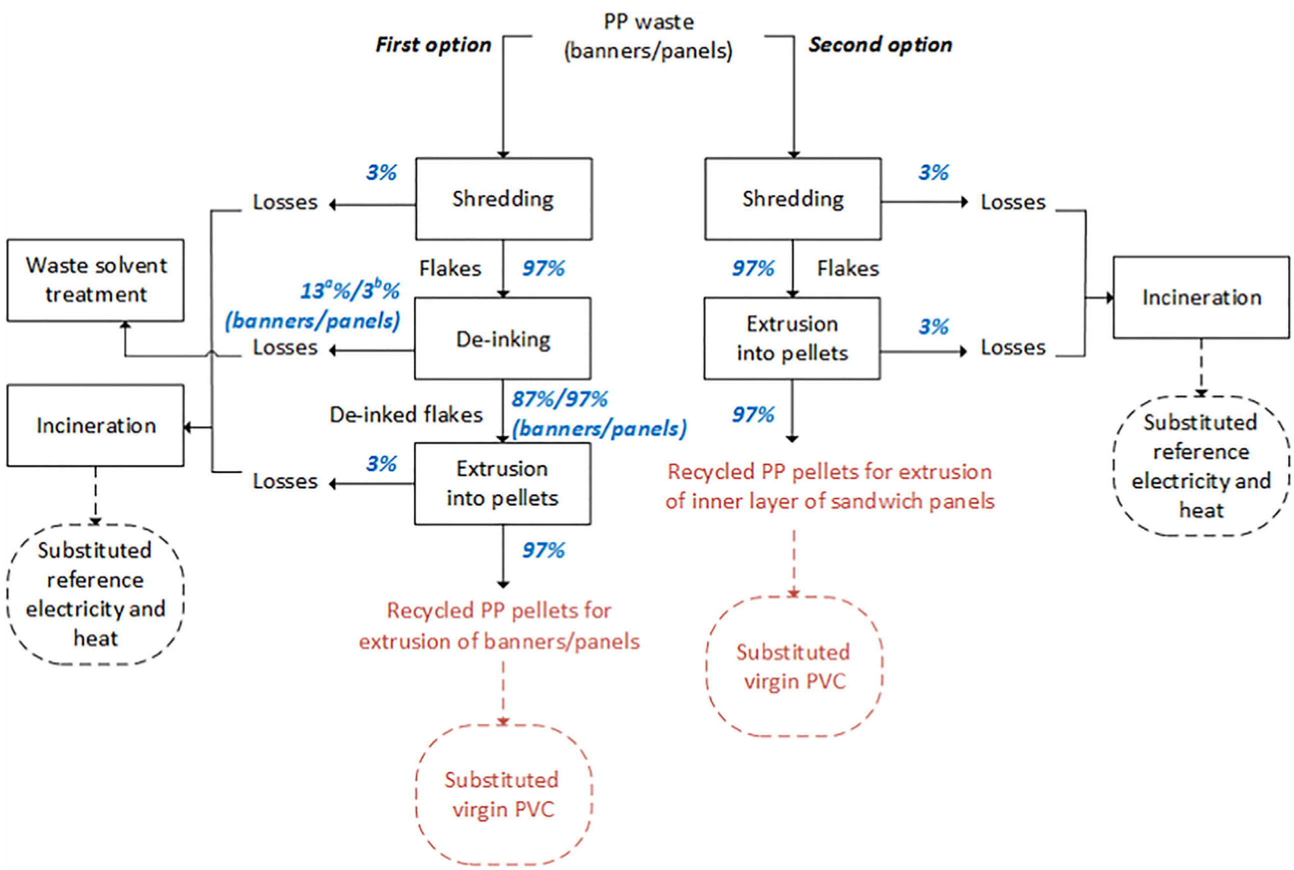

Fig. 3. Overview of the different processes and plastic flows involved in the recycling of PP information carriers. Mass percentages are provided in blue, and substitutable products visualised in a dotted oval. In red, the secondary material and the substitutable material for which the technical substitutability coefficients were calculated. [a]13% = 11% PMMA loss + 2% other material loss, [b]3% = 1% PMMA loss + 2% other material loss.

fixed carbon (measured as Total Organic Carbon or TOC). In this case study, the (precious) metals are extracted from the ashes (step 3) as they are of high (economic) value and can be recycled quite well. The ferrous metals such as steel and iron can be separated easily with magnets, while non-ferrous scrap is separated by eddy-current separators in Valomac in Grimbergen (Belgium) and includes e.g. aluminium and precious metals. More details regarding the processes linked to bottom ash production are shown in Fig. 4.

Flue gases leave the oven and enter the steam boiler (step 4) where heat of the gas is transferred to steam and drives a turbine with heat recuperation (step 5). The turbine produces electricity, which is partly used at IVAGO and the rest is brought to the grid. Steam at a lower temperature serves as heat supply, partly for IVAGO and partly for the Ghent University hospital. The flue gases enter a semi-wet washing stage (step 6) where $Ca(OH)_2$ and activated carbon are injected to turn acids into salts and to catch dioxins and furans respectively. Secondly, the flue gas is cleaned by sleeve filters where remaining dust particles and salts are taken out at this stage (step 7). Thirdly, caustic soda is showered over the flue gases (step 8) to remove metals and non-neutralised acids. Subsequently, flue gases enter a deNOx reactor, which contains a catalyst to reduce NOx and oxidise remaining dioxins and furans. Finally, flue gases leave through the chimney, meeting all legal requirements (Walgraeve, 2016).

2.2.2. Plastic waste from information carriers

Information carriers used at events and inside a company/institute, such as roll-up banners and temporary panels, are typically made from polyvinyl chloride (PVC) because it is a cheap, robust and well printable material (Ragaert et al., 2019). However, at end-of-life these PVC carriers are usually added to mixed waste (low volumes do not warrant any form of separate collection as a mono-stream) and eventually incinerated, because PVC reduces the recyclability of mixed plastic waste (Ragaert et al., 2020). To avoid the incineration of the information carriers after their generally short lifetime, information carriers made from polypropylene (PP) could be used instead, because PP does not reduce the recyclability of mixed plastic waste. Composition analysis of PP carriers available on the market, however, revealed that they were coated with a transparent polymethylmethacrylate (PMMA) top layer to improve printability (Ragaert et al., 2019). The PMMA top layer represented 11% and 1% in terms of mass in case of the PP banners and the PP panels, respectively. The composition analysis also revealed that the PP carriers included talcum and calcium carbonate (together about 10% of the mass), both of which are common and cheap fillers for PP (Ragaert et al., 2019). Ragaert et al. (2019) successfully tested the mechanical recyclability of the PP carriers into new plates for information carriers. Two recycling strategies of PP carriers were investigated and are presented in Fig. 3. The first recycling strategy of the PP carriers included shredding, de-inking, extrusion into pellets and extrusion into newly extruded plates. Once the materials are blended during recycling, PP is expected to become the matrix, in which the immiscible PMMA, talcum and calcium carbonate will be dispersed (Paul, 2009). The second option excluded the effort of de-inking, but then the recycled material could only be used to produce the inner layer of sandwich panels (representing 30% of the total mass). For the

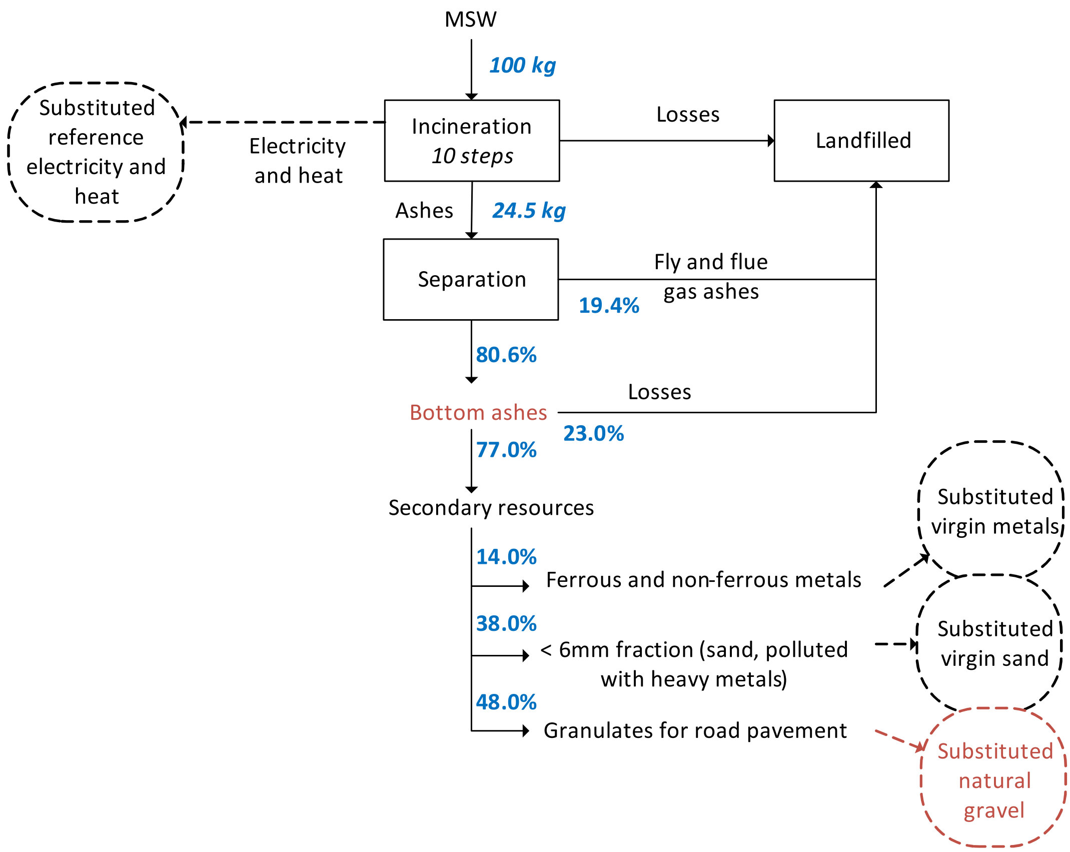

Fig. 4. Overview of the different processes and flows involved in the case study regarding bottom ashes from incineration of municipal solid waste (MSW). Mass percentages are provided in blue, and substitutable products visualised in a dotted oval. In red, the secondary material and the substitutable material for which the technical substitutability coefficient was calculated.

remaining part of these panels still virgin (clean/white) material has to be used. Losses of plastic material should be taken into account in every process step. The amount of lost material was estimated to be 3% in each of the processes of shredding and extrusion. Moreover, the de-inking step caused the removal of the PMMA top layer and a further loss (2%) of the other material (Ragaert et al., 2019). For the losses (except deinking losses going to waste solvent treatment), it can be considered that they go to incineration (with potential recovery of electricity and heat).

3. Results

3.1. Technical substitutability coefficient of the bottom ash case study

About 77% (mass %) of the bottom ash can be used as a secondary resource (covering 48% granulates, 38% sand, 14% non-ferrous and ferrous metals) and 23% is landfilled (filter cake, heavy metals and other residuals) (Indaver, 2017).

As explained in section 2.2.1, both ferrous and non-ferrous metals are recovered. It can be estimated that, on average, 90% (mass-basis) of all metals available in the bottom ashes can be recovered (non-ferrous metals are the most difficult ones to recover). The substitutability of these secondary metals compared to virgin metals depends on their degree of alloy confirmation (Rigamonti et al., 2018), however, as there was no such information available for this particular case study, it was not possible to calculate the substitutability coefficient.

After metal recovery, the ash was sieved to remove all particles with a diameter greater than 50 mm, which are fractured to smaller particles. The fraction of particles between 6 and 50 mm are deemed suitable as road filling material (Youcai, 2017), replacing natural gravel (SubM) (Forteza et al., 2004). A typical road pavement consists of a set of the following layers, from the top driving surface down: wearing course, road base, sub-base and subgrade, of which each layer requires a material with very specific physical and geotechnical properties. According to Izquierdo et al. (2001) and Forteza et al. (2004), the ashes are specifically suitable to be included in the road sub-base layer. The fraction with particles smaller than 6 mm (sand-alike, including still many non-ferrous heavy metals), however, are found unsuitable for road applications as they may end up in leachate (Dierckx et al., 2013), polluting that way the environment (Nielsen et al., 2007). To meet the requirements for replacing natural gravel in road sub-base layers, physical characteristics of bottom ash aggregates such as particle size distribution, compactability, permeability, shear strength, morphology, density, abrasion resistance are important. Indeed, according to Forteza et al. (2004), Becquart et al. (2009), ISWA (2015) and Lynn et al. (2017), the granulates retained after the sieving process (i.e. respecting the technical property particle size distribution so it matches the granulometric curves of natural gravel), meet all those requirements.

A technical substitutability coefficient needs thus to be calculated for bottom ashes (SecM) because a 1:1 substitution on mass basis (as was proposed by e.g. Birgisdottir et al., 2007; Allegrini et al., 2014) is not a fair comparison as only a fraction of the ashes (having a proper particle size) is suitable in sub-base layers. The TSC for bottom ashes is calculated according to Equation (2), based on the mass balance of Fig. 4:

$$\begin{aligned} TSC &= TP(BA) \,/\, TP(NG) = (0.77\ SR/BA \times 0.48\ GR/SR) \,/\, 1 \\ &= 0.37\ \text{kg natural gravel} \,/\, \text{kg BA} \end{aligned} \tag{2}$$

and if we want to consider metal-free bottom ash, the TSC becomes:

Table 2
Overview of the densities of the information carriers. The densities of the recycled PP carriers consider the presence of talcum and calcium carbonate after both options of recycling, while PMMA is also still included after the second option of recycling.

Information carrier	Density (kg/m^3)
PVC banner	1275
PP banner (produced by first option of recycling)	1050
PVC panel	600
PP panel (produced by first option of recycling)	250
inner x-shaped layer of PP panel (produced by second option of recycling)	65

$$\begin{aligned} \mathrm{TSC} &= \mathrm{TP(metal-free\ BA)} \,/\, \mathrm{TP(NG)} \\ &= [(0.77\ \mathrm{SR/BA\ x}\ 0.48\ \mathrm{GR/SR})/(1-0.14\ \mathrm{M})] \,/\, 1 \\ &= 0.42\ \mathrm{kg\ natural\ gravel} \,/\, \mathrm{kg\ metal-free\ BA} \end{aligned} \tag{3}$$

with BA = bottom ashes (SecM), NG = natural gravel (SubM), SR = secondary resources (Fig. 4), GR = granulates (Fig. 4), M = metals (Fig. 4).

One has to bear in mind that the ash composition can differ quite substantially based on the type of waste incinerated. A careful interpretation of the technical substitutability coefficient is therefore needed.

3.2. Technical substitutability coefficients of the plastic waste case study

The purpose of this case study is the comparison of a PP-carrier recycling system with a PVC-carrier non-recycling system. When comparing information carriers made from PVC (SubM) or recycled PP (SecM), the functional unit is the available surface area for printing (for example 1 m2). To obtain 1 m2 with similar functionality, material and geometric characteristics, as well as printability need to be considered. For printability reasons, the use of PP requires the addition of a (transparent) PMMA top layer in both options of recycling, while also an outer (just below the top layer and visible through it) layer of virgin (clean/white) PP has to be added for the sandwich panels in case of the second option of recycling. The need for additional virgin material different from PVC should not be taken into account in the substitutability coefficient for PVC, but the additional virgin material use (PMMA and PP) should be considered when performing an LCA on the final products (banners or panels). The material properties together with the product's geometry determine the product's functional behaviour. Regarding material characteristics, tensile mechanical properties are relevant to consider for information carriers. Based on tensile experiments by Ragaert et al. (2019), tensile mechanical properties such as yield strength and modulus (material properties independent of the product's geometry) of recycled PP (with presence of talcum/calcium carbonate/PMMA) were adequate for functional replacement of PVC in information carriers and, therefore, not selected as the main technical property to calculate the substitutability coefficient for PVC. Regarding geometry of the information carriers, a similar thickness (and thus volume) of the panels is considered in this case study, in accordance with the studied PVC and PP panels in Ragaert et al. (2019). For the banners, the thickness of the studied PP banners was only about half of the thickness of the selected PVC banner. However, based on user experience tests, the thinner PP banners were more easily crinkled, therefore, a similar thickness (and thus volume) was also considered for the banners in order to compare similar functionality. Because there exists a density difference between the PVC and the recycled PP products (Table 2), a similar volume of the products leads to a different mass demand. Therefore, we select density (or the volume for one kg of the materials, cfr. Equation (1)) as the main technical property to calculate the substitutability coefficient for PVC. The density difference between the products is caused by a different density between the materials, i.e. PVC vs. PP (with presence of talcum/calcium carbonate/PMMA), but also by different production methods. The densities of the panels were lower compared to the banners because the PVC panels were made up of foamed flexible PVC and the PP panels were sandwich panels (full outer layers with x-shaped internal space structure).

For banners (first recycling option), the calculated technical substitutability coefficient equals 1.21 kg virgin PVC/kg recycled PP:

$$TSC = TP(SecM)\,/\,TP(SubM) = (1050^{-1}\ \mathrm{m^3/kg\ SecM}) \,/(1275^{-1} m^3/kgSubM) = 1.21\ kgvirginPVC/kgrecycledPP \tag{4}$$

while for panels (first recycling option) the coefficient is 2.40 kg virgin PVC/kg recycled PP:

$$TSC = (250^{-1}\ \mathrm{m^3/kg\ SecM}) \,/\, (600^{-1}\ \mathrm{m^3/kg\ SubM}). \tag{5}$$

For the inner x-shaped layer of the panels in the second recycling option, the coefficient equals 9.23 kg virgin PVC/kg recycled PP:

$$TSC = (65^{-1}\ \mathrm{m^3/kg\ SecM}) \,/\, (600^{-1}\ \mathrm{m^3/kg\ SubM}). \tag{6}$$

The obtained substitutability coefficients are larger than one, showing that less recycled PP mass compared to virgin PVC mass is needed to substitute the corresponding volume of virgin PVC in the information carriers. Note that the product design / production method (for example the PP sandwich panel compared to the foamed PVC panel) has a major influence on the density of the products. A careful interpretation of the substitutability coefficients is therefore needed. Finally, also note that the substitution of virgin PVC with virgin PP would lead to a lower mass needed per surface area.

If we would focus on the replacement of virgin PP, and based on the current knowledge, the substitutability coefficient for virgin PP in case of the first recycling option could be considered equal to 1 as the tensile mechanical properties of the recycled PP are not inferior to the virgin PP (Ragaert et al., 2019). For the second option of recycling (inner x-shaped layer of PP panel), the need for additional virgin PP outer layers should be taken into account, resulting in a substitutability coefficient for virgin PP of 0.28 (calculated based on the mass ratio of recycled PP over virgin PP in sandwich panels). However, more research is needed on the effect of multiple recycling loops. Note that in reality the PP carriers at their end-of-life would most probably be collected as a part of mixed plastic waste, followed by a separation of the PP fraction (including also other products than banners/panels) as a pre-treatment step before recycling. The PP waste that enters the recycling process consists most probably of a combination of virgin PP and already recycled PP. Due to the dilution with virgin PP, the potentially cumulative negative effect of multiple recycling on the tensile mechanical properties of recycled PP is compensated.

4. Discussion

Table 3 summarises the results of the application of the methodology as suggested in section 2.1 in the described case studies (Sections 2.2, 3.1 and 3.2) whereas Table 1 summarises the values of the technical substitutability coefficients already present in literature (Section 1.3). Indeed, these last values were not referred to as technical substitutability coefficient in the original papers, but according to our understanding of the procedure followed in their calculation, we can assume them as such.

Table 3
Substitutability coefficients based on the technical functionality calculated in the waste management case studies presented in this paper.

Secondary material	Application (s)	Substitutable material (s)	Technical propert(y)(ies) considered to calculate the coefficient	Value of the technical substitutability coefficient	Source
Treated BA from MSW incineration	Sub-base road	Natural gravel	Particle size distribution and weighted fractions	0.37 kg natural gravel / kg BA or 0.42 kg natural gravel / kg metal-free BA	Section 3.1
Recycled PP[a]	Extrusion application	Virgin PVC	Density	1.21 kg virgin PVC / kg recycled PP for banners produced by the first option of recycling; 2.40 kg virgin PVC / kg recycled PP for panels produced by the first option of recycling; 9.23 kg virgin PVC / kg recycled PP for the inner x-shaped layer of panels produced by the second option of recycling	Section 3.2

[a] Note that, for printability reasons, in addition to recycled PP, other virgin material is needed to produce the final banners/panels: the addition of a (transparent) PMMA top layer in both options of recycling, while also a middle layer of (clean/white) PP has to be added in case of the second option of recycling.

In total, 16 technical substitutability coefficients are given for 10 secondary materials: recycled wood, recycled paper, recycled HDPE, recycled HIPS, recycled plastic mix, recycled PLA, recycled PP, mixed RA, reclaimed asphalt pavement, and treated BA from MSW. These comprehend most of the materials (e.g. the different polymers) for which the evaluation of the benefits associated with their recycling is usually critical because of the phenomenon of downcycling.

The fact that for some secondary materials more than one coefficient is given underlines the importance to take into account in the calculation of the coefficient both the application in which the secondary material will be used and what the secondary material replaces. In fact, a different application implies a different request in terms of technical characteristics to fulfil that certain function.

The technical properties used in the calculation of the technical substitutability coefficients are different for the different secondary materials even if some are recurring: this is the case of density (used for recycled plastic mix, recycled PP and mixed RA), tensile strength (used for recycled paper and recycled HIPS), and thickness (used for recycled wood and reclaimed asphalt pavement). Other technical properties considered in the calculation are the impact strength, the molecular weight, the flexural modulus, the bearing capacity, and the particle size distribution.

5. Conclusions

The paper has addressed a pending LCA issue regarding the calculation of the substitutability of secondary materials produced by recycling activities. A procedure to be followed by an LCA practitioner (guidelines) has been suggested based on the concept of technical functionality. In total, sixteen technical substitutability coefficients are given for ten secondary materials, including some of the most critical ones due to the phenomenon of downcycling of which they are subjected to during the recycling phases.

The paper represents thus a step forward in quantifying the replacement potential or substitutability of secondary materials in waste management LCA studies. Other case studies can follow the guidelines and may calculate other technical substitutability coefficients for secondary materials not tackled yet or for the same materials as presented here but having another application. The enriched list of coefficients could therefore be used by all LCA practitioners in a harmonized way when they apply the system expansion with substitution approach in assessing the impacts associated with recycling activities. This would allow to have more correct conclusions than when the LCA study is conducted with the assumption of a full replacement (1 : 1) by secondary materials.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Acknowledgement

The authors would like to thank the persons involved in data collection for the waste management case study of municipal solid waste, in particular Tom Claeys (IVAGO, Belgium) and Alderik Scheirlinckx (former master thesis student Ghent university 2017-2018). Also, regarding the plastic waste case study, the authors would like to acknowledge the support of Sara Hubo (Ghent University), Karakters, Stad Gent and Mr. David van der Ha at the UGent Sustainability office, as well as master student Sam Destoop for his experimental work.

Funding

This research was partly funded by (i) the REPAiR project (ID 688920) under H2020-EU.3.5.4.—Enabling the transition towards a green economy and society through eco-innovation, WASTE-6b-2015—Eco-innovative strategies (Sue Ellen Taelman) and (ii) OVAM-Vlaanderen Circulair within the ReDESign project (Sophie Huysveld and Sophie Sfez).

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