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Deliverable 6.1. Life Cycle Assessment of additives

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Life Cycle Assessment of additives

1. Life Cycle Assessment of additives: an introduction

Additives are substances added to certain materials to provide them with certain properties. Examples are preservatives, flame retardants, colorants, fillers etc. These substances sometimes have toxic properties, leading to risks for health and the environment. During production, use and/or waste management processes, additives may be emitted to the environment. Risk assessment methods can be applied to assess the environmental and health risks of such emissions. These are developed in other Work Packages of the Riskcycle project. This report deals with Life Cycle Assessment methods and studies and the conclusions that can be based on those studies.

1.1 Life Cycle Assessment: the methodology

Life Cycle Assessment, in short LCA, is one of the tools out of the Industrial Ecology toolbox. It describes cradle-to-grave chains of certain products or services. All processes involved in this chain, including mining, production, use and waste treatment processes, are described in physical terms. Of each process, the environmental interventions are specified: the extractions from and emissions to the environment. By combining these processes into a chain, the ecoprofile is established: the total of extractions from and emissions to the environment related to the product or service in question. These emissions then can be translated into contributions to certain environmental impact categories. In this manner, the main points of attention in the chain can be identified, or comparisons can be made between different products fulfilling the same function.

The methodology to conduct LCA studies is standardized by the ISO in the ISO 14040 series (ref). The ISO standard distinguishes four parts within the LCA methodology, as depicted below:

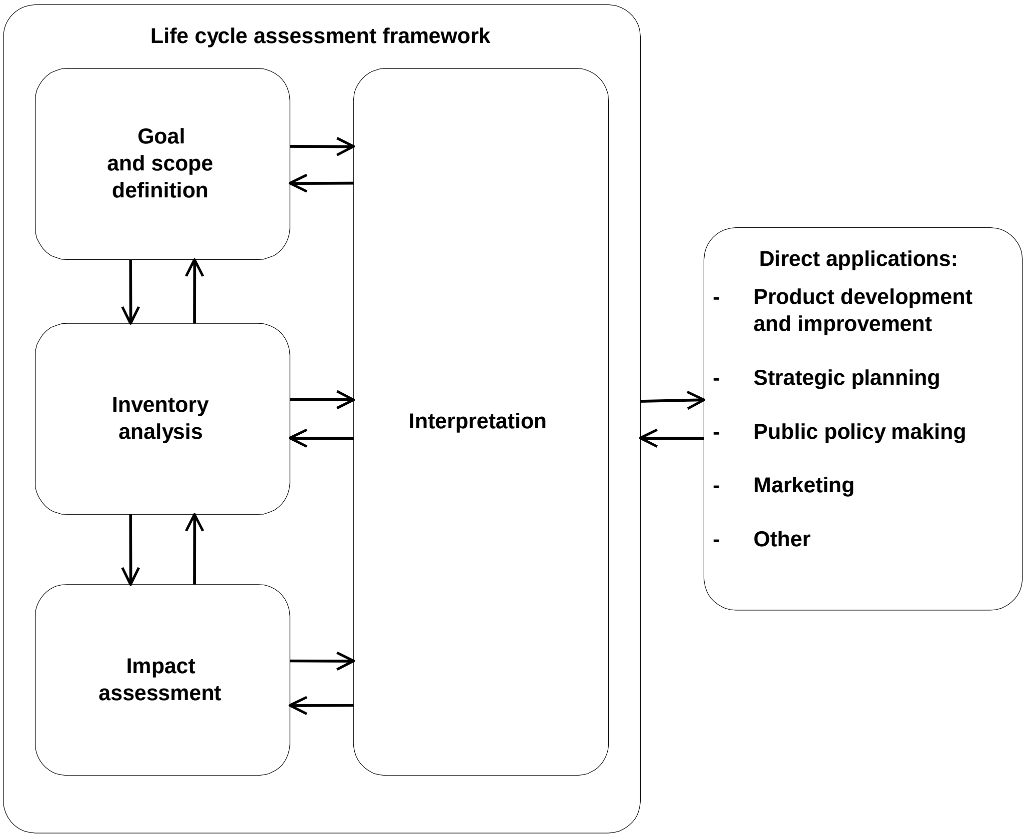

Figure 1: ISO framework for LCA

1. Goal and scope definition: here, the purpose of the study is defined and based on that the system is defined and alternatives are selected.
2. Life Cycle Inventory analysis (LCI): data are collected to quantify the system, including environmental interventions. The LCI ends with the ecoprofile: the overview of emissions and extractions related to the system. For this purpose, LCI databases are available and are continuously being developed.

3. Life Cycle Impact Assessment (LCIA): the ecoprofile is translated into a limited number of impact categories or even one final score, to enable interpretation and to facilitate comparisons.
4. Interpretation of the results: this refers to sensitivity and uncertainty analyses to be performed, to test the robustness of the results; and to contribution analyses to assess which processes cause the main environmental damage.

For all four parts of the framework, rules are established in the ISO-framework. And for all four parts the scientific debate is ongoing. The main issues related to the LCI are, of course, data availability and data uncertainties, but also allocation of multi-output processes. Allocation can be done in different ways, e.g. based on economic value, based on weight, based on energy content, based on avoided processes etc., with sometimes large consequences for the outcomes. For the LCIA different ways to translate emissions into impact categories are the main issue. For some of the impact categories, such as acidification and climate change, consensus is reached on how to make this translation. For others, such as toxicity, consensus is yet far away and procedures are very much work in progress. This is especially relevant for additives, as they often have toxic properties. In the LCIA, the same data are used as in Risk Assessment: toxic properties of substances, related if possible to some kind of acceptable or no-effect concentration or intake levels, and information about the environmental fate of the emissions. While in Risk Assessment the fate is established with as much local information as possible, Life Cycle Assessment uses generalized information and standardized environments for the fate assessment. The reason for this is that it is often unknown exactly in which location certain processes of a cradle-to-grave chain have taken place. In LCA, therefore, the outcome is in terms of potential environmental impacts rather than actual environmental impacts.

1.2 Life cycle assessment: the results and the comparison with Risk Assessment

If conducted properly, an LCA provides insight in the potential environmental impacts of cradle-to-grave functional chains. All processes related to the single product or service are quantified and translated back into their environmental interventions, which in turn are translated into potential environmental impacts. This indicates at the same time the most important difference with Risk Assessment: RA deals only with the substance itself, while LCA includes all emissions and extractions involved in the chain, related to energy production, auxiliary materials, waste treatment, capital goods etc. Emissions of the substance itself are part of this; in many cases, however, only a small part.

This enables to detect side-effects: if a certain substance is replaced by another, less toxic one, side-effects may occur related to mining, energy use, transportation etc. These side effects can be co-damages that may in the end undo the environmental benefits of the replacement. Or they could be co-benefits, that even add to the benefits of reduced toxicity – this is difficult to predict beforehand. LCA thus is less accurate than RA in the prediction of actual toxic impacts of the substance itself, but includes the side-effects that are absent in RA but are very important for a substitution decision.

In short, LCA and RA are complementary: they each provide results that the other does not, although these results are in part based on the same information. Both are relevant and both can and should play a role in the definition of a risk-based management of additives.

1.3 Contents of this report

In this report, we will focus on LCA. We assess the availability and quality of LCA data on additives, with a focus on plastics and plastic additives.

LCA data on plastics and plastic additives can be distinguished into:

1. LCI data on the production, use and waste treatment of plastics and plastic additives; these will be treated in Chapter 2;
2. LCIA data which express the relative contribution of 1 kg of emitted additive within a specified impact category, e.g. human toxicity and ecotoxicity – these will not be treated in this report but in a separate report by IVL and DTU
3. LCA (case) studies on plastics or plastics and additives; these are the subject of Chapter 3.

In Chapter 4, conclusions are formulated.

The overview of existing LCI data and LCA studies on plastics and plastic additives is based on the following sources:

1. LCI databases
2. Articles in relevant Journals
3. Grey literature by searching on the internet

2. LCI databases

2.1 Overview of available LCI data

An LCI database contains process data. Process data are a quantified description of the inputs and outputs of a process. That is the consumption of goods to produce a specific product or products and the accompanying extractions from and emissions to the environment.

At the moment there are many different LCI databases that contain process data related to the production, use and waste treatment of plastics and plastic additives. There are at least two initiatives that try to facilitate the overview of available LCI databases:

1. LCA resources directory by JRC-IES[1]
2. Database Registry (the registry) by UNEP/SETAC[2]

LCA resources directory by JRC-IES

An overview of existing LCI databases is given by JRC-IES.[3] Table 1 summarizes the LCI databases reported by JRC-IES. For some of the databases a quick scan has been made on the availability of data regarding plastics and plastic additives (see indication in third column).

[1] Joint Research Centre – Institute for Environment and Sustainability
[2] United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC)
[3] http://lca.jrc.ec.europa.eu/lcainfohub/directory.vm

Database + version	Supplier	checked/decribed in this workbook
CPM LCA Database	Center for Environmental Assessment of Product and Material Systems - CPM	
DEAM™	Ecobilan - PricewaterhouseCoopers	
DEAM™ Impact	Ecobilan - PricewaterhouseCoopers	
DIM 1.0	ENEA - Italian National Agency for New Technology, Energy and the Environment	
ECODESIGN X-Pro database V1.0	EcoMundo	
ecoinvent Data v1.3	ecoinvent Centre	PlasticsEurope
EIME V8.0	CODDE	
EIME V9.0	CODDE	
esu-services database v1	ESU-services Ltd.	
Eurofer data sets	EUROFER	
Franklin U.S. LCI database	Franklin Associates, A Division of ERG	x
GaBi databases 2006	PE International GmbH	PlasticsEurope+
GEMIS 4.4	Oeko-Institut (Institute for applied Ecology), Darmstadt Office	
IO-database for Denmark 1999	2.-0 LCA consultants	
IVAM LCA Data 4.04	IVAM University of Amsterdam bv	PlasticsEurope
KCL EcoData	Oy Keskuslaboratorio-Centrallaboratorium Ab, KCL	
LC Data	Forschungszentrum Karlsruhe	
LCA Database for the Forest Wood Sector	Bundesforschungsanstalt für Forst- und Holzwirtschaft (BFH)	not relevant
LCA_sostenipra_v.1.0	Universitat Autònoma de Barcelona (UAB)	
MFA_sostenipra_v.1.0	Universitat Autònoma de Barcelona (UAB)	
Option data pack	National Institute of Advanced Industrial Science and Technology (AIST)	
PlasticsEurope Eco-profiles	PlasticsEurope	x
ProBas	Umweltbundesamt	
Sabento library 1.1	ifu Hamburg GmbH	not relevant
SALCA 061	Agroscope Reckenholz-Tänikon Research Station ART	not relevant

SALCA 071	Agroscope Reckenholz-Tänikon Research Station ART	not relevant
SimaPro database	PRé Consultants B.V.	PlasticsEurope (Ecoinvent), IVAM
sirAdos 1.2.	LEGEP Software GmbH	not relevant
The Boustead Model 5.0.12	Boustead Consulting Limited	PlasticsEurope
Umberto library 5.5	ifu Hamburg GmbH	PlasticsEurope
US Life Cycle Inventory Database	Athena Sustainable Materials Institute	x
Waste Technologies Data Centre	UK Environment Agency	

Table 1. Overview of LCI databases (taken from JRC-IES)

Database Registry (the registry) by UNEP/SETAC

The UNEP/SETAC life Cycle Initiative[4] has made an overview of available Life Cycle Inventory (LCI) databases around the world (Curran and Notten, 2006; Norris and Notten, 2002). The overview is one of the deliverables of Task Force 1 (Database Registry) of the Life Cycle Inventory Programme.

Task Force 1 is responsible for developing the UNEP/SETAC Database Registry: a comprehensive, web-based listing of available LCI databases for the world LCA community. The UNEP/SETAC Database Registry (the registry)[5] is implemented and made available on web, since end of 2009. The present status is still work in progress, and will continue to evolve.

Also the UNEP/SETAC Database Registry (the registry) has been queried on data on plastics and plastic additives.
The registry seems to be incomplete. In (Curran and Notten, 2006) more databases are included, with a lot of overlap with the JRC overview. The registry might be incomplete because it is still in development. If this is not the case, it is not clear which criteria are used to be included in the registry.

The result of this quick scan is reported in an excel spreadsheet, which is titled "LCI_database_overview_(plastics&additives).xls". Each of the processes in the database is labeled:

1) plastic type/additive (additive, PE, PVC, PP, etc.)
2) cradle to grave stage (upchain, polymer production, polymer processing, product production, product use, waste management)
3) location (Europe, world, USA/Canada, France, Germany etc.)
4 database source (GABI, ECOINVENT, ELCD, NREL, PlasticsEurope, Umberto, IVAM)

[4] http://lcinitiative.unep.fr/
[5] http://lca-data.org:8080/web/guest

2.2 Conclusions LCI databases

Polymers production

1) There are many LCI databases containing data on the production of polymers.
2) LCI data on the production of polymers in the ECOINVENT, ELCD, and (part of the) GABI and IVAM database are based on industrial data from the PlasticsEurope database.
3) LCI data of NREL are not based on the PlasticsEurope database and refer to processes in USA/Canada
4) The PlasticsEurope and NREL database contain LCI data for uncompounded plastic resins. This means that the data are exclusive the production and use of additives.
5) The properties of plastic materials depend on the addition of plastic additives and further processing. So to compare plastic materials the plastic resin data can not be used as such. Plastic resin data should be combined with data for plastic conversion (see below, point 7 and 8).
6) The PlasticsEurope database contains aggregated cradle to gate data The LCI data of NREL are unit processes.

Plastic conversion, production of plastic (half)products

7) The databases of PlasticsEurope, GABI, ECOINVENT, Umberto and IVAM contain some data of semi manufactured products, like sheet, film, pipe, bottle, window frame.
8) However, these conversion modules mainly contain transport, energy consumption and packaging data. The modules need raw materials, like resins and additives, as input data!

Additive production

9) In general process data on the production of additives, like phthalates or brominated flame retardents etc., are missing.
10) An exception is the production of some metals(compounds) and Bisphenol A. The IVAM database also contains data on the production of DEHP and lead stabilizer.

Polymer waste treatment

11) Most of the LCI databases contain some data on the incineration of (specific) plastics, like ECOINVENT, ELCD, GABI and IVAM.
12) A few databases contain data on landfill of (specific) plastics, like ECOINVENT and IVAM.
13) However, data related to recycling of plastics are very poor.
14) Furthermore, it is unclear whether emissions of additives in waste treatment processes are accounted for. For example the ECOINVENT database reports no emissions of phthalates for PVC waste treatment.

In all, it can be concluded that the LCI databases on plastics contain relevant data for the production of plastic resins and the conversion of resins into materials or (half) products, but that data on the production of specific additives are missing. Furthermore, the conversion processes do not take into account the consumption, and thus possible emissions, of additives. The conversion processes are modules that mainly focus on energy consumption. Additional data about the consumption of additives and possible emissions should be added to the conversion module and will depend on specifications of the produced (half) product. Data related to recycling of plastics are missing or very limited.

3. LCA case studies on plastics and additives

3.1 Overview of available LCA articles on plastics

Three Journals have been screened on relevant articles:

1) International Journal of Life Cycle Assessment; 265 hits http://www.springerlink.com/content/112849/
2) Journal of Industrial Ecology; 118 hits http://www3.interscience.wiley.com/journal/118902538/home?CRETRY=1&SRETRY=0
3) Journal of Cleaner Production; 113 hits http://www.elsevier.com/wps/find/journaldescription.cws_home/30440/description#description

The Journals are queried using the keywords LCA and plastics (and specific plastics, like PVC, PE, PP, PS). Furthermore a query has been made using "google scholar"[6] based on the keywords "PVC" and "Life Cycle Analysis". This lead to 1400 hits of which 808 hits of publications since 2000.

A first screening of all these publications has been made in which all the obvious non relevant documents were skipped. These are for example LCAs of products (like buildings, vehicles, electronics) in which plastics are a (small) part of the total of materials. This finally has lead to a list of about 110 documents (see references).

[6] http://scholar.google.nl/

These remaining 110 documents are reviewed in more detail. The following criteria are used:

1. Is the article about LCA?
2. Is it about plastic materials? Is plastic one of the alternatives in the LCA comparison? Is it about plastic containing products?
3. Is waste treatment, and particularly recycling, part of the (LCA) study?
4. Is there any attention for plastic additives? The role of plastic additives in recycling? Or the effects of plastic additive emissions?

This more detailed review resulted in a reduced number of (partly) relevant articles, about 29 relevant (marked black) and 28 partly relevant (marked gray), see table 2. In the table is indicated whether or not the studies have recycling and/or additives as a topic. The column “plastics only” indicates if the studies are focused on plastics only.

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Additives for the Manufacture and Processing of Polymers	Höfer R;Hinrichs K;		not LCA, but general info about additives				additives	
USEtox - the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment	Rosenbaum R;Bachmann T;Gold L;Huijbregts M;Jolliet O;Juraske R;Koehler A;Larsen H;MacLeod M;Margni M;McKone T;Payet J;Schuhmacher M;van de Meent D;Hauschild M;		tox factors				additives (characterisation factors)	

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
National inventory of emissions of additives from plastic materials	Westerdahl et al.		not LCA, but MFA model and emission factors for additives in plastics in Sweden					
SOCOPSE Source Control of Priority Substances in Europe: Material Flow Analysis for selected Priority Substances	Pacyna, J.M.		not LCA, but MFA for some for additives in plastics in Europe				additives	
An Inventory and Assessment of Options for Reducing Emissions: DEHP	Lindeboom R;		not LCA but SFA, incl assessment of options for reducing emissions				additives (DEHP)	

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Comparison and analysis of different approaches for estimating the human exposure to phthalate esters	Franco A;Prevedouros K;Alli R;Cousins IT;		tox factors				additives (phthalates)	factors are underestimated , because only a limited number of pathways that are relevant for plasticizers are accounted for.
Using LCA to Assess Eco-design in the Automotive Sector: Case Study of a Polyolefinic Door Panel (12 pp)	Muñoz I;Rieradevall J;Domènech X;Gazulla C;						automotive door skin	prototype scores better, energy recovery in a cement kiln might be a good alternative for mechanical recycling
How Biobased Products Contribute to the Establishment of Sustainable, Phthalate Free, Plasticizers and Coatings	Haveren Jv;Oostveen EA;Micciché F;Weijnen JGJ;						biobased additives	isosorbide diesters as substitutes for the currently phthalate based plasticisers for PVC and other resins

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings - Part 1: Characterisation Factors (8 pp)	Meijer A;Huijbregts M;Reijnders L;		tox factors, indoor				building materials	damage effects of indoor emissions can not be neglected
Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings - Part 2: Damage Scores (10 pp)	Meijer A;Huijbregts M;Reijnders L;		tox factors, indoor				building materials	
Environmental evaluation of single-use and reusable cups	Garrido N;varez del Castillo M;						cup	minimum number of reuses of the reusable cup to make the associated environmental impact smaller than that associated with the single-

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
								use cup is 10 uses. In practice the reuse is far less than 10.
Life cycle assessment and eco-efficiency analysis of drinking cups used at public events	Vercalsteren A;Spirinckx C;Geerken T;						cup	The comparative LCA study according to ISO did not provide an overall environmentally superior cup system.
Life cycle assessment of flooring materials: Case study	Jönsson Å;Tillman AM;Svensson T;			energy			floor covering	impacts: vinyl > linoleum > wood
Life cycle assessment study on resilient floor coverings	Günther A;Langowski HC;		no material specific ranking possible: differences within groups > differences between groups;				floor covering	

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
			recycling reduces env. impact					
Life cycle assessment study on resilient floor coverings by Albrecht Günther and Horst-Christian Langowski, Int. J. LCA 2 (2) 73GÇô80 (1997)	Finnveden G;		review of several flooring LCA studies				floor covering	impacts: vinyl > polyolefin > linoleum
Life-cycle assessment of four types of floor covering	Potting J;Blok K;		contains some process data for additives, probably outdated				floor covering	linoleum best, others not significant different

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Estimating Levels of Micropollutants in Municipal Wastewater	Rowsell V;Tangney P;Hunt C;Voulvoulis N;		not LCA, but relevant because of STP and micopolutants				Municipal Wastewater treatment service	
The influence of impact assessment methods on materials selection for eco-design	Bovea MD;Gallardo A;		general LCIA story				Packaging Plastic	result to a large extend depends on IA method used
Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology	Madival S;Auras R;Singh SP;Narayan R;		bio polymer				Packaging Plastic	PET is worste
Biodegradable packaging based on raw materials from crops and their impact on waste management	Davis G;Song JH;		not LCA, but general info about additives				Packaging Plastic bioplastic	composting of bioplastics most favorable. But what about leaching of additives (Lauran van Oers)?

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
An Engineering Approach to Plastic Recycling Based on Rheological Characterization	Kuswanti C;						PCR (Post Consumer Resins)	PCR characterisation to facilitate recycling by identifying plausible uses and processing parameters
Life Cycle Assessment of a Personal Computer and its Effective Recycling Rate (7 pp)	Choi BC;Shin HS;Lee SY;Hur T;						Personal Computer	PC recycling reduces the total environmental impact of the product. Exception for ozone depletion and ecotoxicity
Design for product retirement and material life-cycle	Ishii K;Eubanks CF;Di Marco P;		not LCA, Design for product retirement (DFPR) applies to retirement strategies				plastic containing products	plastics are difficult to recycle in high value products. This model of material degradation might help.

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Database generation for olefin feedstocks and plastics	Matthews V;Fink P;		plastics database, out dated				plastic containing products	
Assessing the Sustainability of Polymer Products	Wolf MA;Baitz M;Kreissig J;		General (methodological) chapter on LCA and plastics				plastic products	Further improving polymers for more sustainable products is hence a process that has already started, by consistently combining existing life cycle approaches, tools, and databases. Herein are summarized misconceptions, rules, standard approaches and need

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
PVC and sustainability	Leadbitter J;		not LCA, but interesting information on PVC and additives				PVC	
Combining SFA and LCA	Tukker A;Kleijn R;van Oers L;Smeets E;		combination of LCA and SFA				PVC containing products	
Uncertainty in life cycle impact assessment of toxic releases practical experiences - arguments for a reductionalistic approach?	Tukker A;		probably outdated				PVC products	high uncertainty in parameters and models to calculate IA factors
New Developments in PVC	Hansen O.G.;		opinions, no quantified info				PVC, medical devices	
Eco-efficiency of recovery scenarios of plastic packaging	Eggels PG;Ansems AMM;Ven BLvd;						waste (MSW and IW) treatment service plastic	

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
							packaging	
The environmental effect of reusing and recycling a plastic-based packaging system	Ross S;Evans D;		limited IA: energy, GWP, POC				waste treatment plastic packaging	recycling reduces energy requirements, GHG and POC emissions
Comparison of Plastic Packaging Waste Management Options: Feedstock Recycling versus Energy Recovery in Germany	Wollny V;Dehoust G;Fritsche UR;Weinem P;						waste treatment plastic packaging mix	CO2 em: feedstock recycling < landfill < incineration; costs of feedstock recycling are high but will decrease
The recycling of plastic wastes from discarded TV sets: comparing energy recovery with mechanical recycling in the context of life cycle assessment	Dodbiba G;Takahashi K;Sadaki J;Fujita T;						waste treatment plastic waste from TV sets	impacts: material recycling < incineration with energy recovery; assumption: easy seperation of plastics

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Analyzing Polyvinyl Chloride in Japan With the Waste InputGêÆOutput Material Flow Analysis Model	Nakamura S;Nakajima K;Yoshizawa Y;Matsubae-Yokoyama K;Nagasaka T;		not LCA, but MFA, based on IO table, relevant for tracking destination				waste treatment PVC	
Solid waste treatment within the framework of life-cycle assessment	Finnveden G;Albertsson AC;Berendson J;Eriksson E;Höglund LO;Karlsson S;Sundqvist JO;		general LCA story				waste treatment service	
Life cycle assessment of energy from solid waste--part 1: general methodology and results	Finnveden G;Johansson J;Lind P;Moberg Å;			energy			waste treatment service MSW	environmental preference of recycling over incineration over landfilling (specifically also for plastics)

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Recycling revisited--life cycle comparisons of global warming impact and total energy use of waste management strategies	Björklund A;Finnveden G;						waste treatment service MSW	GWP and energy consumption:preference of recycling over incineration over landfilling (but not for all plastics scenarios)
Analysis of energy footprints associated with recycling of glass and plastic--case studies for industrial ecology	Krivtsov V;Wäger PA;Dacombe P;Gilgen PW;Heaven S;Hilty LM;Banks CJ;		limited IA: energy				waste treatment service MSW	primary energy use: mechanical recycling < cement kln < incineration (without heat recovery??)
Environmental Life-Cycle Comparisons of Recycling, Landfilling and Incineration: A Review of Recent Studies	Denison RA;						waste treatment service MSW	recycling better than incineration and landfilling
A study of the plastic life cycle assessment	Koo CH;		voegt wrsch. niet echt veel toe				waste treatment service MSW, plastic waste	energy use, GWP: recycling < incineration < landfill

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Economic Evaluation of PVC Waste Management	Brown KA;Holland MR;Boyd RA;Thresh S;Jones H;Ogilvie SM;		not LCA, but economic analysis, but with attention for additives				waste treatment service PVC	
State of the art of plastic sorting and recycling: Feedback to vehicle design	Froelich D;Maris E;Haoues N;Chemineau L;Renard H;Abraham F;Lassartesses R;		not LCA, but about a simplified methodology for car design integrating plastic recycling constraints				waste treatment service, automotive	
End-of-life of a polypropylene bumper skin	Le Borgne R;Feillard P;						waste treatment service, automotive bumper skin	incineration with energy recovery and 90% recycling seem to be best

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
The role of product information in automotive plastics recycling: a financial and life cycle assessment	Duval D;MacLean HL;		limited IA: energy, GWP				waste treatment service, automotive plastic recycling	recycling reduces impacts, however costs are high, eco efficiency GHG reduction is low
Waste treatment in product specific life cycle inventories	Kremer M;Goldhan G;Heyde M;		probably outdated				waste treatment service, incineration of plastic waste	
Waste treatment in product specific life cycle inventories	Bez J;Heyde M;Goldhan G;		probably outdated				waste treatment service, landfill of plastic waste	
Recycling of Polymeric Materials Used for Food Packaging: Current Status and Perspectives	Arvanitoyannis IS;Bosnea LA;		not LCA, but general information on recycling and other waste treatmetnt options				waste treatment service, Packaging, food	

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Materials and products from UK-sourced PVC-rich waste	Coates,P.D; Kelly,A.L.; Rose,R.M		impacts (excl tox!); mechanical seperation (and recycling is best option)				waste treatment service, PVC (windows, pipes, flooring)	
LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency	Frischknecht R;		methodological issues of importance for recycling				waste treatment service, recyclable materials	choice may have very large influence and depends on weak/strong sustainability approach
Modelling and analysis of international recycling between developed and developing countries	van Beukering PJH;van den Bergh JCJM;		not LCA, but modelling of international recycling				waste treatment service, recycling	
Life Cycle assessment of a plastic packaging recycling system	Arena U;Mastellone M;Perugini F;		limited IA: energy				waste treatment service, Recycling for Packaging,	energetic (and then environmental) savings by recycling

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
							Plastic	
Plastics recycling: challenges and opportunities	Hopewell J;Dvorak R;Kosior E;						waste treatment service, recycling, plastics	recycling of waste plastics is an effective way to improve the environmental performance of the polymer industry.
Study on the selection of waste streams for end-of-waste assessment	Villanueva A;Delgado L;Luo Z;Eder P;Catarino AS;Litten D;		not LCA, but relevant waste and waster treatment data in Europe				waste treatment services	
Environmental issues in polymer processing: A review on volatile emissions and material/energy recovery options	Patel SH;Xanthos M;		not LCA but measuring methods, energy analysis for cradle to				waste treatment services and processing, plastics	energy consumption: reuse < recycling << landfill

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
			grave chain					
Technological Reference Paper on Recycling Plastics	Delgado C;Stenmark A;		not LCA, but description of sorting and recycling processes, techniques, secondary markett and bottle necks, including the role of additives				waste treatment, recycling, plastic containing products	

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
Sustainability analysis of window frames	Asif M;Muneer T;Kubie J;						window frames	It has been found that timber- and aluminium-clad timber windows are sustainable products due to their environment-friendly characteristics i.e., low embodied energy, low environmental impacts, better durability and longer service life. While aluminium an
Environmentally benign manufacturing: Observations from Japan, Europe and the United States	Gutowski T;Murphy C;Allen D;Bauer D;Bras B;Piwonka T;Sheng P;Sutherland J;Thurston		not LCA, but interesting because of information on recycling options of plastics (PVC)					

title	authors	relevance for RiskCycle	remark	recycling	plastics only	additive	product	conclusion
	D;Wolff E;							

Table 2 Overview of publications about Life Cycle Analysis and plastics

3.2 Conclusions

Waste treatment of plastic waste

Many of these 25 articles have as primary topic the assessment of waste treatment alternatives for plastic waste or Municipal Solid Waste, including plastics. Most of the articles, approximately 30, take recycling options for plastics into account, being either incineration with energy recovery, feedstock recycling, materials recycling or reuse.

In general the conclusion for waste treatment options for plastics is that recycling has the lowest impacts, followed by incineration and finally landfill. The general remark is that recycling leads to a reduction in use of virgin materials and thus use of primary energy. The energy necessary for collecting, sorting and recycling into secondary materials is far less than the energy for the production of virgin material.

However, a few remarks can be made.

1) Additives and waste management: Most of the articles about the waste management of plastics do not seem to take into account the plastic additives. That is not the emissions of additives in waste treatment processes and not the role of additives in waste treatment management.
2) Allocation method: In most studies the allocation method used for recycling alternatives is the substitution method. This means the impacts for production of virgin materials are subtracted from the system in case the plastic waste is recycled. Other allocation methods might lead to less rigid reduction of impacts. In Frishknecht (2010) the influence of the type of allocation method used for recycling is the topic of the article. It is concluded that the choice of allocation method may have very large influence on the results and depends on weak/strong sustainability approach.
3) Recycling options: Some articles state that recycling of plastics into high value secondary materials might be problematic (e.g. Ishii *et al.,* 1994;

Brown et al., 2000; Kuswanti, 2002; Delgado *et al*., 2005; Asif *et al.,* 2005; Davis & Song, 2006; Nakamura et al., 2009) or the costs are high (Duval & MacLean, 2007). This partly may be caused by the unknown composition of the plastic waste and particularly the additives that might influence the properties of the secondary material and its processing. It is not clear how is dealt with this probably problematic recycling of plastics when the substitution method for allocation is applied. In Le Borgne & Feillard (2001) it is concluded that material recycling and incineration with energy recovery are more or less equal best options. And in Muñoz (2006) it is suggested that energy recovery in a cement kiln might be a good alternative for mechanical recycling.

4) Impact assessment: Some of the LCAs use a limited impact assessment restricted to energy consumption and CO2 emissions (Arena et al., 2003; Duval & MacLean, 2007; Ross & Evans, 2003; Krivtsov, 2004;) or have a more encompassing assessment but without toxicity assessment (Coates *et al.,* 2004). So in all these studies the effects of possible emissions of additives are not accounted for.

Some of the studies on waste treatment services are not LCA studies but might contain relevant information for RiskCycle because of relevant waste and waste treatment data in Europe (Villanueva et al., 2010), descriptions of sorting and recycling processes, and bottle necks for recycling, including the role of additives (Delgado & Stenmark, 2005; Gutowski *et al*., 2005) or the relation between developed and developing countries in international recycling (van Beukering & van den Berg, 2006).

Impact assessment factors

A number of articles (4) deal with characterization models and the factors for LCA impact assessment. In Rosenbaum *et al*. (2008) the USEtox model and recommended characterization factors for toxicity are described. Also characterization factors for some of the additives are available.

In Franco *et al.,* (2007) it is concluded that the characterization models, like EUSES and ACC-Human, underestimate human exposure to phthalate esters because they consider only a few key pathways. It is unclear whether the more relevant pathways for phthalate esters are taken into account in the USEtox model?

In Meijer *et al.,* (2005) a characterization model and characterization factors for indoor emissions are presented. In the articles also indoor emissions of some building materials are estimated and their effects calculated. It is concluded that damage effects of indoor emissions can not be neglected.

Comparative LCA product studies

There are a number of articles about comparative LCAs. Approximately 7 articles are about (waste treatment of) packaging plastics, 5 articles about flooring (PVC), 3 articles about (waste treatment of) automotive plastics, 2 articles about single use and reusable plastic cups, 1 article about window frames. The results of these product LCAs naturally depend on the alternative materials with which plastic products are compared.

In none of the articles the plastic additives are mentioned as an important issue in the impacts of plastics. Partly this is caused by the fact that additives are neglected in the LCAs, for example on (waste treatment) of plastic packaging (Eggels et al., 2001; Ross & Evans, 2003; Wollny et al., 2001; Arena et al., 2003; Arvanitoyannis & Bosnea, 2001; Madival et al., 2009; Bovea & Gallardo, 2006)), plastic cup studies (Garrido *et al.,* 2007; Vercalsteren *et al.,* 2010) and some studies on automotive parts (Le Borgne & Feillard, 2001; Duval & MacLean, 2007).

In the LCAs about PVC containing flooring (Jönsson et al., 1997; Günther & Langowski, 1997; Potting & Blok, 1995) and window frames (Asif et al., 2005) the production of additives is taken into account. However, only Potting & Blok (1995) and Asif *et al.,* (2005) also refer to emissions of additives, like DEHP and lead stabilizers.

Additives

About 25 articles also pay attention to plastic additives, mostly phthalates (DEHP), but also pigments (TiO2), and stabilizers (lead). These are the articles about impact assessment factors, the comparative LCAs of flooring and window frames, and a few of the LCAs of the waste treatment options. However, for the latter most articles only give qualitative information on additives.

There are also some studies that are not LCAs but still might be relevant for RiskCycle. Lindeboom (2009) is a Substance Flow Analysis of DEHP, including an assessment of options for reducing DEHP emissions. In Höfer & Hinrichs (2010) general information about additives is given. Leadbitter (2002) gives general information about additives in PVC. Rowsell *et al.* (2010) is an article about estimating micropollutants in Municipal Wastewater.

4. Conclusions and recommendations

4.1 Conclusions

For the cradle-to-chain environmental assessment of additives in plastics there seem to be serious data gaps in both the LCI databases as also the LCA case studies. The LCI databases lack data about production of additives, with an exception for heavy metals. Most if not all LCI databases lack data about consumption (and thus emission) of additives in the production of plastic (half)products. Some LCI databases contain process data for incineration and landfill of (specific) plastics. Data for recycling of plastics are mostly lacking. Furthermore, it is not clear whether emissions of additives in waste management are taken into account.

A review of LCA literature shows that LCA case studies hardly provide quantified information on the effects of additives and the role of additives in waste management.

Most relevant articles for additives relate to the characterization models for the impact assessment of toxic releases. In none of the case studies, additives are identified as a source of emissions contributing significantly to the total impact of plastics. This can have various reasons:

- in many of the LCA studies the impact assessment is limited to just energy related emissions, or toxicity is not included as an impact category
- in many of the LCA studies, additives are not included – this may not even be intentionally, since it is not directly apparent that additives are not included in the LCI data on plastics production
- it may be that the contribution of additives to total impacts is indeed limited. Some studies do include additives, and still these are not mentioned as important sources of emissions.

In waste management related studies, additives are mentioned as barriers for material recycling, but no quantification is provided.

4.2 Recommendations

In all, the state of the information regarding additives in LCA is really bad. A first recommendation, therefore, is to explicitly include additives in LCI data on plastics production, use and waste treatment. This is the only option if we want to do LCA studies with relevance for the problems related to additives. However, it will take a long time to complete such data. For this project, this is too large an effort to undertake.

For the moment, we cannot rely on standard LCI databases nor on the literature, and therefore we will have to use other information. Therefore alternative estimation methods for additive emissions in the cradle-to-grave chain of plastics are proposed. The possibilities and limitations of this approach is partly described below and should be further investigated.

One option is to use data from other studies, such as Material/Substance Flow Analysis studies or emission inventories, and combine those with LCA data. In the reviewed articles there are some studies that are not LCAs but which still might be relevant for the assessment of additive emissions of plastics. In these studies emissions of additives of PVC product chains are estimated by using MFA data and emission factors (Westerdahl *et al.,* 2010; Tukker *et al.,* 1996). In contrast to LCA studies, these studies are restricted to a limited number of emissions of toxic substances only. However, like LCA these MFA-studies are able to take into account emissions during the cradle-to-grave chain of plastic products. The SOCOPSE project (Pacyna, 2009; Lindeboom, 2009) is a European project within the sixth framework programme. Within this project Material Flow Analysis for selected Priority Substances has been carried out, including some additives like DEHP, TBT, Nonylphenol en PBDE in Europe.

The study of Westerdahl et al. (2010) is part of the research program ChEmiTecs[7]. ChEmiTecs is funded by the Swedish EPA. The program's goal is to improve the understanding of emissions of organic substances from articles and to clarify and determine the magnitude of this problem.

In Westerdahl *et al.* (2010) emissions of additives (organic chemicals, incl. phthalates and bromated substances) from plastic materials consumed in Sweden are estimated. The emissions are based on a generic emission model that has been developed an applied to the stocks of plastic products assuming different plastic product categories with specific lifetimes, chemical composition and surface areas. The estimates of the stocks are based on trade and manufacture statistics and assumptions on the average lifetime of products. Also in Tukker et al. (1996) emissions of additives (phthalates, lead stabilizer) from plastic materials consumed in Sweden are estimated. The estimates are based on MFA data and emission factors from literature or guestimated by experts. Emissions are estimated for the production, use and waste phase. Also the emission estimates in Tukker (1996) will be highly uncertain because they are to a large extend based on assumptions and expert judgments. Furthermore, the MFA part of the method is not as formalized as in Westerdahl (2010). Application of this method for another region in another time is therefore believed to be more difficult.

The generic emission model for plastic additives from ChEmiTecs is a promising model for the RiskCycle project. However, there is an important drawback. At present only emissions during use phase are estimated. For RiskCycle inclusion of the waste treatment into the model is a requirement. Within the ChEmiTecs program developments to incorporate emission estimates during waste treatment are foreseen. However, it is not clear whether these developments are publicly available to the RiskCycle project in time.

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[7] http://www.chemitecs.se/english/startpage.4.712fb31f12497ed09a58000589.html

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