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Calculating the pre-consumer waste footprint: A screening study of 10 selected products

Rafael Laurenti, Åsa Moberg and Åsa Stenmarck

Abstract
Knowledge about the total waste generated by the production of consumer goods can help raise awareness among policy-makers, producers and consumers of the benefits of closing loops in a future circular economy, avoiding unnecessary production and production steps and associated generation of large amounts of waste. In strict life cycle assessment practice, information on waste outputs from intermediate industrial processes of material and energy transformation is translated into and declared as potential environmental impacts, which are often not reported in the final results. In this study, a procedure to extract available intermediate data and perform a systematic pre-consumer waste footprint analysis was developed. The pre-consumer waste footprint concept was tested to analyse 10 generic products, which provided some novel and interesting results for the different product categories and identified a number of challenges that need to be resolved in development of the waste footprint concept. These challenges include standardised data declaration on waste in life cycle assessment, with a separation into waste categories illustrating the implicit environmental and scale of significance of waste types and quantities (e.g. hazardous waste, inert waste, waste for recycling/incineration) and establishment of a common definition of waste throughout sectors and nations.

Keywords
Waste footprint, streamlined life cycle assessment, pre-consumer waste, waste quantification and communication, consumer goods

Introduction

In addition to the waste that results as a product is used and discarded, waste is generated during the production process (i.e. during extracting resources, transporting, producing fuels and electricity, manufacturing, etc.). Although most consumers are aware of the amount of waste they generate themselves, relatively few are aware of the waste generated in the course of producing the goods that they consume. Without adequate tools that can help counteract this low transparency owing to temporal and spatial separation of production, consumption and waste management, there is a risk of awareness remaining low or being based on invalid information. This relevant knowledge is also important in a larger context of policy making, when possibilities for reduction of waste need to be identified and progress measured.

Previous studies have estimated the post-consumer waste footprint (Tsukui et al., 2015) and the pre- and post-consumer waste footprint (Jensen et al., 2013; Knight, 2009) using so-called extended input-output analysis. The results of these types of region- and sector-aggregated analysis are relevant to governments monitoring and evaluating progress of regions and economic sectors overall.

In contrast to preceding efforts, in this study a product-related pre-consumer waste footprint metric based on the life cycle assessment (LCA) method was developed, tested and discussed. This LCA-based waste footprint metric is directed towards policy-makers, product engineers, designers and consumers and aims to improve understanding and awareness about the total waste created during the production of consumer goods.

LCA practice and literature to date extensively discuss and account for various environmental impacts, including global warming, acidification, eutrophication, cumulative energy demand, toxicity and resource depletion (Finnveden et al., 2009). In LCA practice, data about waste/residue outputs, presented in the material balance calculation between elementary inputs from nature and elementary outputs to nature, are aggregated to different environmental impacts, or left out of the assessment step if there are no relevant characterisation factors. Consequently, although life cycle inventory (LCI) accounts for waste outputs, they are often not reported or analysed separately within the assessment or interpretation stages (Suh and Huppes, 2005).

The waste footprint metric proposed here aims to quantify orders of magnitude and define types of waste generated by

IVL Swedish Environmental Research Institute, Stockholm, Sweden

Corresponding author:
Rafael Laurenti, IVL Swedish Environmental Research Institute, Valhallavägen 81, 100 31 Stockholm, Sweden.
Email: rafael.laurenti@ivl.se

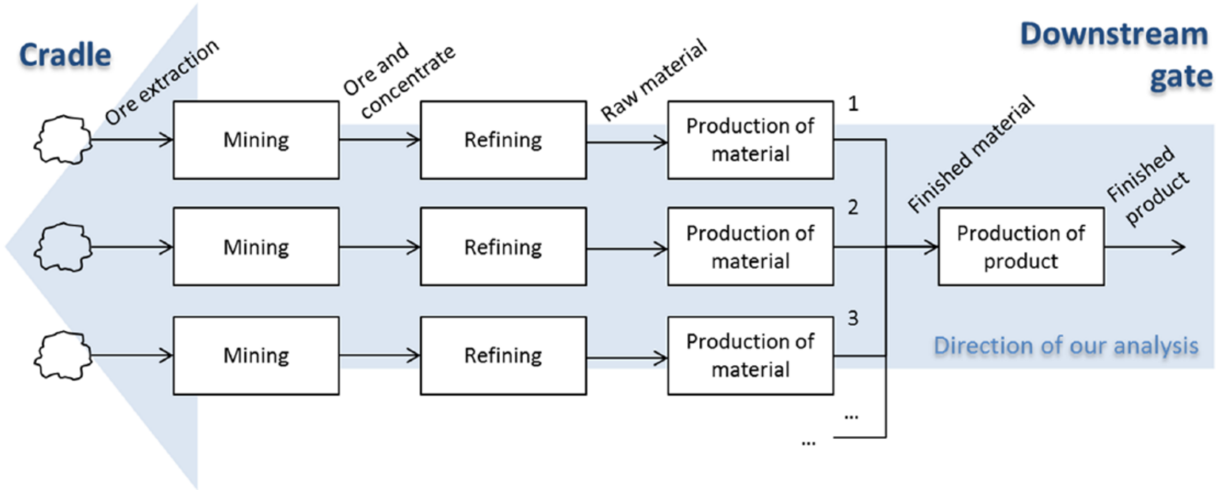


Figure 1. Representation of the cradle-to-gate analysis involved in measuring the waste footprint. Ore extraction on the far left-hand side is a generic name for the processes representing the cradle. The numbers 1, 2, 3 denote the different materials and components that comprise a finished product (first box on the right-hand side). The production of material, refining and mining boxes represent generic transformations to which each finished material that enters the product is subjected.

single products. The study was a first attempt to use available LCA-data for examining quantities, types, sources and reasons of waste generated in the course of producing consumer goods. During development, the method was applied to 10 generic products – chicken, beef, milk, laptop computer, smartphone, pair of trousers, training clothes (T-shirt and shorts), leather shoes, milk carton and newspaper, mainly using data from the commercial LCA database Ecoinvent 3. Although the definition of waste of the EU Waste Framework Directive was adopted for ideally conceptualising the waste footprint metric, the classification of waste in the Ecoinvent 3 database was used in the application to 10 selected products owing to data constraints.

The results clearly present the amount of product-related waste generated during upstream (from the point of consumption) life cycle stages and for detailed waste types, which have not been reported in previous studies using waste input-output analysis. Based on the application and analysis of results, pertinent challenges were perceived, new insights and knowledge were gained and ideas for further development were then formulated.

The pre-consumer waste footprint

Screening LCA

The waste footprint metric is based in life cycle thinking and the data used are LCI data. In a LCA, inputs (resources such as materials, water and energy) and outputs (products, by-products, recyclable material, waste and emissions to air, water and soil) are compiled for each of the relevant processes/activities occurring in the life cycle stages of a product. This LCI phase is carried out based on a predefined functional unit and system boundaries set in the goal and scope definition phase. The results from the LCI are then assigned to potential environmental impacts using so-called characterisation factors in the life cycle impact assessment (LCIA) phase. Throughout the interpretation phase, conclusions and recommendations for improvement actions are formulated based on the findings made in the LCI and LCIA phases and relating to the goal and scope defined (for more information on LCA see for example ISO 2006; Ecoinvent Centre 2014).

The waste footprint metric suggested here can thus be compared with an LCI focusing on waste (i.e. LCI including only waste flows), and the assessment made can be seen as a type of screening LCI in the sense that easily available generic data about the selected products are used.

A cradle to gate analysis

The production of a product obviously starts at its cradle and the materials, undertaking various transformations, eventually reach the factory downstream gate[1] in the form of the product (before being shipped to retailers or consumers). Waste footprint analysis covers the waste arising as the materials and components are extracted, produced and transported. The analysis starts with the product at the factory downstream gate, and materials and components needed for the product are followed upstream, through the intermediate transformations to the cradle/s of the product (i.e. extraction of materials needed to produce the product).

In line with the LCA methodology, a functional unit and the material and component composition should be defined first in a waste footprint study. The total amount of waste generated in the course of producing the product can then be examined from the gate of the selected product to the cradle/s of its materials. Figure 1 illustrates this concept of cradle-to-gate and the direction of analysis.

Guidelines for quantification of waste

The waste footprint as defined here illustrates the waste generated during production of the product. Waste related to the use or

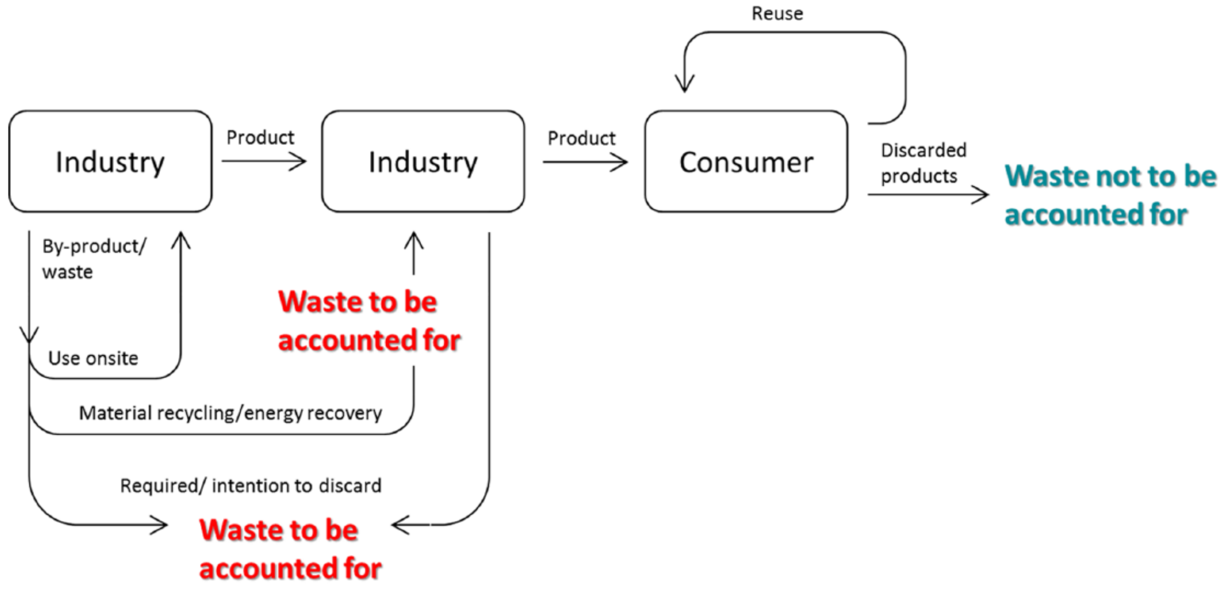


Figure 2. Illustration of flows that should and should not be accounted for in a pre-consumer waste footprint. Diagram based on European Commission Directorate-General (2012).

waste management life cycle stages is not included, for example waste produced in generation of the energy needed in the product use phase is not included, nor is the weight of the product itself once it becomes waste.

In order to interpret and account for all 'waste' in quantification and communication in waste footprint studies, the EU Waste Framework Directive was adopted. It defines waste as a 'substance or object which the holder discards or intends or is required to discard' (The European Parliament the Council of the European Union, 2008). Based on this definition, the following guidelines for the quantification of waste flows were established.

- Material flows specified in the data sources as 'waste' or 'sent to disposal' should be accounted for.
- Materials that are defined as possible to recycle should be accounted for.
- Waste incinerated with and without energy recovery should be accounted for.
- Output material flows from material transformation processes that are recovered onsite should not be accounted for.
- For some materials there is an 'end-of-waste criterion' (materials that are recycled and thus considered a by-product rather than waste), but these should still be accounted for.

All processes in the value chain should be considered, including for example electricity generation and transportation activities. Unlike in the EU Directive, wastewater (e.g. from textile production and leather tanning) should be included in the scope of waste footprint analyses.

Figure 2 illustrates the waste flows that must be accounted for in a pre-consumer waste footprint. The system boundary is set at the industry downstream gate, and thus distribution to retailer or consumer is not covered.

Application to 10 selected products

Steps in application

The main source of data used for the material and component composition and LCI in the screening assessment of the 10 products was the Ecoinvent v3.1 database (Ecoinvent Centre, 2014). When information was not available in the Ecoinvent database, data were collected from technical reports, academic theses and scientific articles (see the references in Table 1, examined later in this article). The GaBi 6 software[2] was used to manipulate, examine and extract data from Ecoinvent datasets and build the waste footprint models.

The Ecoinvent system model 'allocation, cut-off by classification' ('cut-off system model' in short)[3] was used to assemble information about the waste origin. In this model, intermediate exchanges from processes in the database are classified into one of three categories: by-product, recyclable material or waste. For the waste footprint, the resulting waste flows are accounted for. 'Waste' in this classification includes materials with no current economic value and no interest in their collection without compensation. The producer, therefore, generally has to pay to dispose of these materials, for example wastewater and hazardous waste (Ecoinvent Centre, 2014). Thus, the 'waste' accounted for with this definition only comprises waste flows that are disposed of without further treatment (e.g. waste that ends up in landfill or is stored in mining tailing dams) or waste flows for which treatment routes are unknown. This implies that some parts of what would normally be regarded as waste, and thus required to be accounted for in the metric suggested above, were not included in the screening assessment.

Operationalisation of the cradle-to-gate analysis resulted in footprint models containing information about components, material types and quantities of waste being built in the GaBi software for each selected product. This was done in iterative steps as follows.[4]

Table 1. Products studied, functional unit, main parts/materials/processes and source of data.

Consumer good	Functional unit	Parts/materials/processes	Dataset in GaBi/reference used (at downstream gate)[6]
Chicken	1 kg of boneless chicken meat	Feed production – chicken	Chicken production – Ecoinvent
		Farm management – chicken	
		Slaughterhouse – chicken	(González-García et al., 2014)
Beef	1 kg of boneless beef	Feed production – cow	Cattle for slaughter, live weight to generic market for red meat, live weight – Ecoinvent
		Farm management – cow	
		Slaughterhouse – cow	(Coop, 2013)
Milk	1 kg of fat and protein corrected milk (FPCM) – raw milk from dairy farms	Feed production – dairy cow	Milk production, from cow – Ecoinvent
		Farm management – dairy cow	
Laptop computer	Typical laptop computer from a leading producer, weight 3 kg	Screen	Liquid crystal display, unmounted – Ecoinvent
		Computer housing	Mix of metals (aluminium, chromium, steel and copper) and plastic (polystyrene) – modelled with Ecoinvent datasets
		Hard disk drive	Hard disk drive production, for laptop computer – Ecoinvent
		CD/DVD-Rom drive	Disk drive production, CD/DVD, ROM, for laptop computer – Ecoinvent
		Printed wiring boards	Printed wiring board, mounted mainboard Printed wiring board, surface mounted – Ecoinvent
		Battery unit	Battery production, Li-ion, rechargeable, prismatic – Ecoinvent
		Cables, plugs and adapters	Cable production, network cable – Ecoinvent Plug production, inlet and outlet – Ecoinvent Power adapter production – Ecoinvent
		Laptop computer assembly	Computer production, laptop – Ecoinvent
Mobile phone	Recent (2015 model) smart phone from a leading producer, weight 0.169 g, 5.5 in screen	Phone housing	Mix of metals (aluminium and chromium – modelled with Ecoinvent datasets
		Glass and display	Liquid crystal display production – Ecoinvent
		Circuit boards	Printed wiring board, surface mounted – Ecoinvent
		Plastic parts	Polycarbonate production – Ecoinvent
		Battery unit	Battery production, Li-ion, rechargeable, prismatic – Ecoinvent
		Cables, plugs and adapters	Cable production, network cable – Ecoinvent Plug production, inlet and outlet – Ecoinvent Power adapter production – Ecoinvent
		Mobile phone assembly	Scaled by weight from: liquid crystal display production, minor components, auxiliaries and assembly effort – Ecoinvent

Table 1. (Continued)

Consumer good	Functional unit	Parts/materials/processes	Dataset in GaBi/reference used (at downstream gate)[6]
Pair of cotton trousers	Pair of cotton trousers, weight 450 g	Cotton bales	Cotton fibre (bales after ginning) – CottonInc 2015 database
		Cotton fabric production	Textile production, woven cotton – Ecoinvent
		Metal parts	Modelled as copper using Ecoinvent datasets
		Trouser production	(Strand, 2015)
Training clothes	Polyester sports t-shirt and pair of shorts for training, weight 300 g	PET fibres	Polyethylene production, high density, granulate – Ecoinvent
		Polyester fabric production	Textile production, woven – Ecoinvent
		Clothes production	(Strand, 2015)
Pair of leather shoes	Pair of leather shoes, weight 800 g	Shoe production	(Muñoz, 2013)
		Adhesives and solvents	Acetone production, liquid – Ecoinvent
		Insole – ethylene vinyl acetate (EVA)	Ethylene vinyl acetate copolymer production – Ecoinvent
		Interlining – cotton	Cotton fabric model (same as for 'pair of cotton trousers')
		Laces – polyester	Polyester fabric model (same as for 'training clothes')
		Sole – thermoplastic rubber (TR)	Synthetic rubber production – Ecoinvent
		Upper and lining – cow leather	8% mass allocated from the beef model (same as for 'beef') Tanning – (Black et al., 2013; Joseph and Nithya, 2009)
		Metal parts	Modelled as copper using Ecoinvent datasets
Milk carton	Beverage package weight 39 g, capable of storing 1 L of beverage, made of layers of paperboard and plastic film and with a plastic spout	Packaging production	(ACE, 2011)
		Paperboard	Paper production, recycled – Ecoinvent
		Printing ink	Printing ink production, offset, product in 47.5% solution state – Ecoinvent
		Plastic film (LDPE)	Polyethylene production, low density, granulate – Ecoinvent
		Spout (HDPE)	Polyethylene production, high density, granulate – Ecoinvent
Newspaper	Newspaper made of recycled paper (deinked pulp – DIP), 35 pages, 70 g	Paper production	Paper production, newsprint, recycled – Ecoinvent
		Printing	Offset printing, per kilogram printed paper – Ecoinvent
Electricity – used for all processes listed in the right-hand side row of this table.			EU-27 Electricity grid mix – PE electricity grid mix (deposited goods, excepting overburden)

CD: compact disc; DVD: digital video disc; ROM: read-only memory; PET: polyethylene terephthalate; LDPE: low-density polyethylene; HDPE: high-density polyethylene; PE: polyethylene.

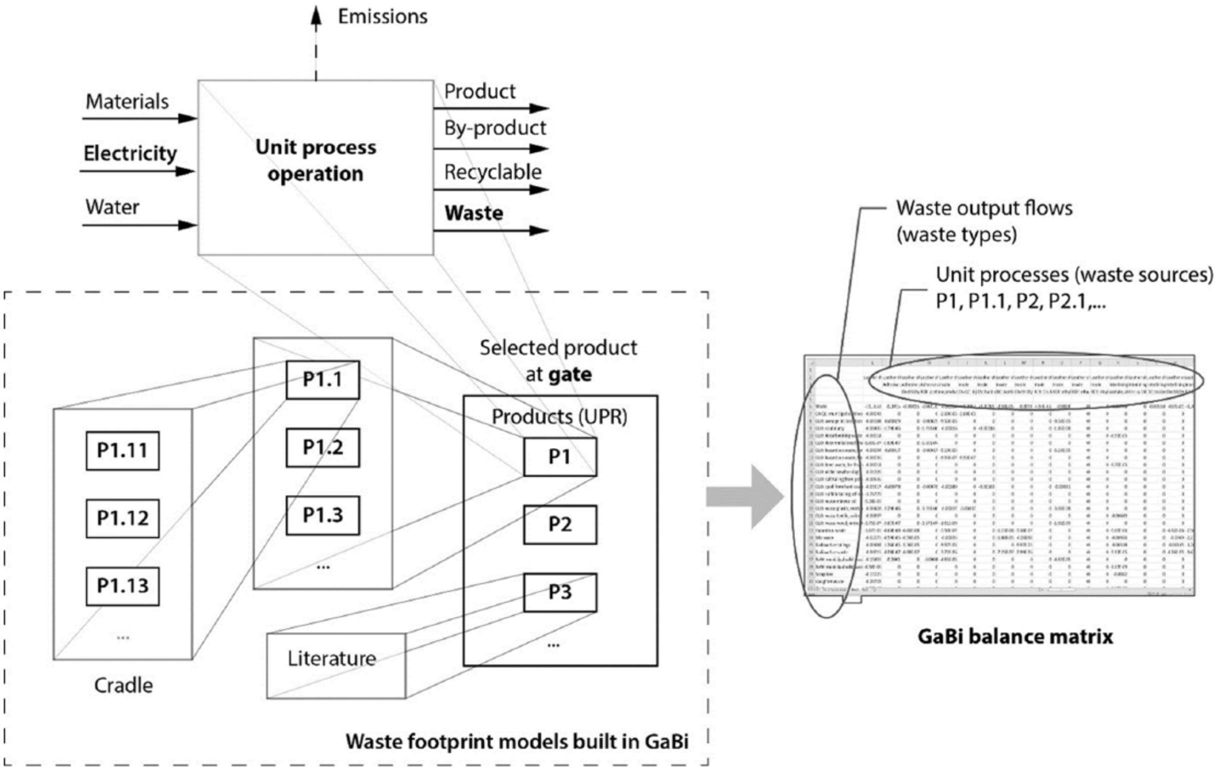


Figure 3. Representation of the inputs and outputs of the processes gathered and iterative steps performed to build the waste footprint models in the GaBi software. For each process, the quantitative amounts of waste were inventoried.
UPR: unit process.

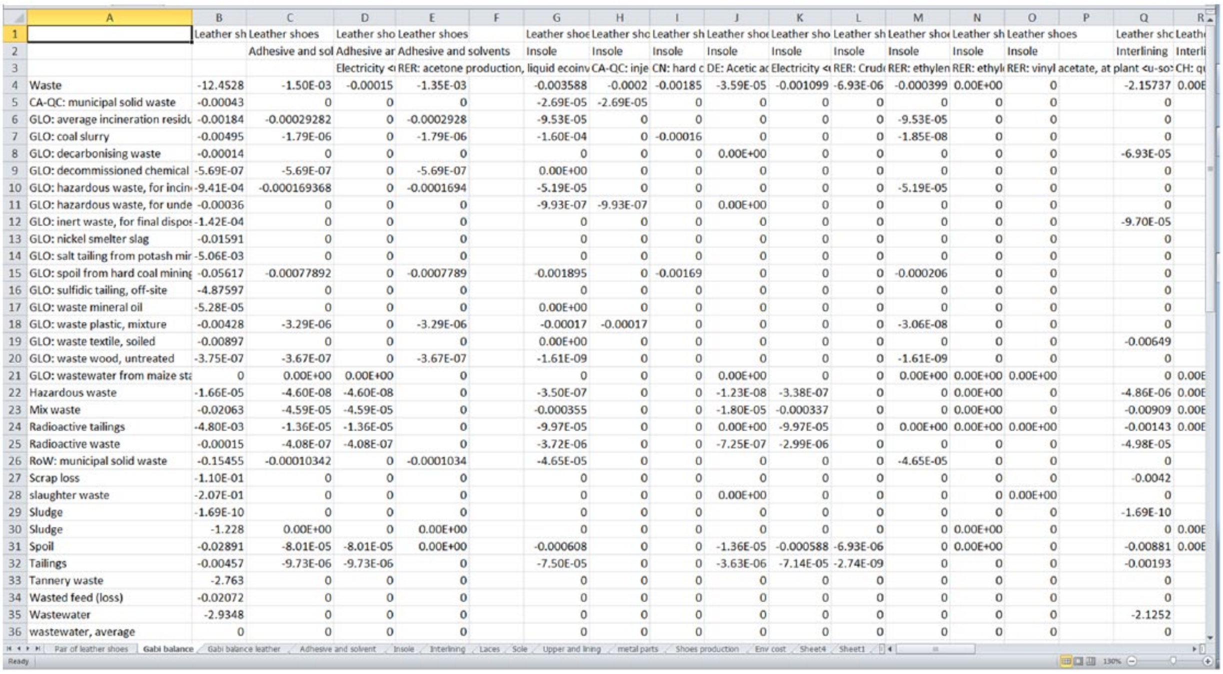
1. The component and material composition was defined by available product declarations or from generic databases (see Supplementary material 1, available online) and related to the functional unit.
2. Datasets were identified for each material and component (P1, P2 and P3 in Figure 3). Data were taken from the Ecoinvent v3.1 database (Ecoinvent Centre, 2014) or, if not available in the database, from technical reports, academic theses and scientific articles. Data on types and quantities of waste flows, material input flows and electricity inputs were collected. The material input flows were handled in order to add the contribution of waste generated upstream in the value chain in the subsequent steps; the waste generated by producing the electricity was integrated in the model. No significant changes in the results (larger than 5%) could be identified when applying a cut-off criterion of 10% of the weight of the material inputs (exclusion of maximum 10% of mass) – see recommendations for sensitivity analysis in ISO (2006).
3. This process of identifying datasets and gathering data was repeated for upstream processes in the value chain until the cradle (P1.1, P1.11, P1.12 and P1.13 in Figure 3).
4. The waste flows were aggregated into total waste from main unit processes, for example for beef these were feed production, farm management and slaughterhouse. Finally, a matrix composed of the waste output flows and each respective process was obtained from the GaBi balance calculation. An example of a GaBi matrix is presented in Figure 4; the raw results (matrices from GaBi) from the application to the 10 products can be seen in the Supplementary material 4, available online.

Study goal and scope

The goal of the screening waste footprint study was to account for the total waste generated to produce a product and investigate intermediate hotspots[5] and types of waste generated. Ten selected products were studied – chicken, beef, milk, laptop computer, smartphone, pair of trousers, training clothes (T-shirt and shorts), leather shoes, milk carton and newspaper. The functional unit, main parts/material/processes and the source of data for each of the products studied are presented in Table 1. Details about the composition of the products and system boundaries description can be found in the Supplementary material 1–4, available online.

Analysis and interpretation

The results of the application are summarised in Figure 5. Among the products analysed, electronic products had the largest waste footprint; beef had a larger footprint than chicken meat; milk had a relatively small waste footprint, but this increased by approximately 10% when the footprint of its carton was added; the waste footprint of clothing was considerable. However, the different waste footprints are not directly comparable, as the types of waste are not the same (see Figures 8–11, detailed later in this article, and Supplementary material 3, available online). Nevertheless, it can be concluded that products with a longer life



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1		Leather sh	Leather shoes	Leather sho	Leather shoes		Leather shoe	Leather sho	Leather sh	Leather shoe	Leather sho	Leather sh	Leather sho	Leather sh	Leather shoes		Leather shc	Leath
2			Adhesive and sol	Adhesive ar	Adhesive and solvents		Insole	Insole	Insole	Insole	Insole	Insole	Insole	Insole	Insole		Interlining	Interli
3				Electricity <	RER: acetone production,		liquid ecoinv	CA-QC: inje	CN: hard c	DE: Acetic ac	Electricity <	RER: Crud	RER: ethylen	RER: ethyl	RER: vinyl acetate, at		plant <u-so	CH: qu
4	Waste	-12.4528	-1.50E-03	-0.00015	-1.35E-03		-0.003588	-0.0002	-0.00185	-3.59E-05	-0.001099	-6.93E-06	-0.000399	0.00E+00	0		-2.15737	0.00E
5	CA-QC: municipal solid waste	-0.00043	0	0	0		-2.69E-05	-2.69E-05	0	0	0	0	0	0	0		0	
6	GLO: average incineration residu	-0.00184	-0.00029282	0	-0.0002928		-9.53E-05	0	0	0	0	0	-9.53E-05	0	0		0	
7	GLO: coal slurry	-0.00495	-1.79E-06	0	-1.79E-06		-1.60E-04	0	-0.00016	0	0	0	-1.85E-08	0	0		0	
8	GLO: decarbonising waste	-0.00014	0	0	0		0	0	0	0.00E+00	0	0	0	0	0		-6.93E-05	
9	GLO: decommissioned chemical	-5.69E-07	-5.69E-07	0	-5.69E-07		0.00E+00	0	0	0	0	0	0	0	0		0	
10	GLO: hazardous waste, for incin	-9.41E-04	-0.000169368	0	-0.0001694		-5.19E-05	0	0	0	0	0	-5.19E-05	0	0		0	
11	GLO: hazardous waste, for unde	-0.00036	0	0	0		-9.93E-07	-9.93E-07	0	0.00E+00	0	0	0	0	0		0	
12	GLO: inert waste, for final dispo	-1.42E-04	0	0	0		0	0	0	0	0	0	0	0	0		-9.70E-05	
13	GLO: nickel smelter slag	-0.01591	0	0	0		0	0	0	0	0	0	0	0	0		0	
14	GLO: salt tailing from potash mir	-5.06E-03	0	0	0		0	0	0	0	0	0	0	0	0		0	
15	GLO: spoil from hard coal mining	-0.05617	-0.00077892	0	-0.0007789		-0.001895	0	-0.00169	0	0	0	-0.000206	0	0		0	
16	GLO: sulfidic tailing, off-site	-4.87597	0	0	0		0	0	0	0	0	0	0	0	0		0	
17	GLO: waste mineral oil	-5.28E-05	0	0	0		0.00E+00	0	0	0	0	0	0	0	0		0	
18	GLO: waste plastic, mixture	-0.00428	-3.29E-06	0	-3.29E-06		-0.00017	-0.00017	0	0	0	0	-3.06E-08	0	0		0	
19	GLO: waste textile, soiled	-0.00897	0	0	0		0.00E+00	0	0	0	0	0	0	0	0		-0.00649	
20	GLO: waste wood, untreated	-3.75E-07	-3.67E-07	0	-3.67E-07		-1.61E-09	0	0	0	0	0	-1.61E-09	0	0		0	
21	GLO: wastewater from maize sta	0	0.00E+00	0.00E+00	0		0	0	0	0.00E+00	0	0	0.00E+00	0.00E+00	0.00E+00		0	0.00E
22	Hazardous waste	-1.66E-05	-4.60E-08	-4.60E-08	0		-3.50E-07	0	0	-1.23E-08	-3.38E-07	0	0	0.00E+00	0		-4.86E-06	0.00E
23	Mix waste	-0.02063	-4.59E-05	-4.59E-05	0		-0.000355	0	0	-1.80E-05	-0.000337	0	0	0.00E+00	0		-0.00909	0.00E
24	Radioactive tailings	-4.80E-03	-1.36E-05	-1.36E-05	0		-9.97E-05	0	0	0.00E+00	-9.97E-05	0	0.00E+00	0.00E+00	0.00E+00		-0.00143	0.00E
25	Radioactive waste	-0.00015	-4.08E-07	-4.08E-07	0		-3.72E-06	0	0	-7.25E-07	-2.99E-06	0	0	0	0		-4.98E-05	
26	RoW: municipal solid waste	-0.15455	-0.00010342	0	-0.0001034		-4.65E-05	0	0	0	0	0	-4.65E-05	0	0		0	
27	Scrap loss	-1.10E-01	0	0	0		0	0	0	0	0	0	0	0	0		-0.0042	
28	slaughter waste	-2.07E-01	0	0	0		0	0	0	0.00E+00	0	0	0	0	0.00E+00		0	
29	Sludge	-1.69E-10	0	0	0		0	0	0	0	0	0	0	0	0		-1.69E-10	
30	Sludge	-1.228	0.00E+00	0	0.00E+00		0	0	0	0	0	0	0	0.00E+00	0		0	0.00E
31	Spoil	-0.02891	-8.01E-05	-8.01E-05	0.00E+00		-0.000608	0	0	-1.36E-05	-0.000588	-6.93E-06	0	0.00E+00	0		-0.00881	0.00E
32	Tailings	-0.00457	-9.73E-06	-9.73E-06	0		-7.50E-05	0	0	-3.63E-06	-7.14E-05	-2.74E-09	0	0	0		-0.00193	
33	Tannery waste	-2.763	0	0	0		0	0	0	0	0	0	0	0	0		0	
34	Wasted feed (loss)	-0.02072	0	0	0		0	0	0	0	0	0	0	0	0		0	
35	Wastewater	-2.9348	0	0	0		0	0	0	0	0	0	0	0	0		-2.1252	
36	wastewater, average	0	0	0	0		0	0	0	0	0	0	0	0	0		0	

Figure 4. Example of a balance matrix of waste types (waste output flows; first column on left) and waste sources (unit processes; top) from the GaBi software.

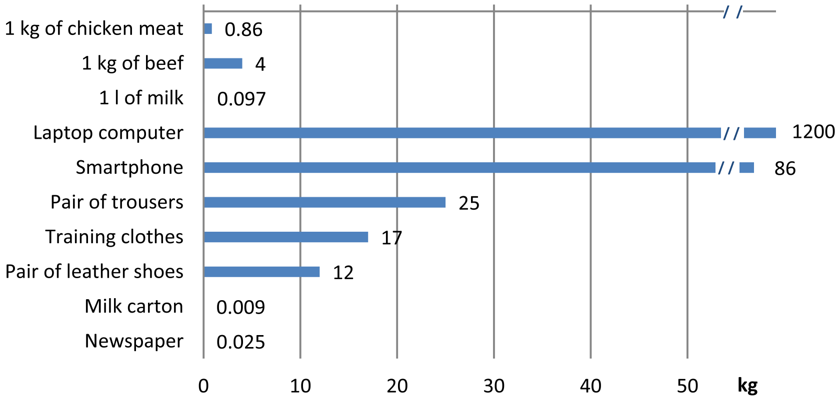


Figure 5. Waste footprint (kilograms) of the 10 consumer goods studied. The bars for the laptop computer and smartphone are not to scale.

have a larger waste footprint than short-life products, and that lighter products have a smaller waste footprint than heavier products, which seems feasible.

The waste footprint analysis indicated that the waste disposed of by consumers is in some cases a small fraction of the total waste generated owing to consumption of a product (Figure 6). Most of the total waste was found to occur upstream from the point of consumption for the beef, electronic products, clothes and shoes. For chicken, the waste amount was similar to the product weight, while for milk, milk carton and newspaper the waste generated in the production chain was actually lower than the weight of the product. It should be noted that in the screening case study using Ecoinvent data, waste for material recycling or incineration with an economic value was not accounted for. Thus the footprints would all be larger if these flows were considered.

Quantities and points of waste generation differed quite radically between the different product groups. This is evident in Figure 7, which shows the percentage contribution of production stages to the waste footprint. For electronic products, for example, the very first production stages of mining and beneficiation were the main sources of large quantities of waste. In contrast, waste from the final production stages were the main contributor to the waste footprint of clothes (wastewater in fabric production) and chicken and beef (slaughterhouse waste). The production of input materials was the largest sources of waste for leather shoes, milk and newspaper. Finally, waste from fuel and electricity production was more significant in the milk carton case.

The profile of types of waste generated during production of the 10 products showed some similarities within the categories of products (meat products, electronics, clothing and footwear and

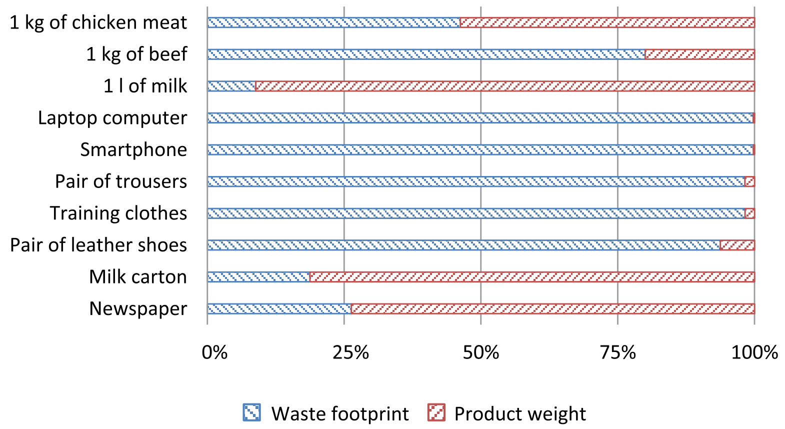


Figure 6. Comparison between the waste footprint (in blue) and the weight (in red) of the 10 consumer goods studied.

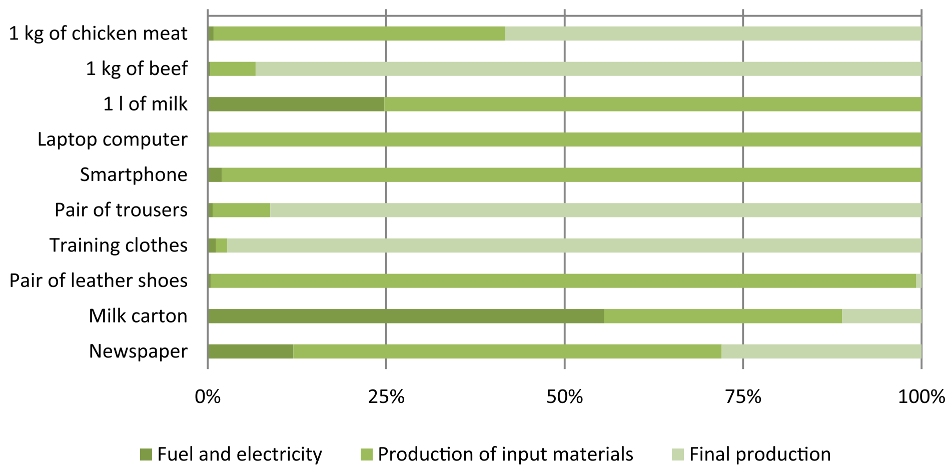


Figure 7. Percentage contribution of production stages to the waste footprint of the 10 consumer goods analysed. 'Final production' represents the company at the top of the supply chain (e.g. the original equipment manufacturer). 'Production of input materials' encompasses the whole supply chain of the materials (i.e. tier 1, 2, 3, etc.). 'Fuel and electricity' are supplied to 'production of input materials' and 'final production'.

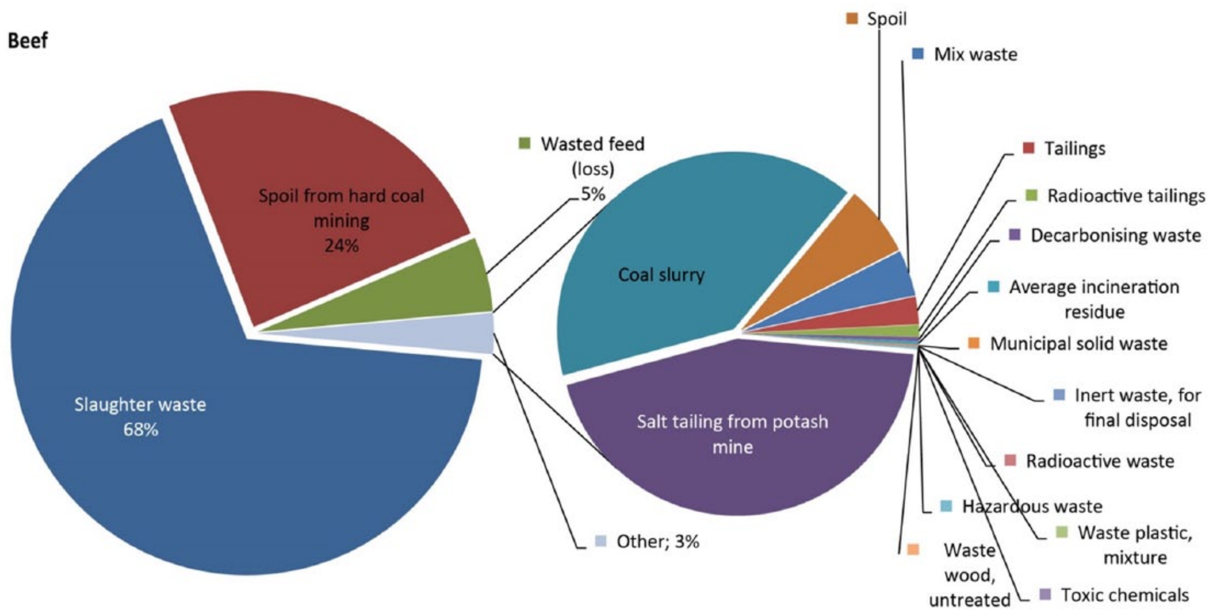


Figure 8. Eighteen types of waste generated from beef production.

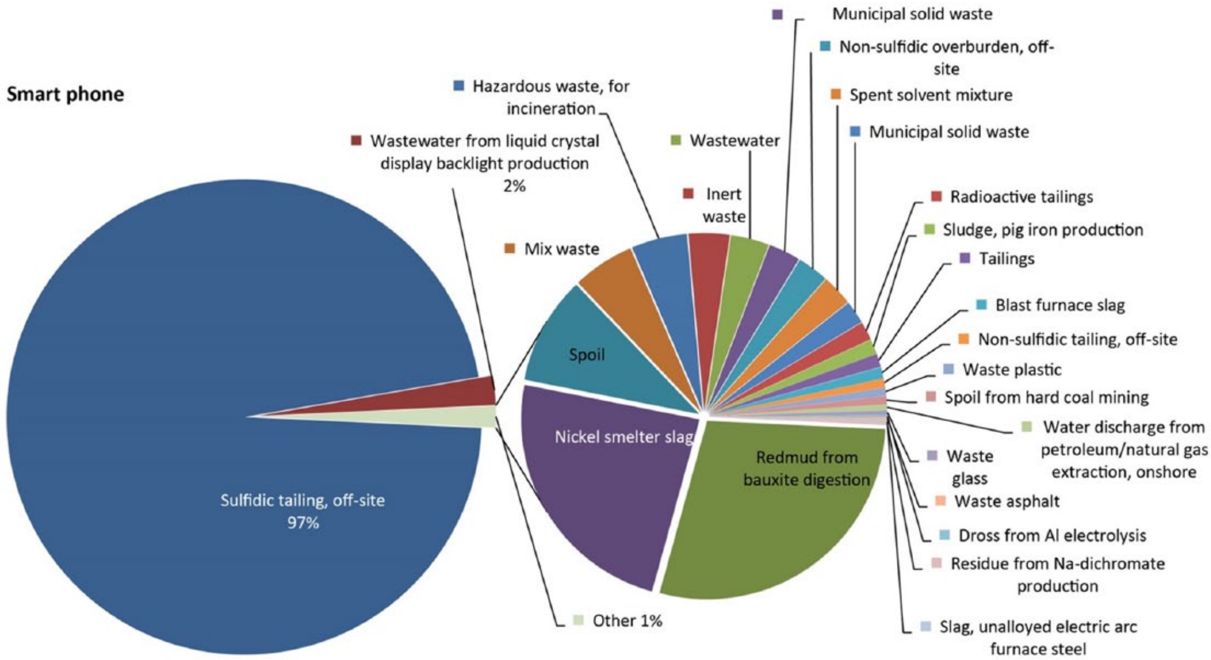


Figure 9. Twenty six types of waste (from a total of 51) generated from smartphone production; cut-off of 0.002%.

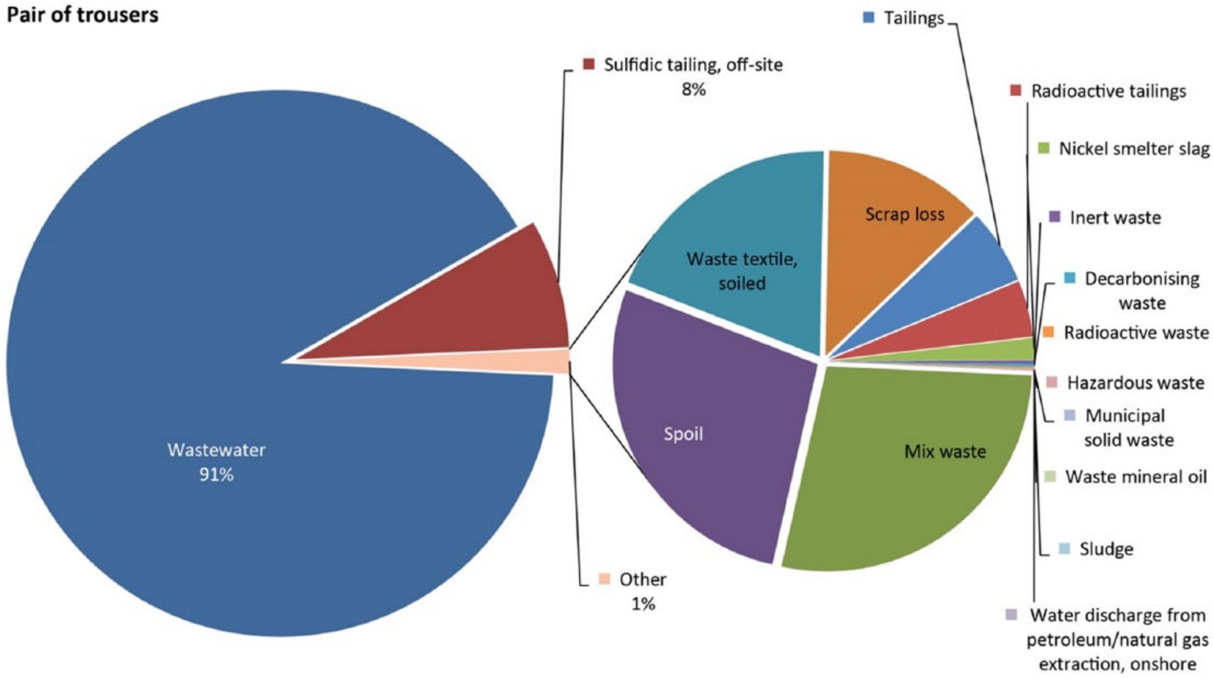


Figure 10. Seventeen types of waste generated from production of a pair of trousers.

paper products). However, this is only an indicative finding, since the results reflect the (secondary) data used and thus need to be confirmed and validated with primary data.[7] For example, 24% of the waste generated to produce beef (Figure 8) was found to be 'spoil from hard coal mining'; this waste fraction was derived from the energy source (coal) cited in reference 'Coop (2013)', which was used to fill in a data gap (slaughterhouse) in the Ecoinvent data (Ecoinvent Centre, 2014) (which is limited to 'cow to slaughter'). Figures 8–11 show the waste types and their corresponding percentages for beef, smartphone, trousers and leather shoes. The charts for all products analysed can be found in Supplementary material 3, available online; the raw results from the application can be seen in the Supplementaty material 4, available online. It is important to stress that Figures 8–11 show the waste footprint profile of the respective products when (mainly) Ecoinvent v3.1 data are used.

The main reason for the waste footprint of beef was the actual slaughter waste, i.e. the parts of the cow that were assumed to be

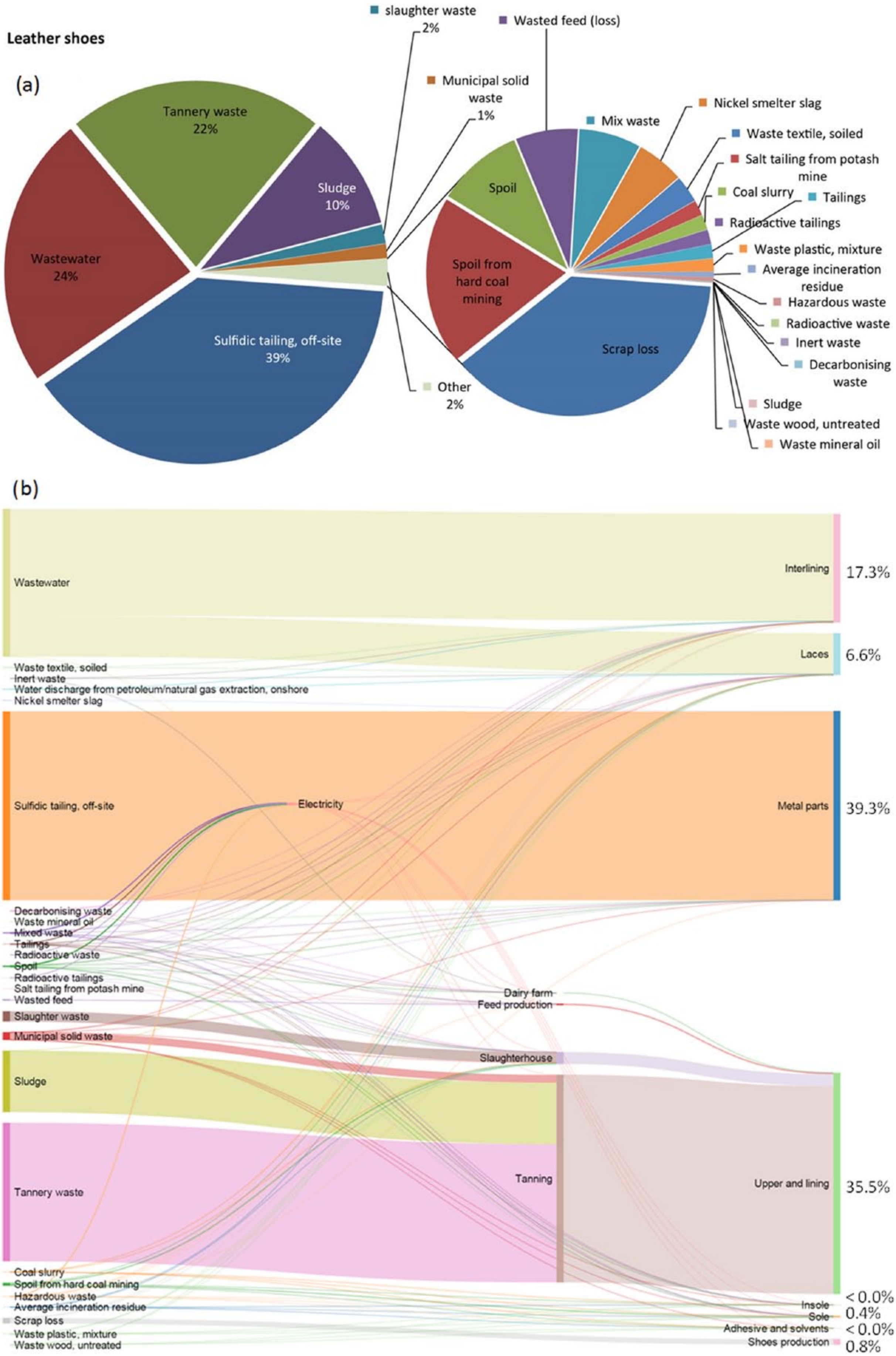


Figure 11. (a) Twenty six types of waste generated from leather shoe production; (b) Sankey diagram illustrating the contribution of waste types to respective fabrication stage and shoe parts.

commonly sent to final disposal without further treatment. For the electronic products, the sulphidic mine tailings (residues from mining activities) were by far the largest part of the waste footprint. For clothes, waste water was the largest category by weight; whereas for shoes, the mining waste relating to metal parts was the largest part of the waste footprint, but waste water was also a major part, together with tannery waste.

When using LCA databases on waste, different methodological choices made in the data sources used may affect the results. One such case is the time boundary used. This is especially relevant when considering mining waste. Furthermore, using secondary data sources and scaling these can be difficult. For example, for the smartphone, the data available in the database refer to a laptop, which has similar components but is not the same size, etc. For a screen, for example, scaling of the data can lead to different results depending on whether it is based on weight or area (Moberg et al., 2014).

As can be seen in Figures 8–11, there are many different waste types for each product and thus there could be potential for improvement of the waste footprint metric. A system enabling the classification of different types of waste could provide more aggregated and clearer results. Moreover, a distinction could be made so that hazardous waste flows of small magnitude are not masked by bulk wastes, which may have a lower overall impact but are generated in much larger quantities. As an example of visualisation of information for aiding designers, Figure 11(b) shows a Sankey diagram that links waste types to respective fabrication stage and mass of the shoe parts.

It should be noted that waste that can be recycled for material or recovered for energy (e.g. manure, etc.) according to the data source was not included in the present waste footprint screening. If such waste had been included, the footprint could have been considerably larger. These categories of waste should also be used in further development of the waste footprint concept, including a defined set of categories.

Discussion

Methodological limitations

There were several obvious limitations in this screening assessment concerning the data, such as availability, reliability, consistency, declaration, format and representation. The following includes some examples.

- The definition of waste of the EU Waste Framework Directive was adopted for conceptualising the waste footprint metric preferably; however, because of limitation of data availability, the classification of waste in the Ecoinvent 3 database was used in the application to 10 selected products.
- Available data represent European average and thus do not reflect any specific case.
- The electricity grid mix used was EU-27. A large part of the waste footprint of many types of consumer goods is generated in producing countries, such as China and India, and the electricity mix in these countries is to a larger degree based on coal, so the figures for waste from electricity production can be expected to be higher than those presented here.
- The amounts of waste accounted here for were based on secondary sources of data and the products studied were generic; thus the quality and completeness of the results are limited to what was declared/accounted for in those data sources. Wide variations exist in real cases.
- The percentage of virgin and recycled material sources in metals was considered according to the Ecoinvent v3.1 datasets (using recycled materials does not lead to the large amounts of mining waste associated with extraction of virgin resources). This percentage may vary between product groups, a difference that was not accounted for in this screening assessment.
- Some materials were accounted for as waste in Ecoinvent, but can be sent to recycling and thus they could have been classified differently. Therefore, a universal definition of waste is necessary to enable fair waste footprint calculations.
- Transportation of materials and products was not included in the present screening assessment because of great uncertainties about actual distances, and thus waste related to fuels for transportation was also not included.

Difficulties in defining and modelling waste

In presenting a waste footprint, a key issue is what to include. This is not straightforward, as the term waste is subjective and frequently debated. What is waste to one actor may be raw material to another. Government organisations and regulators provide legal definitions and guidance for classifying waste. For example, the Statistics Division of the United Nations defines waste as (United Nations, 2000: 227): '[…] materials that are not prime products (that is, products produced for the market) for which the generator has no further use in terms of his/her own purposes of production, transformation or consumption, and of which he/she wants to dispos/e […]'. The EU Waste Framework Directive establishes waste as an object the holder discards, intends to discard or is required to discard (The European Parliament the Council of the European Union, 2008). The Environment Protection Act 1993 of South Australia (EPA, 2013) defines waste as '[…] (a) any discarded, rejected, abandoned, unwanted or surplus matter, whether or not intended for sale or for recycling, reprocessing, recovery or purification by a separate operation from that which produced the matter; or (b) anything declared by regulation (after consultation under section 5A) or by an environment protection policy to be waste'. The general picture is thus that countries around the globe and also each of the European Member States can have a particular interpretation and thus legislation and classification of waste, which can also be sector-specific. The major difference between these definitions concerns what is considered prime product, by-product and waste.

The environmental product declaration (EPD) system[8] has played an emerging and important role for the collection and compilation of LCA and additional relevant environmental performance-related information for environmental labelling. EPDs provide additional information on waste generated along the whole life cycle production chain. The quantities must be declared as non-hazardous, hazardous and radioactive waste and as stated by specific product category rules (EPD Environmental Product Declaration, 2015; The International EPD® System, 2015).

Technically, in a strict LCA perspective, the recommendation by the International Reference Life Cycle Data System (European Commission – Joint Research Centre – Institute for Environment and Sustainability, 2010) specifies that all product and waste inputs and outputs must be completely modelled until the final inventories exclusively show elementary flows. Thus, waste should be further modelled as treated towards ending up as final emissions in incinerators or landfill bodies, if the waste pathway is known (e.g. according to waste directives or industrial practices). Therefore, waste should not be a final output in LCAs.

Environmental and scale of significance – are these implicit in waste types and quantities?

Although an inventory of waste types and quantities, such as the waste footprint performed in this study, does not explicitly convey any indicator of direct or specific environmental relevance (i.e. impacts such as human/terrestrial/aquatic toxicity, resource depletion, etc.), many of the waste types inventoried inherently carry an intrinsic environmental significance, either because of their high toxicity (e.g. radioactive and hazardous waste), or because of their high potential damage and large quantities involved (e.g. mining waste). In this respect, there are several societal goals pointing to decreased amounts of waste, minimisation of hazardous waste, increased recycling, etc., which the waste footprint could support.

Mining waste is a special category. For every metric tonne (mt) of metal ore consumed, at least the same amount of mining waste (i.e. tailings) is generated (Bernd, 2010) (about three dam failures each two years!). Calculations indicate that approximately 15,000–20,000 mt of solid mine waste are produced and stored in dams annually around the world, and there have been over 100 significant upstream tailings dam failures documented in the past 70 years (Bernd, 2010). The most recent occurred in Brazil in November 2015, when a dam burst and released 50 million cubic metres of iron mining waste into one of Brazil's largest rivers outside the Amazon basin. The waste mud was laced with high concentration of heavy metals, including arsenic, copper and mercury. Immediate social and ecological impacts of the unleashed mud were severe and the long-term impacts are unknown. The mud travelled 600 km to reach the Atlantic Ocean, but whether and how such toxic contamination will persist and spread through the food chain is not clear (Escobar, 2015). There are several other environmental aspects related to mining activities, such as land use (change, cultural heritage, etc.), that may be important to address in waste footprint analyses.

Adding an adequate number of waste categories to the waste footprint metric would give a more relevant level of detail and information about the types of waste. Definition of these categories and of whether and what type of waste to recycling/incineration should be accounted for in the metric requires further consideration. These fundamental issues could be addressed by a standard procedure and requirements for quantification and communication of the waste footprint of products.

A useful concept in decision-making context?

Does the lack of possibility to directly compare the waste footprint of different product categories go against to the concept (and utility) of using 'footprints'? Tests of the waste footprint metric on 10 consumer goods revealed that it may not be the best for comparisons between products when only waste quantities are shown (Figure 5) for improved decision making because of obvious reasons of data aggregation. Instead, it can be an effective vehicle of communication with consumers because waste is common to everyone's lives. Furthermore, valuable physical information is maintained in the metric in relation to pressure exerted by industrial and consumption activities, and this is probably the initial purpose of footprint analysis. Despite subjective choices inherent in characterisation factors (e.g. the time horizon determined for global warming potential), in a decision-making context the waste footprint of products may be accompanied by an indicator that characterises emissions (e.g. carbon footprint).

A family of footprint indicators (Lifset, 2014; Ridoutt and Pfister, 2013) with different levels of aggregation, i.e. inventory-orientated footprints and impact-orientated footprints (Fang and Heijungs, 2015), is probably needed in a decision-making context. This is evident when the carbon footprint ($CO2_{eq}$. emissions) is compared with the waste footprint scores. As can be seen in Figure 12, the carbon footprint gave a different picture than the waste footprint (Figure 5). The laptop computer and smartphone again scored highest; but beef and leather shoes appeared in third and fourth position, respectively. Beef also had a much higher carbon footprint than chicken meat. The CO_{2eq}. emissions for producing a pair of (cotton) trousers and (polyester) shorts and t-shirt (training clothes) were quite similar. However, unlike the case for the waste footprint, the carbon footprint of 1 L of milk was much higher than that of the carton.

Concluding, the resulting waste footprint values presented in this article should be viewed as indicative rather than as a definitive picture of reality. This study was a first attempt (screening) to use the pre-consumer waste footprint concept to examine quantities, types, sources and reasons of waste generated in the course of producing consumer goods. However, the waste footprint metric and the results presented above are still a good and important first contribution to increase awareness of pre-consumer waste generation. Of course, being an inventory-oriented footprint analysis, the present study did not

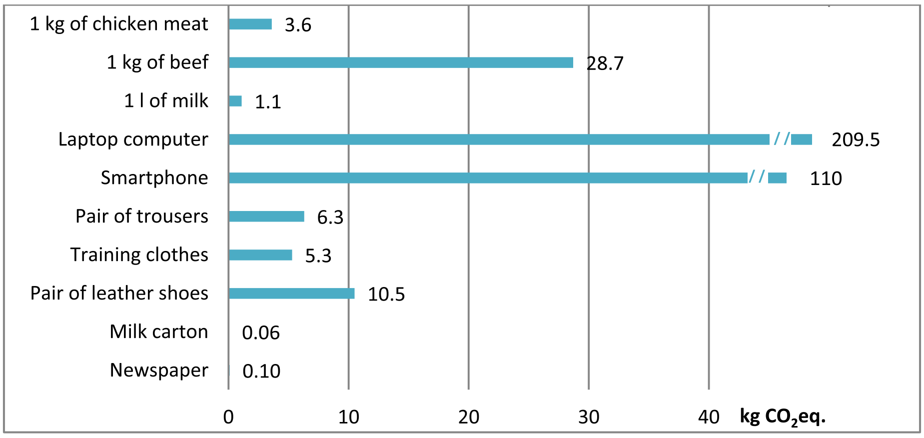


Figure 12. Carbon footprint (kg CO_{2eq}.) of the 10 consumer goods analysed. The bars for laptop computer and smartphone are not to scale.
Sources: Chicken meat and beef (Weidema et al., 2008); laptop computer (Ecoinvent Centre, 2014); smartphone (Apple, 2014); pair of trousers and training clothes (Strand, 2015); pair of leather shoes (Gottfridsson and Zhang, 2015); milk packaging (Jelse et al., 2009); newspaper (Ecoinvent Centre, 2014).

convey the environmental significance as an impact-oriented footprint would have done (for differences between inventory- and impact-oriented footprints, see Fang and Heijungs (2015)). Therefore, other indicators, such as the carbon footprint, should accompany the waste footprint scores in a decision-making context. The concept of a pre-consumer waste footprint may potentially stimulate discussion and generate controversy in the waste and LCA field.

Conclusions and further research needs

A pre-consumer waste footprint metric to account for the waste generated in the course of producing consumer goods was developed in this study. The proposed metric can be an effective vehicle in fostering environmentally preferable producer and consumer practices and communicating to consumers and other actors that the waste discarded by households is only a fraction of the total waste generated to produce the goods consumed.

Several methodological limitations were encountered in developing and testing the waste footprint metric, partly because of the difficulty in defining waste and partly owing to data availability. Significantly, if the legal and financial responsibilities of waste generators are both country- and sector-specific, and if waste-related terms and definitions continue to be dissimilar among industries and among nations, an international standard (resolving these disparities) on principles and procedures for waste declaration in LCA should be developed. This would advance LCA practice regarding waste accounting. Furthermore, sector and country specificities, and how to effectively convey the environmental and scale of significance of inventoried waste, could be addressed using such an international standard. It could also be important in the larger context of the recent action plan for a circular economy suggested by the EU Commission, where the minimisation of waste is the focus and waste needs to be visualised and progress measured.

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Notes

1. The term ‘gate’ refers to a factory gate, that is, a product has been produced and is at the factory gate ready to be transported to retailers/consumers; likewise, the term ‘cradle’ signifies the place where the product started, namely at the extraction site of the raw materials, and in fact there are most often several cradles, as many different raw materials are needed.
2. www.gabi-software.com/.
3. The Ecoinvent 3 database offers three system models to choose from: (1) cut-off system model, (2) APOS (allocation at the point of substitution) system model and (3) consequential system model. For detailed information about each system model, see http://www.ecoinvent.org/database/ecoinvent-version-3/system-models-in-ecoinvent-3/system-models-in-ecoinvent-3.html.
4. Here the Ecoinvent terminology was used. For more information, consult http://ecoinvent.org/.
5. Stages, processes, activities or materials that contribute most to a certain metric, which in our case was waste.
6. Many other datasets upstream towards the material cradles were used in the modelling, but the complexity of these long chains could not be represented here.

7. Primary data refers to that observed or collected directly from first-hand experience; secondary data regards published data and the data collected in the past or other parties.
8. An EPD is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products. This document disclosures a product's life cycle-based environmental impact that has been validated by an independent third party. An EPD reports the results of a product's LCA as well as other information relevant to a product's environmental profile (EPD Environmental Product Declaration, 2015).

Supplementary material

1. Composition of products.
2. System boundaries of the waste footprint analyses.
3. Waste types and percentages.
4. Raw results from GaBi balance.

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