LCA Case Studies

A Database for the Life-Cycle Assessment of Procter & Gamble Laundry Detergents

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Abstract. A Life-Cycle Inventory (LCI) and Assessment (LCA) database for laundry detergents of the Procter & Gamble Company (P&G) was constructed using SimaPro software. The input data needed to conduct a product LCI came from several different, supporting databases to cover supplier (extraction and manufacturing of raw materials), manufacturing of the detergent product, transportation, packaging, use and disposal stages. Manufacturing, packaging and transportation stages are usually representative of European conditions while the use and disposal stages are country specific and represent how consumers are using a specific product and how wastes are disposed of. The database has been constructed to allow Procter & Gamble managers to analyse detergent products from a system-wide, functional unit point of view in a consistent, transparent and reproducible manner. For demonstrative purpose, a life cycle inventory and a life cycle impact assessment of a P&G laundry detergent used in Belgium is presented. The analysis showed that more than 80% of the energy consumption occurs during the consumer use stage (mainly for heating of the water). Air and solid waste follow the same pattern, most of these being associated with the energy generation for the use stage. More than 98% of the biological oxygen demand, however, is associated with the disposal stage even after accounting for removal during treatment. Future challenges are the completion and/or updating of all detergent ingredient inventories.

Keywords: Database; detergent ingredient; laundry detergents; LCA; LCI; life-cycle assessment; life-cycle inventory

Introduction

Life-Cycle Assessment (LCA) is a methodology developed to evaluate the mass balance of inputs and outputs of systems and to organise and convert those inputs and outputs into environmental themes or categories relative to resource use, human health and ecological areas. The mass balance of these inputs and outputs, or Life-Cycle Inventory (LCI) spans the entire life cycle of a product: raw material extraction, production of energy and energy feedstocks, manufacturing of ingredients (raw materials), processing of the final product (in this case the laundry detergent) transport, packaging, use and disposal. In recent years, LCA methodology has evolved considerably. Since the publication of the Society of Environmental Toxicology and Chemistry code-of-conduct [1] its standardization has taken place within ISO with the 14040 series [2–5].

The work reported in this study is not a life cycle assessment *sensus stricto*, but a description of a database to perform life cycle inventory and life cycle impact assessment. The ISO principles, however, have been followed by compiling inventories of relevant inputs and outputs of a system; evaluating the potential environmental impact associated with those inputs and outputs; and interpreting the results. For this database description, an attempt to follow ISO reporting format has been made.

1 Goal and Scope Definition of the Study

1.1 Goal

The main objective of the work reported in this study is the customisation of an *LCI database*, so that Procter & Gamble managers can 1. analyse detergents from a system-wide, functional unit point of view in a consistent, transparent and reproducible manner 2. analyse the energy and resource use in the detergent system, 3. analyse various emissions, wastes, and resources using environmental themes, 4. identify what parameters are most likely to be significant to monitor and control, 5. identify opportunities for improving overall system performance and 6. benchmarking the product over time and reporting progress. To achieve the objective, the following goals were set:

- The customisation of an existing database (SIMAPRO 4.0)
- Verification, streamlining and completion of supporting *inventory* databases we use to construct the full product LCI.

The objective of this article is also to document and to report to external parties in a transparent and most accurate way how P&G managers are calculating life cycle inventories and life cycle impact assessment of P&G products.

For an illustrative purpose only, a life cycle inventory and a life cycle impact assessment of a P&G laundry detergent used in Belgium is provided in this article. The goal, scope, assumptions, functional unit, etc. of this illustrative LCA are specific to this analysis. All future LCI/LCA to be conducted with this database could have a different goal and scope.

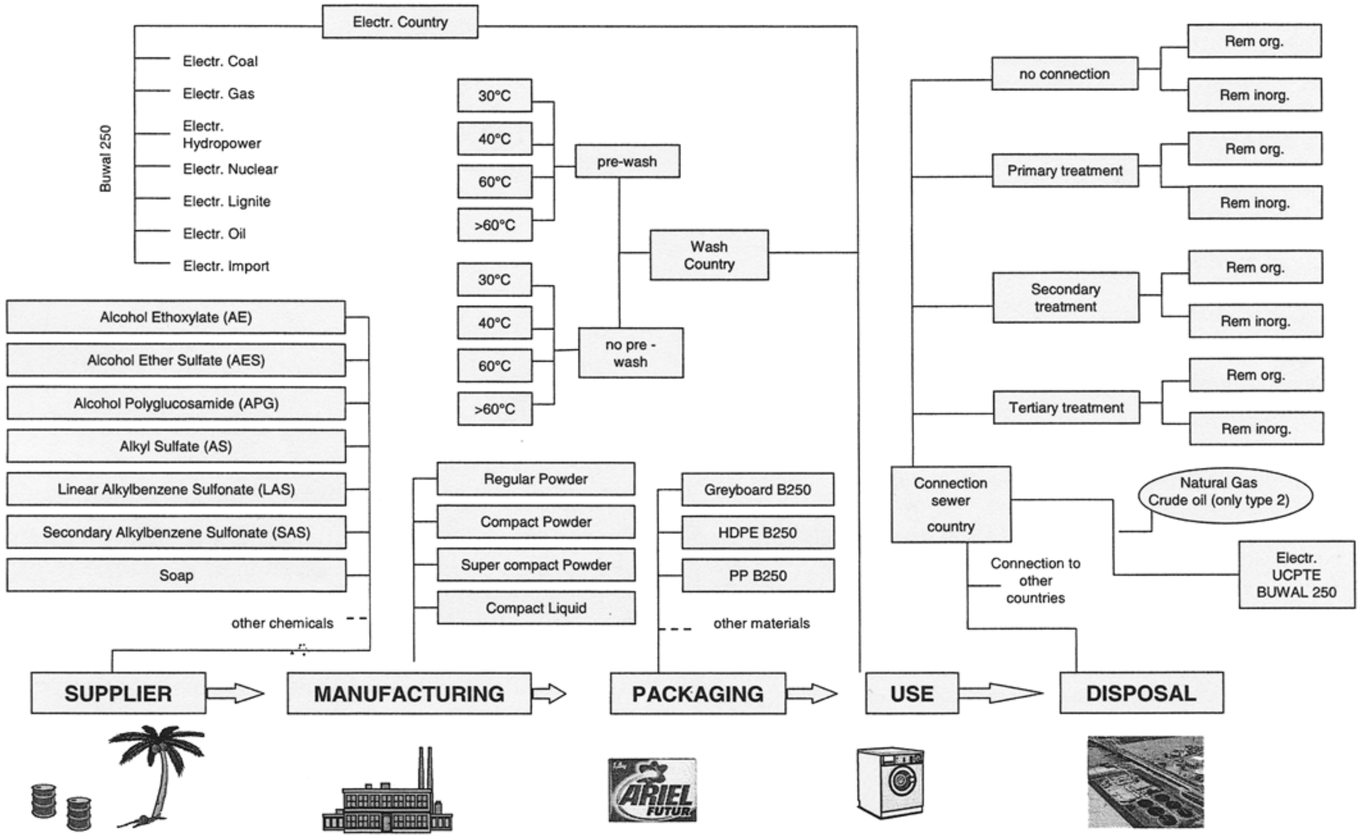

Fig. 1: Structure of the life cycle of 'laundering' as organised in the SimaPro software

1.2 Scope of the study, boundaries and functional unit

1.2.1 Description of the system studied

The database constructed with SimaPro version 4.0 [6] includes the following phases: the raw materials supply (extraction and manufacturing of raw materials including transportation), formulation of the detergent product (manufacturer), transportation, packaging, use and disposal stages (**Fig. 1**). Manufacturing, packaging and transportation stages are usually representative of European conditions while the use and disposal stages are country specific and represent how consumers are using a specific product and how wastes are disposed of.

The detergent database has been constructed in a series of steps. In a first step, LCIs of the ingredients' manufacturing processes for laundry detergent powders or liquids are combined based on their respective levels in 1 kg of product.

Second, the LCI of the packaging needed to contain 1 kg of product is calculated from the raw materials (cardboard, plastics, cellophane, etc.) needed to construct the package. Third, the LCI data sets of product and packaging components are added. In a fourth step, the consumption of energy, raw materials and environmental emissions associated with the laundry process are calculated based on the energy requirements for several common wash temperatures (30°C, 40°C, 60°C and >60°C). Only washing laundering is assumed. In a final step, the inventory data associated with the disposal of the wash water are integrated into the overall LCI. Emissions and raw materials consumed by the wastewater treatment process are taken into account.

1.2.2 Functional unit

The results can be reported on a mass basis, e.g. 1 kg of finished product, or on the basis of washing cycles. The functional unit is dependant on the goal and scope of the study to be conducted. For the illustrative LCA reported in this article, a functional unit of 1000 wash cycles is used.

1.2.3 Data and data quality requirements

1.2.3.1 Production of detergent ingredients

Several inventories related to the production of detergent ingredients have been published during the last 10 years. An overview of the inventories incorporated in our database is presented in **Table 1**. Several of these were either compiled or provided by Franklin Associates, Ltd. for the purpose of construction of LCIs for commonly used surfactants [7] or to support LCA research previously conducted for laundry detergents by P&G. The purpose of the latter was to quantify the energy requirements and emissions resulting from the production, packaging and use of granular Tide® detergent formulations [8]. The methodology used by Franklin Associates, Ltd. has been documented for the US Environmental Protection Agency and is incorporated in the EPA report 'Product LCA Inventory Guidelines and Principles' [9]. It is consistent with the LCI methodology and guidelines described by SETAC [1]. The work performed by Franklin Associates, Ltd. on Tide® was peer-reviewed by an expert panel (R. Parrish, Exec. Dir., Society for Environ-

Table 1: Overview of ingredients and product life cycle inventories incorporated in the database

Ingredient Names	Sub-category	Period covered	Energy database	Coverage	Production process	Reference
LAS-Pc	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[32]
AS-Pc (C12/15)	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[33]
AS-CNO (C12/14)	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[33]
AS-PKO (C12/14)	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[33]
AS-PO (C16/18)	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[33]
SAS-Pc	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[34]
AE3S-Pc (C12/15)	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[35]
AE3S-CNO (C12/14)	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[35]
AE3S-PKO (C12/14)	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[35]
Soap-CNO/PO	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[36]
Soap-CNO/Ta	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[36]
Soap-PKO/PO	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[36]
Soap-PKO/Ta	anionic surfactant	1990-1994	Boustead 1992	Europe	average	[36]
AE3-Pc (C12/15)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
AE3-CNO (C12/14)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
AE3-PKO (C12/14)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
AE7-Pc (C12/15)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
AE7-CNO (C12/14)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
AE7-PKO (C12/14)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
AE11-PO (C16/18)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
APG-CNO (C12/14)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[37]
APG-PKO (C12/14)	non-ionic surfactants	1990-1994	Boustead 1992	Europe	average	[38]
Esterquat (CNO / PKO)	cationic surfactant	1998	Buwal 250	Europe	1 site	[14]
Phosphate STPP	Builders	1998	Buwal 250	Europe	average	[14]
Zeolite A powder	Builders	1993-1994	Buwal 250	Europe	average	[14]
Zeolite A slurry	Builders	1993-1994	Buwal 250	Europe	average	[14]
Na- Silicate powder	Builders	1990-1995	Buwal 250	Europe	average	[14]
Layered silicate (SKS-6)	Builders	1998	Buwal 250	Europe	average	[14]
Citric acid	Builders	1990	Buwal 250	USA	average	[8]
Perborate mono hydrate	Bleaches	1990-1995	Buwal 250	Europe	average	[14]
Perborate tetra hydrate	Bleaches	1995	Buwal 250	Europe	average	[14]
Percarbonate	Bleaches	1994	Buwal 250	Europe	average	[14]
Hydrogene Peroxide	Bleaches	1990-1995	Buwal 250	Europe	average	[14]
NaOH	Buffers	1994	Buwal 250	Europe	average	[39]
Na-Carbonate	Buffers	1994	Buwal 250	Europe	1 site	[11]
Na-Bicarbonate	Buffers	1974-1992	Buwal 250	USA	average	[8]
Polyacrylate	Auxiliaries	1989-1995	Buwal 250	UK	1 site	[14]
Proteases	Auxiliaries	1990-1994	ETH 1994	Europe	1 site	[40]
Sodium sulphate	Auxiliaries	1990-1994	Buwal 250	Europe	average	[17]
Polyethyleneglycol	Auxiliaries	1974-1990	Buwal 250	USA	average	[8]
Silicone	Auxiliaries	1990-1994	Buwal 250	USA	average	[8]
FWA DSBP	Auxiliaries	1997	Buwal 250	Germany	1 site	[14]
FWA DAS-1	Auxiliaries	1997	Buwal 250	Germany	1 site	[14]
Compact powder	final product	1990-1994	Buwal 132	Germany	average	[15]
Regular powder	final product	1990-1994	Buwal 132	Germany	average	[15]
Super compact	final product	1998	Buwal 250	Belgium	1 site	P&G, unpubl.
Compact liquid	final product	1990-1994	Buwal 132	Germany	average	[15]
Fabric conditioner	final product	1998	Buwal 250	Germany	1 site	P&G, unpubl.

mental Toxicology and Chemistry), D. Allen (U. of California), M. A. Curran (US Environmental Protection Agency), Dr. G. Keoleian (U. of Michigan) and J. Wessel (Ohio State U.). Neither the peer review nor the report were ever published, although both were made available to the Ecobilan group who audited the entire database.

The data provided by Franklin Ltd. which all represent US manufacturing processes were incorporated in our database. Energy-related emissions, however, were recalculated using the Buwal 250 database. These inventories are usually used to construct a product LCI when European manufacturing-based inventories are not available.

Another important source of inventories for detergent ingredients is the work performed by the Swiss Federal Laboratories for Materials Testing and Research or EMPA [10–13]. Various groups within The European Chemical Industry Council (CEFIC) have commissioned LCI work from EMPA. These LCIs are considered representative of European production processes. An effort to harmonize the data related to energy sources and emission parameters was recently conducted by EMPA for a number of chemicals based on Buwal 250 [14]. The fraction of these updated inventories needed to construct an LCI of our products were entered in our database.

The detergent ingredient inventory database is of a mixed quality, based on different energy databases, and representative of average European processes or of a single plant. Some studies are clearly outdated (early 1980s) while others have been conducted very recently according to ISO 14040 guidelines.

1.2.3.2 Manufacturing processes

Two sets of data on manufacturing sites are available in our system. One set refers to published inventories and covers the manufacturing of traditional and compact powder detergents as well as compact liquid detergents [15]. These data represents an average of different manufacturing sites from different companies located in Germany. The manufacture of a traditional detergent starts from a hot slurry (~100°C) which is spray-dried in a tower (up to 300°C). The first generation of compact detergents around the 1990s were produced from a mixed technology still involving some spray drying tower and dry mix. This LCI was compiled by the German Detergent Industry Association (IKW) and follows SETAC guidelines [1]. The companies participating in this study represented more than 90% of the German detergent market volume. The input-output information provided in this study, however, is limited to a few key parameters. The quality of this data is considered to be medium.

The second set of data is unpublished and refers exclusively to P&G manufacturing sites and processes for super compact powders and fabric conditioners, among other products. This unit process data involves estimates; the datasets are not necessarily complete and should therefore only be used for screening purposes.

1.2.3.4 Packaging

All the inventories for packaging raw materials were included with the SimaPro software and used as such [16; 17]. Environmental emissions from production of packaging are listed in the inventories of the corresponding raw materials (i.e. cardboard, plastic, etc.). Energy consumption and environmental emissions from the disposal of the packaging is not currently included in our system. The quantity of packaging needed for a particular life cycle stage is considered to become a solid waste following its use and is therefore included in the total solid waste along with others such as the ashes from energy generation and the sludge from wastewater treatment plants. This data is considered to be of high quality and is representative of the European production process.

1.2.3.5 Use stage

Once the product is made at P&G manufacturing sites, it is distributed to consumers via a distribution network and retailers. The LCI input data for the transportation between manufacturing sites and retailers can be estimated from the transportation inventories (train, truck, etc.) already included in SimaPro.

The data for the consumer use stage required a reasonable understanding of how consumers are using laundry detergents all over Europe: the amount of chemicals used per wash load, what fraction of loads is pre-washed, what wash program parameters are used (wash and rinse temperatures, water level, fabric softener use, bleach use, number of rinses, etc.). Our consumer use information is for machine wash only. Habits such as hand wash, pre-soaking, pre-treatment of stains, etc. are not included in our system. All of our data is country-specific.

The amount of chemicals per wash load is based on the recommended dosage indicated on the package. Even though differences at the consumer level between the recommended dose and normal practice can affect the overall results of the LCA, a reliable database on consumer practices regarding dosage is not available for every country. The impact of variability in dosage could be assessed via uncertainty analysis.

As for wash temperature selection, a recent statistical compilation was commissioned by L'Association Internationale de la Savonnerie, de la Détergence et des Produits d'Entretien (AISE) from Taylor Nelson Sofres (Brussels, Belgium) in Nov. 1997, although the full report is only available to AISE members. The foundation for the work came from 14-day diaries completed by more than 4900 consumers across 16 countries and reports wash temperature distribution between 30°C, 40°C, 60°C and >60°C wash cycles with liquid and powder detergents. The new data differed slightly from the data published earlier in the GEA (Group of Electrical Appliances) report [18] that we used for previous work [19]. The Taylor Nelson study aimed at providing a baseline measurement of wash temperatures for the purpose of understanding consumer behaviour and to allow monitoring of change from then onwards in context of the AISE's code of Good Environmental Practice for household detergents [20,21]. The distribution of wash temperatures (average between liquid and powder detergent) per country was published in the Annual Report of the AISE [22] (**Fig. 2**).

Energy requirements for the spin cycle were included on our system, but we simplified by assuming that maximum spin cycle speed was always used. We entered into our system the energy consumption of the washing process for each wash temperature selection, as reported by the European Washing Machine Manufacturer Association (CECED) to AISE in the context of its Code of Good Environmental Practice. The data corresponds to a weighted average of the energy requirement of washing machines per European countries in 1996 for the main wash only. To include additional energy use due to a pre-wash, the main wash energy consumption is multiplied by 1.17. This multiplication factor comes from the GEA report [18] and is based on data from Finland and The Netherlands.

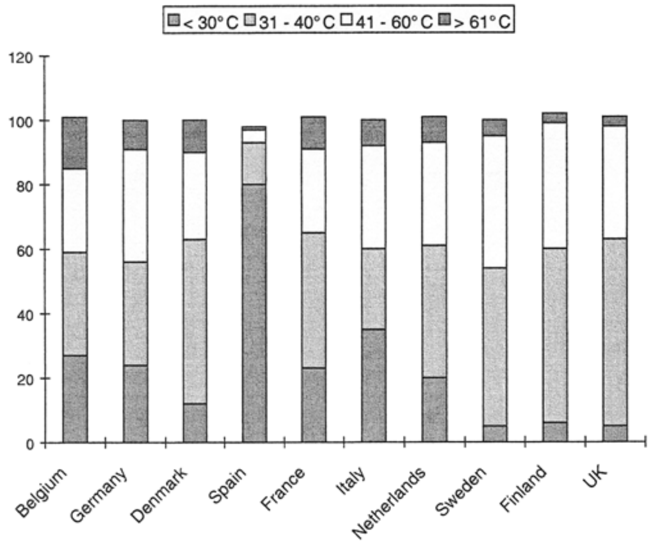

Fig. 2: Wash cycle washing-machine temperature distribution across various European countries for liquid and powder detergents

These data are considered to be of very high quality and are representative of the specific European counties.

The amount of water used per wash load is calculated and reported as a raw material consumption. Energy use and environmental emissions associated with the production and distribution of the water have not been taken into account. The Group of Electrical Appliances estimated the average water consumption per wash load for a number of European countries which ranges between 68 and 99 litres [18].

1.2.3.6 Disposal stage

Once the wash is completed, the wash water is discharged to the sewer. Depending on the country, this wastewater is treated in primary (settler) and/or secondary (activated sludge, tickling filters, etc.) possibly followed by tertiary treatment (sand filtration, nutrient removal, etc.), or it is directly discharged into the environment without any type of treatment. Country statistics on wastewater treatment were included in our system (**Table 2**). Other types of wastewater disposal (septic tanks, oxidation ditches, soils, etc.) have not been considered.

The removal of each ingredient of a detergent by wastewater treatment is taken into account to calculate the amount potentially discharged into the environment. If the ingredient is eliminated through sorption and hence contributes to the sludge generation, this is also taken into account. Two types of elimination are therefore considered: 1) total removal, due to biodegradation and sorption, which is used to calculate the amount of chemical discharge with the effluent and 2) removal through sorption on solids only, which is used to calculate sludge production. Removal by primary treatment was estimated using various sources of information [23,24] or was estimated with the mathematical model SIMPLETREAT [25] (**Table 3**). Removal by secondary treatment was derived from the EU Ecolabel Detergent Ingredient Database [26]. It was assumed that removals in secondary and tertiary treatment would be the same except for phosphate where the removal is assumed to be 90% in tertiary treatment, but only 40% in secondary treatment. The amount of sludge formed in each type of treatment was assumed to equal the amount of ingredient removed by sorption.

Emissions due to the waste water treatment plant (WWTP) operation were also accounted for. All emissions are attributable to the generation of energy by on-site burning of gas or oil. The data was derived from emission factors for Dutch WWTPs [27–29]. Emissions from energy consumption were calculated with the UCPTE model [17] instead of using the energy grid of a specific country as this is done at the use stage. This simplification was based on the expectation that energy requirement at the disposal stage (wastewater treatment plant) constitutes a relative low contribution in the total energy requirement. The impact of this simplification is discussed in the result section.

The energy feedstock, energy requirements and environmental emissions (CH_4 and CO_2) associated with the treatment of organic and inorganic ingredients in a laundry detergent can be calculated for primary and secondary treatment from the values presented in **Table 4** for the treatment of 1 kg of product. Energy requirements for tertiary treatment were assumed to be identical to those of primary treatment, as the technology involved is very similar (sand filtration, decantation). The energy feedstock, energy requirements and emissions associated with the treatment of the product are the summation of these same values for the individual ingredients.

Table 2: Fraction of households connected to different types of wastewater treatment in European countries

Country	No connection (%)	Primary Treatment (%)	Secondary Treatment (%)	Tertiary Treatment (%)
Belgium (B)	37	30	30	3
Denmark (DK)	0	20	71	9
England (UK)	26	23	43	8
France (F)	0	35	62	3
Germany (D)	14	9	57	20
Italy (I)	40	15	45	0
Netherlands (NL)	10	9	79	2
Spain (ES)	53	5	40	2
Sweden (S)	5	1	10	84

Table 3: Removal of detergent ingredients in primary, secondary and tertiary wastewater treatment expressed as % of total removal (biodegradation + sorption) and % removal by sorption only

			Primary removal		Secondary removal	
Ingredient	**BOD_5 Kg O_2/kg**	**COD Kg O_2/kg**	**Total (%)**	**sorption (%)**	**Total (%)**	**sorption (%)**
LAS	0.92	2.3	44	44	95	44
AS	1.4	2.1	27	27	98	27
SAS	1.2	2.3	27	27	95	27
AES	1.3	2.2	22	22	97	22
Soap	1.4	2.9	59	59	95	59
AE	1.5	2.6	29	29	97	29
AE-7	1.1	2.3	29	29	97	29
APG	0.8	2.1	27	27	97	27
STPP	n.a.[a]	n.a.	5	5	40	40
Zeolite	n.a.	n.a.	50	50	95	95
Silicate	n.a.	n.a.	10	10	20	20
Citric acid	0.5	0.6	27	27	91	27
Perborate	n.a.	n.a.	10	10	20	20
Percarbonate	n.a.	n.a.	10	10	20	20
NaOH	n.a.	n.a.	0	0	0	0
Carbonate	n.a.	n.a.	10	10	20	20
Bicarbonate	n.a.	n.a.	10	10	20	20
Polyacrylate	0	0.1	20	20	50	50
Proteases	0.7	2	27	27	95	27
Sodiumsulfate	n.a.	n.a.	0	0	0	0
PEG	0.02	1.65	30	30	50	50
PDMS[b]	0		50	50	95	95
FWA[c]	0		30	30	50	50
SKS-6	n.a.	n.a.	10	10	20	20

a) not applicable; b) polydimethylsiloxane; c) fluorescent whitening agent (brightener)

Table 4: Energy requirements for operation of municipal WWTP, per kg of organic and inorganic matter treated and by treatment type

	per kg of Inorganic Matter		per kg of Organic Matter (COD)	
	Primary	**Secondary**	**Primary**	**Secondary**
Gas (m^3)	$5.83\ 10^{-6}$	$2.11\ 10^{-2}$	$1.84\ 10^{-3}$	$9.3\ 10^{-3}$
oil (g)	–	0.011	–	0.005
Electricity (kWh)	$1.44\ 10^{-3}$	0.65	0.459	0.29
Process energy (MJ)	0.0054	3.163	1.724	1.407
Primary energy (MJ)	0.0169	8.372	5.402	3.731
CO_2 fuel (g)	$1.03\ 10^{-2}$	34.7	3.295	15.3
CO_2 degradation (g)	–	–	–	577.2
CH_4 (g)	–	–		6.56

1.2.4 Validation of the system and peer- review

SimaPro version 4.0 [6], a calculation program specifically developed for LCA, was used for customisation of the database. One of SimaPro's features is an option to develop user interfaces that guide less experienced users and thereby ensure a consistent use of the database. Information entered in the database as well as assumptions and calculations performed by the system can be changed and updated to include new findings and methodologies. Franklin Associates, Ltd. (Prairie Village, Kansas) and the Consultancy and Research Center of Chemistry, Occupational Health and Environment (Chemiewinkel, University of Amsterdam, The Netherlands) assisted P&G with the collection of inventory data, customisation and completion of the database. Upon completion, the Ecobilan PwC Group (Paris, France) audited the system[1]. P&G, however, is solely responsible for the choice of assumptions, the calculations and the results produced by the system. All individual LCAs to be performed

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[1] The peer-review report from Ecobilan PwC can be made available upon request.

from this database and used for comparative purpose will undergo internal or external critical review as recommended by ISO guidelines [2]. The data is entered in SimaPro using individual process cards for each unit process. The format of these process cards is derived from the recently developed SPOLD format (Society for the Promotion of Life Cycle Development) [30]. Each process card refers to the origin of the data, the time period of data collection, the geography, representative, judgements and assumptions, type of technology, literature or private sources, etc.

2 Inventory Analysis

2.1 Allocation procedure

No allocation rules had to be defined since the system is a single output system. The allocation rules in the published inventory data incorporated in our system were not altered.

2.2 Calculation procedures

All energy and raw material consumption and environmental emissions listed in individual inventory are allocated to a product LCI/LCA on a mass basis, according to the specified functional unit. Energy and energy feedstock consumption and environmental emissions for each stage are calculated from the level of each ingredient in the product and the corresponding values from each ingredient inventory based upon the functional unit. For energy, the system distinguishes between process energy, transportation energy, feedstock energy and primary energy (total energy) or process energy corrected for electrical production efficiency in the country considered. Environmental emissions are reported in the inventories. Recall that the ash produced during electricity generation and the sludge produced during wastewater treatment are added to solid waste.

For the use stage, energy and energy feedstock consumption and environmental emissions are calculated by the system based on the percentage of wash loads performed at 30, 40, 60 and >60°C. The system takes its input data from the BUWAL 250 database and the country-specific energy grids to report all emissions attributable to the consumption of electricity during the use stage. 'Process Energy' in the output is the consumption of electricity by the washing machine.

During the wastewater treatment plant stage, the CO_2 and CH_4 from biodegradation of the detergent are added to the CO_2 emissions from the operation of the plant. The fraction of each ingredient that is not removed by sewage treatment is reported as a waterborne emission. Any counter-ions that are not removed by sewage treatment are also considered as waterborne emissions. All ingredients that can form salts are assumed to enter the wastewater treatment plant as such (i.e. Na-LAS, Na-carbonate).

LCI results in SimaPro can be analysed using a variety of methods; a few examples of which are provided here. One method is the grouping and summation of the same type of inputs and outputs from the full inventory, to answer specific questions such as "What is the total life-cycle energy required for product X?", "What is the total life cycle solid waste generated by product X?" or "What is the contribution of each life cycle stage?". Another method is the grouping of inputs and outputs by stage, to answer questions such as "How does the total energy required for transportation of product Y compare to the total energy required for transportation of product Z?" To facilitate the interpretation of the inventory tables, we created methods of analysis focusing specifically on energy use, air and waterborne emissions and solid waste:

Airborne emissions consist of the subcategories CO_2, CO, SO_x, NO_x, CH_4, particulates, volatile organic compounds (VOC) and metals. CO_2 and CH_4 are the total quantities emitted, but excluding quantities from renewable resources. NO_x is the sum of all nitrogen oxides and SO_x is the sum of all sulfur oxides. The list of VOCs includes approximately 110 chemicals inventoried in all of the accumulated databases used.

Waterborne emissions are expressed as BOD (biological oxygen demand) and COD (chemical oxygen demand) Detergent-specific BOD and COD emissions can be calculated by applying conversion factors to each chemical in the formula. Other subcategories in waterborne emissions are total P (including detergent specific chemicals), total N (including detergent specific chemicals), solids (suspended and dissolved solids), grease/oil, phenol, ammonia (total NH_3 and NH_4^+) and metals.

Solid waste distinguishes between 2 subcategories: sludge (from wastewater treatment) and 'other solid waste', which includes approximately 60 different types of waste.

3 Impact Assessment

A variety of impact assessment methods can also be applied to the full inventory table. It is beyond the scope of this article to discuss the merits and limitations of impact assessment within LCA. An updated version of the CML92 [31] method is used to analyse the inventory tables. The aquatic toxicity impact category of the CML 92 method has been modified by applying characterization factors to detergent chemicals emitted after they have undergone wastewater treatment and are discharged with the effluent. These characterization factors are calculated as the inverse of the long-term effect concentration listed in the EU Ecolabel DID list [26]. The aquatoxicity score of the product is calculated as the sum of the aquatoxicity scores for each of the ingredients. If desired, other impact assessment methods can be implemented in the database to address specific needs in line with goal and scope of each individual study to be performed with this database.

4 Results and Discussion of the Life Cycle for Belgium

4.1 Goal and Scope description of this specific LCA

To illustrate the LCI/LCA database described thus far, the results presented in this section are for an hypothetical laundry detergent used under Belgian conditions. This country's electricity grid, therefore, is used as the basis for the energy calculations. The data used to construct the full inventory and to conduct the impact assessment calculations is dis-

Table 5: Chemical inventories and other data used as inputs for LCI of granular laundry detergent used in Belgium

Selected ingredient inventories		**Other data**	
AE11-PO	2%	Dosage of product per load	100 g
AE7-pc	4%	Distribution of wash temperatures in Belgium	
LAS-pc	7.8%	30$_o$C	25%
Citric acid	5.2%	40$_o$C	28%
Na-Silicate powder	3%	60$_o$C	28%
Zeolite	20.1%	>60$_o$C	19%
Sodium carbonate	17%	Packaging materials	
Perborate mono hydrate	8.7%	Paper woody U B250 (1998)	21.7g
Perborate tetra hydrate	11.5%	Corrugated cardboard	108.2g
Antifoam S1.2-3522	0.5%	HDPE B250 (barrier)	8.1g
FWA DAS-1	0.2%		
Polyacrylate	4%		
Protease	1.4%		
Sodium sulfate	0.4%		
Water	14.2%		

played in **Table 5**. The following phases have been taken into account: ingredient supplier, detergent manufacturer, packaging, consumer and disposal stage. Transportation from supplier to manufacturer, manufacturer to retailers, as well as retailer to consumers has been excluded from this specific analysis since no database is readily available. The contribution of the transportation, however, is expected to be relatively low. A quantification of these stages will be done in future studies. The results presented in this section are for illustrative purposes. The relative values between different life-cycle stages, however, is believed to still be representative even though the absolute values are expected to change over time and from country to country due to differences in the electricity grids, consumer habits, products, disposal practices, etc.

4.2 Inventory results of washing in Belgium

Results for energy and emissions were obtained using the methods described earlier in this section and are presented in **Table 6**. For a few selected inventory end-points (primary energy, CO_2, BOD and total solid waste) the distribution between the different stages is presented in **Fig. 3**.

In terms of total energy, the majority of consumption occurs during consumer use (~80%), followed by the manufacturing of the ingredients (~16%). The formulation process, the disposal of spent wash water and the manufacturing of packaging raw materials constitute only a minor fraction (1.4, 1.5 and 0.4%, respectively) of the total energy use. This distribution reflects the electricity grid of the country, its consumer habits and, to a lesser extent, the composition of the detergent. The primary energy reported by the LCI is the summation of the energy usage at each stage in the life cycle, corrected for production efficiency. Consequentially, an electricity grid composed of fossil fuel will result in a much higher total energy consumption at the consumer use stage than a grid composed nuclear power or hydro-electrical power, even if the consumption of electricity by the washing machine is the same.

An important conclusion supported by this LCI is that an evident way to decrease the total energy consumption by laundry detergents is by promoting the use of lower wash temperatures. This would require the design of laundry detergents that can deliver high cleaning performance at lower temperatures. The ideal laundry detergent would deliver good performance at ambient temperatures.

The results of the solid waste phase of this LCI show that ~64% of total solid waste is generated as a result of consumer use and is directly correlated with the production of ashes from energy generation. The two next largest contributors are the disposal (due to sludge from WWTP) and ingredient supply stages (19.4% and 12.6%, respectively). Disposal of packaging and the solid waste associated with the manufacturing of the packaging and its raw materials represent merely 3.3% of the total solid waste production. This number could decrease even further if disposal routes other than landfilling such as incineration, recycling, composting, etc. were considered.

Air emissions occur primarily during the supplier and consumer use stages, are proportionally higher during consumer use and are directly correlated to energy generation from fossil fuels. In countries that derive most of their energy from nuclear or hydro-energy, like France and Sweden, air emissions such as CO_2, SO_X, NO_X are expected to be much lower. For other air pollutants such as dust particles and VOCs, the highest emissions are reported at the supplier stage. For example, in the case of citric acid 50% of dust particle emissions are associated with the production of the material (data not shown).

Emissions to water have a totally different profile. Their distribution among the different stages is highly dependent on the chemical considered. More than 98% of BOD and COD emissions to water occur during the disposal stage. This is not surprising, since almost 100% of the chemicals used during the wash are discharged to the sewer. These

Table 6: LCI of a traditional granular laundry detergent used in Belgium, based on 1000 wash loads

Life-Cycle Stage → Energy & Emissions ↓	Units	Raw Material Supply	Manufacture	Consumer Use	Disposal	Packaging
Energy						
Process energy	GJ	1.73	0.25	3.93	0.09	
Transport energy	GJ	0.26	0.00	0.00	0.00	
Feedstock	GJ	0.68	0.00	0.00	0.00	
Primary energy	GJ	2.78	0.25	13.70	0.26	0.07
Solid waste						
Sludge solids	kg	0.39	0.00	0.00	18.70	0.02
Other solids	kg	12.60	0.73	66.20	1.24	3.09
Total solids	kg	13.00	0.73	66.20	20.00	3.11
Air emissions						
CO_2	kg	125.00	13.30	387.00	16.20	2.21
CO	g	67.80	6.00	81.40	2.08	1.57
SO_x	g	707.00	69.60	1280.00	48.10	24.00
NO_x	g	390.00	32.90	918.00	20.40	9.16
CH_4	g	228.00	0.00	1370.00	107.00	3.17
C_xH_y	g	516.00	109.00	107.00	5.96	7.67
Particles/dust	g	500.00	17.60	461.00	10.80	1.79
Metals	g	1.48	0.00	21.10	0.48	0.09
Waterborne emissions						
BOD	g	117.00	4.90	0.07	8580.00	1.59
COD	g	175.00	10.10	1.48	20700.00	9.01
Total P	g	45.90	0.00	3.98	0.06	0.00
Total N	g	19.10	0.00	4.72	0.12	0.15
Solids	g	56.60	0.00	0.00	0.00	0.00
Oil/grease	g	10.20	0.00	13.50	0.91	0.70
Phenol	g	0.17	0.00	0.07	0.00	0.00
Ammonia	g	1.09	0.00	3.50	0.07	0.04
Metals	kg	0.10	0.00	0.41	14.20	0.00

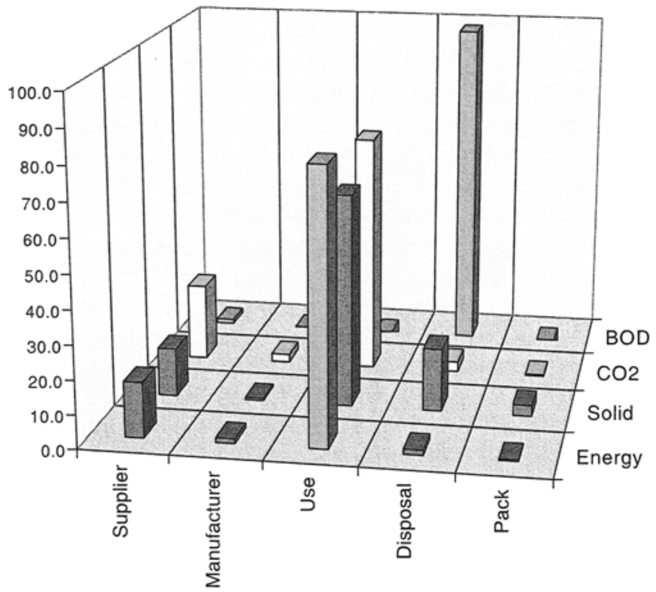

Fig. 3: Total energy consumption, solid waste, CO_2 and BOD distribution between supplier, manufacturer, use, wastewater treatment and packaging from the LCI of 1000 wash cycles in Belgium using a traditional laundry detergent powder

discharges represent a very low percentage of the total BOD originally present in the detergent, as a large fraction (90% on average for BOD) is removed during wastewater treatment. More than 96% of metal emissions occur during the disposal phase. Most of the discharged metal (99.95%) is sodium (data not shown), which is the counter-ion for many detergent ingredients and is discharged as a salt (sodium carbonate, sodium silicate, sodium perborate, etc.).

4.3 Impact assessment results of washing in Belgium

Impact Assessment Methods were developed as tools to broaden the information and context of LCI data which is largely mass and energy. In addition to amounts of resources used and pollutants released, the environmental context can be obtained, e.g. the conversion and aggregation of carbon dioxide, methane, etc., into an overall greenhouse gas release or burden by the system. The fact that LCI indicates that certain emissions are associated with certain environmental themes or impact categories does not imply that the detergent actually causes effects. It means, however, that in the course of the detergent's life-cycle, emissions are generated that contribute to a pool of similar emissions known to be associated with these environmental themes or impact

Table 7: Results of Impact Assessment using an updated version of the CML92 method for a granular laundry detergent used in Belgium. Bold numbers highlight the highest contribution phase for each impact category

Life-Cycle Stage → **Impact Category ↓**	**Raw Material Supply**	**Manufacture**	**Consumer Use**	**Disposal**	**Packaging**
Acidification	32.6	2.9	**61.6**	2.0	0.9
Aquatic toxicity	3.2	0.0	21.7	**74.9**	0.1
Eutrophication	11.7	0.7	20.1	**67.3**	0.2
Greenhouse effect	22.7	2.4	**71.5**	3.1	0.4
Human toxicity	31.3	2.8	**62.6**	2.1	1.1
Ozone depletion	43.0	0.0	**50.2**	3.6	3.2
Photochemical	**66.3**	14.0	17.7	1.0	1.0

Table 8: Impact of the electricity grid (UCPTE, Belgium and Norway grids) used at the disposal stage (wastewater treatment plant) to calculate impact assessment scores based on the modified CML92 method. The Table reports results at the disposal stage only (percentage versus UCPTE) and taking into account all the stages (full LCA)

		Disposal only			**Full LCA**		
Class	**Unit**	**UCPTE**	**Belgium**	**Norway**	**UCPTE**	**Belgium**	**Norway**
Acidification	Kg SO$_2$	100	62.5	3.1	100	99.5	98.4
Aquatic toxicity	m^3 water polluted	100	100.2	99.6	100	100.0	99.7
Eutrophication	Kg PO$_4^{3-}$	100	100.0	99.3	100	100.0	99.6
Greenhouse effect	Kg CO$_2$	100	91.4	47.2	100	99.7	98.3
Human toxicity	kg body weight	100	61.8	6.2	100	99.1	98.3
Ozone depletion	Kg CFC-11	100	27.1	2.3	100	97.0	95.8
Photochemical	Kg C$_2$H$_4$	100	54.5	23.0	100	99.8	99.5

categories. Used this way, LCIA is the appropriate tool to help determine to what extent a particular product, process or ingredient's emissions may be associated with a particular impact category.

The result of the LCA identifies the use stage as the largest contributor for the impact assessment categories related to air emissions (greenhouse effect, acidification, ozone depletion and human toxicity) (**Table 7**). In each case, the major contributing emissions are energy-related due to the heating of the water in the washing machine, and not to the use of a specific detergent or ingredient.

As would be expected from the inventory table, the largest contributor for aquatic toxicity and eutrophication occur at the disposal stage (Table 7). This is due to the discharge of the fraction of chemicals assumed not to be removed in wastewater treatment plant effluents. Since the detergent analysed in this study was phosphate-free, any eutrophication impact potential would be attributable to nutrients other than phosphate, in addition to any organic matter (BOD) released.

Having 66% of the total score associated with it, the supplier stage was identified as the largest contributor to the photochemical smog impact category. These emissions consisted almost entirely (98.8%) of volatile organic carbons (VOCs) from process fuel emissions.

5 Interpretation of the Result of Life Cycle Washing in Belgium

5.1 Impact of use of UCPTE model at the disposal stage

When a life cycle inventory is constructed for a specific country, the environmental emissions related to the energy consumption at the disposal stage (wastewater treatment) are always calculated based on the UCPTE Buwal 250 database. We made this simplification with the assumption that energy consumption in the disposal stage will have a small contribution to the overall energy consumption of the system studied (1.5% of the total energy consumption). To verify this assumption, the life cycle assessment presented in Table 7 was recalculated using Belgium and Norway electricity grids. The Norway electricity grid is used to see the impact of a grid composed mainly of hydropower (99.2%). The results of the analysis show that the use of different electricity grids for minor energy consuming stages such as disposal has a very low impact on the *overall* impact assessment scores (**Table 8**). With the extreme situation of Norway, where energy related emissions are very low (99.2% of the electricity is produced from hydropower), the impact assessment scores have decreased from 0.2 up to only 1.7%. However, when the disposal stage is analysed alone, the choice of the appropriate electricity grid is crucial: individual impact assessment scores for the disposal stage can decrease up to 97.7% (Table 8). The choice of the electricity grid for different life cycle stages will therefore have to be adapted to the goal and scope of individual studies. The database system that we have constructed allows for such flexibility.

5.2 Limitations of the current system

A number of limitations can be listed:

1. The life cycle assessment performed with this database is based on ingredient inventory studies representative of manufacturing processes at a certain time period. It is highly probable that the chemical production processes performed by the suppliers have been improved leading to lower energy requirements and environmental emissions. The results, therefore, are not a true reflection of the environmental profile of the product, but should be seen as an estimation only. The limited number of ingredient inventories available also greatly limits the possibility to analyse a formula in all detail. For some ingredients present in the formula, there is no inventory available. Based on the current database, the discriminative power of the life cycle approach for a detergent product comparison is therefore limited and interpretations should be made with great care.
2. The inventory studies incorporated in our database are mainly based on BUWAL 250, but 2 other energy database are also used: ETH94 and I. Boustead. A harmonisation of the energy database may be needed.
3. The type of washing machines used by consumers in the different European countries, which may be different, has also not been included. The impact of this omission, however, is difficult to assess without a first understanding of the situation in each country.
4. The disposal stage of the packaging (recycling, landfill, incineration, etc.) is not yet included in the current system.
5. A sensitivity analysis is not yet available from our current system.

6 Conclusion and Outlook

The SimaPro database was customized specifically to conduct life-cycle inventories and impact assessments of P&G laundry detergents. LCI can take into account the manufacturing of the ingredients and the formulation of the end product, transportation, the packaging operation, consumer use of the product, the disposal of the product by the consumer and the wastewater treatment plant operation. For the ingredient's supply, the manufacturing process and packaging, life cycle inventories used are representative of the average European situation. For the consumer use and disposal stages, the LCI relies on country-specific data (wash habits, disposal practices).

The construction of the database allows a rapid, consistent and transparent execution of an LCI for P&G laundry detergents. It enables the ranking of the life-cycle phases in terms of their contributions to a certain emission or impact category. The analysis presented here clearly demonstrates the qualitative conclusion that, from an LCA point-of-view, the product use stage is the most important one; most of the emissions and therefore most of the environmental impact scores are driven by how the consumer uses the detergent. Most of these emissions are generated during the production of energy to heat the water. Quantitatively, the impact of the consumer use stage is very sensitive to variability in consumer habits as well as the characteristics of the local electricity grid.

It is clear that the validity of a comparison between two isolated stages of the life cycle of a detergent (i.e comparing 2 products only) is more limited with the current database. The number of inventories available is rather small when compared to the multitude of ingredients used in laundry detergents. In some cases more robust links need to be established between the product's ingredients and the available inventories. Some inventories are outdated , some are of limited use because they are representative of only one manufacturing site. Different energy databases have also been used to calculate the ingredient inventories and the consistency between fuel values, reduction to elementary flow, inclusion and exclusion criteria, allocation, etc. has not been assessed.

For the purpose of an LCA with the intent to examine the different stage for one product, the variability associated with the selection of the chemical inventories is less critical. It is recommended that the most recent inventories be used since they are considered of superior quality and more representative of the current situation. The most recent inventories published by [14] are therefore highly recommended.

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