

LCA Case Studies

The Effect of Compact Formulations on the Environmental Profile of Northern European Granular Laundry Detergents

Part II: Life Cycle Assessment

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Abstract. The environmental profile of laundry detergents at three time points (1988, 1992, and 1998) were compared on the basis of two distinct, complementary approaches: Environmental Risk Assessment (ERA) and Life-Cycle Assessment (LCA). The results are presented in this paper and its accompanying paper in this issue (Part I: Product Environmental Risk Assessment). Life-Cycle Inventory (LCI) data from The Netherlands and Sweden were used for this retrospective analysis. The chosen time period studied (1988 – 1998) spans significant, multiple formulation and process change in laundry detergents, including the introduction of compact, then super-compact, granular detergents. Cradle-to-Gate LCAs based on 1 kg of finished product (from raw material supply to packaged finished product leaving the suppliers site) revealed no significant differences between the products themselves, as manufactured between 1988, 1992 and 1998. Cradle-to-Grave LCAs based on 1000 wash cycles (from raw material supply to disposal of used product) indicated that the consumption of raw materials and energy, as well as environmental emissions (air, water and solid waste), decreased after the introduction of compact detergents in 1988. The LCAs revealed that a number of category indicator values decreased (for acidification, aquatic toxicity greenhouse effects, eutrophication, toxicity, ozone depletion and smog). Furthermore, the results of the LCAs support the conclusion that the differences between The Netherlands and Sweden are due to (1) differences in electrical generation between the countries, (2) differences in energy consumption during consumer use, (3) differences in detergent dosage per wash and (4) differences in the wastewater treatment infrastructure.

Keywords: Compact detergent; consumer habits; granular laundry detergents; LCA case studies; LCA; LCI; life cycle assessment; life cycle impact assessment; life cycle inventory; regular detergent

Introduction

The introduction of compact powder detergents in the early 1990s was the result of major technological innovation in the detergent industry. In order to accomplish this, products with higher weight-efficiency had to be developed. The 'compacts' required less packaging and were accompanied by a reduction in manufacturing waste and less laundry detergent use per wash load, hence a reduction in environmental

releases from several points in the life cycle, including households [1-4]. The compact products promised the same number of wash loads along with environmental benefits such as smaller packages. However, compacts have met with varying degrees of consumer acceptance in different European markets, ostensibly due to differences in consumer laundering practices and cultural preferences. The high level of success of compact detergents in Northern Europe may be related to a more environmentally-conscious consumer and a clearer perception of environmental benefits in terms of resource-efficiency and safety. However, such perceived benefits have not been systematically analyzed nor communicated to consumers to date.

The environmental profiles of 1988-regular, 1992-compact and 1998-super compact granular detergents, as represented by formulations of The Procter & Gamble Company (P&G), were analyzed using two different, complementary approaches: Environmental Risk Assessment (ERA) and Life-Cycle Assessment (LCA). ERA is the evaluation of the probability that a specific, adverse effect will occur as the result of a certain exposure. LCA is a methodology developed to evaluate the mass balance of inputs and outputs of industrial systems in their entirety. The Life-Cycle Inventory (LCI) refers to the mass balance itself. Each approach provides a unique environmental analysis by compiling different information from distinct perspectives. The Environmental Risk Assessments of the products discussed herein are presented in Part I (this volume). Part II: Life-Cycle Assessment (this paper) follows here with the results of the Life-Cycle Inventories and Impact Assessments.

1 Goal and Scope Definition of the Study

1.1 Goal of the LCA

Our objective was to compare the environmental profiles of Procter & Gamble granular laundry detergents over time in The Netherlands and Sweden. P&G products for Sweden have been developed to be compliant with the national Ecolabel scheme¹ since 1996, while this has not been the

¹ A discussion about the relevance and benefit of the Nordic Swan Ecolabel or national ecolabelling schemes in general is outside the scope of this paper

case for The Netherlands. If these assessments would demonstrate positive or negative differences, an additional objective was to characterize those differences and understand the formulation and process changes that caused them.

The analysis was performed into two successive steps:

1. A product comparison based on 1 kg of finished product, focusing on changes on raw material usage (chemicals and packaging) and manufacturing processes. This step is referred later as 'cradle-to-gate' analysis.
2. A life cycle comparison using country specific product usage and disposal practices. This step is later referred to as 'cradle-to-grave' analysis.

Three products selected for this analysis were: Ariel Regular (1988-regular), representing the traditional granular detergent; Ariel Ultra (1992-compact), representing the first-generation compact granular detergent and Ariel Futur (1998-super compact), representing the second generation or 'super-compact' granules. The years 1992 and 1998 were selected for this analysis because, these dates reflect the timing when compacts and super compacts were the majority of detergents sold in the Dutch and Swedish markets [5].

The LCA presented in this article was peer-reviewed by the Ecobilan PwC group² (Paris, France) as defined by ISO standards [6,7].

² The critical review report from Ecobilan PwC as well as the full P&G LCA report can be made available upon request

1.2 Scope of the Study

1.2.1 Description of the system studied and Functional units

The different stages of a detergent's life-cycle that are included in this analysis are: chemical raw material supply (supplier), product formulation (manufacturer), packaging of finished product, transportation from formulator to retailer, consumer use and disposal (Table 1). The transportation of raw materials to product formulator and from retailer to consumers' homes were not included. The information is not readily available and is not expected to significantly affect the results of the LCA.

A first analysis (step 1: product comparison, see Table 1) was conducted on the following stages: chemical raw material supply, formulation of finished product and packaging. The packaging includes the detergent pack (primary packaging) and any additional packaging materials needed during the transportation of the products (secondary and tertiary packaging). All results were expressed on the basis of a functional unit of 1 kg of finished product. Specifications of product and package for 1988-regular, 1992-compact, and 1998-super compact detergents are provided in Table 2. Raw material quantities were not reported, because this information is considered to be confidential by the formulator.

Table 1: Description of the life-cycle stages taken into account to compare laundering with P&G 1988-regular, 1992-compact and 1998-super compact detergents in The Netherlands and Sweden

Step 1: Cradle-to-gate analysis	Included	Excluded	Comments
1. Manufacturing of detergent ingredients (supplier)	– Extraction of raw materials, transportation and manufacturing of final chemicals	– Transportation from chemical suppliers to detergent manufacturer (i.e. P&G)	– The same life cycle inventory ingredient database for 1988-regular, 1992-compact and 1998-super compact detergent products is used
2. Packaging	– Manufacturing of packaging raw materials – Additional packing materials used for the transportation of product to retailers (see stage 4)	– Manufacturing of the pack – Packaging solid waste disposal practice (100% of the packing materials are considered as solid waste) – Transportation to detergent manufacturer (i.e. P&G)	– The same life cycle inventory packaging database for 1988-regular, 1992-compact and 1998-super compact detergent products is used
3. Product formulation (Manufacturer)	– Formulation of finished detergents		– Manufacturing process of 1992-compact is used for 1998-super compact product
Step 2: Cradle-to-grave analysis	Included	Excluded	Comments
4. Transportation from product manufacturer (i.e. P&G) and retailers	– Diesel truck transportation from Belgium to one single point delivery considered in The Netherlands and in Sweden	– Distribution of the products inside the country to all retailers	– Same transportation energy data used for 1988 and 1998
5. Consumer use	– Product dosage – Wash temperature distribution	– Transportation from retailer to consumer's house	– Same composition of electricity grid [10] used across the time period studied – Same energy washing machine requirements
6. Disposal (wastewater treatment plants, WWTP)	– Collected sewer (Untreated, primary, secondary and tertiary treatment)	– Other type of treatments (septic tank, etc.)	– WWTP process representative of the Dutch situation – Same electricity grid [10] used across the time period studied

Table 2: Product and packaging specifications of the 1988-regular, 1992-compact and 1998-super compact granular laundry detergent in The Netherlands and Sweden

	The Netherlands			Sweden		
	1988	1992	1998	1988	1992	1998
Product type	regular	compact	super compact	regular	compact	super compact
Packaging specifications	carton	carton	carton / refill (5/95)	carton	carton	carton
Total Package weight (g/pack)	595.2	247.8	182.1/75.9	595.2	247.8	80.7
Primary (g/pack)	582.3	245.1	109/12.5	582.3	245.1	46
Secondary (g/pack)	-	-	66/62.5	-	-	31.8
Tertiary (g/pack)	12.9	2.7	7.1/0.9	12.9	2.7	2.9
Package capacity (kg)	10	5	1.5	10	5	0.75
cardboard [10]	x	x	x	x	x	x
Corrugated Cardboard [10]	x			x		
HDPE [10]	x	x	x	x	x	x
Paper [10]	x	x	x	x	x	x
PET [10]			x			
PP [10]			x			
Steel [10]	x	x		x	x	
Formula specification						
Material inventories included						
Percentage of formula (weight basis excluding water) for LCI inclusion	98.8%	91.9%	90.3%	84.3%	91.9%	90.5%
AE3S-pc [16]			x			x
AE7-pc [22]	x	x	x		x	x
AE11-PO [22]		x		x	x	
Antifoam [18]	x	x	x	x	x	x
APG-CNO [15]			x			x
AS-pc [14]			x			x
AS-PO [14]	x		x			x
Cationic surfactant [17]			x	x		x
Citric acid [18]		x	x		x	x
Carboxy methylcellulose [17]	x		x	x		x
FWA DAS-1 [17]	x	x	x	x	x	
LAS-pc [19]	x	x	x	x	x	
Na-silicate [17]	x	x	x	x	x	x
Perborate tetrahydrate [17]	x	x		x	x	
Perborate monohydrate [17]	x	x			x	
Percarbonate [17]			x			
Polyacrylate [17]	x	x	x	x	x	x
Savinase 10 TA+ [20]	x	x	x	x	x	x
Layered silicate [17]			x			x
Soap PKO/Ta [21]				x		
Sodium bicarbonate [18]			x			
Sodium carbonate [17]	x	x	x		x	x
Sodium sulfate [10]	x	x	x	x	x	x
Sodium tri-poly-phosphate [17]				x		
Zeolite A powder [17]	x	x			x	x
Inventories missing						
Percentage of formula (weight basis excluding water) excluded from LCI	1.2%	8.1%	9.7%	5.7%	8.1%	9.5%
Ethylene Diamine Tetraacetic Acid A	x			x		
Dye	x	x	x	x	x	x
P&G proprietary ingredient				x		
Clay				x		
Perfumes	x	x	x	x	x	x
Sodium toluene sulphonate				x		
Phosphonate	x	x	x		x	x
TAED	x	x	x		x	x
AE25 or 80	x					x
Polymer			x			x
Soil release polymer			x			x
Starch			x			x
Sorbitol			x			x
Ethylene diamine disuccinate			x			x
Water	5%	6.3%	3.8%	8.3%	6.3%	3.7%
x: used in corresponding product						

Table 3: Wash temperatures and recommended dosages for P&G products in The Netherlands and Sweden

	The Netherlands			Sweden		
	1988	1992	1998	1988	1992	1998
Product specifications						
type	regular	compact	super compact	regular	compact	super compact
name	Ariel	Ariel Ultra	Euro Futur	Ariel	Ariel Ultra	Ariel Futur
recommended dosage (g/wash)	153	109	75	115	51	37.5
Temperatures (% of loads)^a						
prewash	25	n.a	12	16	n.a	16
30°C	7	n.a	18	3	n.a	4
40°C	32	n.a	40	47	n.a	49
60°C	41	n.a	33	37	n.a	42
>60°C	20	n.a	9	13	n.a	5
Disposal practices^b						
no treatment	13	n.a.	10	6	n.a.	5
primary treatment	8	n.a	9	1	n.a	1
secondary treatment	72	n.a	79	11	n.a	10
tertiary treatment	7	n.a	2	82	n.a	84

a) Data from 1998 are from [2], data from 1988 Sweden are from [2;24] and data from 1988 in The Netherlands are from the P&G internal database

b) Data for 1988 represent disposal practices in 1985 [25] and data for 1998 represent disposal practices in 1993 [26]

n.a: not available

The second analysis (step 2: wash-cycle comparison, see Table 1) included transportation from formulator (P&G) to retailer as well as the consumer use stage and the disposal stage. All data was expressed on the basis of a functional unit of 1000 wash cycles, using the recommended product dosage data for each year and country. Supporting data is provided in Table 3. Because of the lack of detailed consumer use data for compacts in 1992, this product scenario was not included in this second analysis. The consumer use data for 1988-regular and 1998-super compacts included the recommended detergent dose per wash cycle and data on the consumer's actual wash temperature selection. The country-specific frequency distribution of wash temperatures (% of washes performed at 30°C, 40°C, 60°C and >60°C) in The Netherlands and Sweden for 1988-regular and 1998-super compacts are summarized in Table 3. The energy requirements for laundering such as water volume, heating efficiency, etc., were assumed to be unchanged between 1988 and 1998. The analysis is further restricted to machine laundering using country-specific consumer use and disposal habits, assuming exclusive use of Procter & Gamble (P&G) granular laundry detergents and a typical wash load weight of 4.5 kg. No distinction was made between fabric types (i.e. white vs. color) and their wash frequencies.

1.2.2 Database and data quality requirements

An LCI and Impact Assessment database for P&G laundry detergents was constructed using SIMAPRO software [8]. The database structure, inherent assumptions and calculation methods are fully described in Saouter et al. 2001 [9]. The principle inclusions and exclusions in the system studied are summarized in Table 1. In brief, the data needed to construct a product LCI were retrieved from the following

supporting databases: 1. Energy consumption and the environmental emissions associated with it were either calculated using the BUWAL 250 energy database [10] for transportation, packaging, use and disposal stages, or were obtained from other sources [11-13] for raw material supply and finished product formulation stages. 2. LCI information on raw materials was retrieved from published sources [14-22]. 3. LCI data describing the different manufacturing processes was from a previously published study [23]. 4. LCI data for different types of packaging is included with commercial SIMAPRO software and was used as such [10,12]. 5. LCI data for the laundry process was obtained from the European Washing Machine Manufacturer Association (CECED) and from the Association Internationale de la Savonnerie, de la Détergence et des Produits d'Entretien (AISE) [2,24]. 6. LCI data associated with different forms of wastewater treatment was from published country statistics [25,26].

Energy consumption and emissions during the packaging stage are included in the corresponding raw material inventories, but these do not include post-consumer disposal. Packaging raw materials are considered a solid waste after use and are included as such in the total solid waste. The same is true for ashes from energy generation and sludge from wastewater treatment plants. All of this data is of high quality and representative of the average European situation.

LCI data for transportation of finished product between P&G manufacturing plants in Belgium and European retailers was calculated based on diesel trucks traveling a distance of 200 km and 1500 km to a single delivery point in The Netherlands and Sweden, respectively. Energy requirements and environmental emissions associated with transport were calculated for a given product and truck capacity. This data is also of high quality and is representative of the average European situation.

2 Inventory Analysis

The calculation methods to report inventory results are fully described in [9] and, therefore, are not repeated here.

The results of the 'cradle-to-gate' LCI of the granular laundry products are presented in **Table 4**. Energy consumption data is reported separately for the raw material supply, the formulation of finished product and the packaging. Environmental emissions are reported as totals for each of these three stages.

The results of the 'cradle-to-grave' LCI are reported in **Table 5**. Energy consumption and environmental emission data is reported separately for the raw material supply, the formulation of the finished product, the packaging, the transportation, the use and disposal stages.

3 Impact Assessments

Among the various LCA methods that are available, CML92 was selected [27] because it was available from the developer of SIMAPRO [8]. Emissions reported in the inventory analysis undergo characterization and classification [28,29]. Among the various impact categories that can be used in LCA, the ones reported in this study are: acidification, aquatic toxicity, eutrophication, greenhouse gases, human toxicity, ozone layer depleting substances and smog formation. The following implementations were made to the eutrophication and ecotoxicity impact categories within CML92:

- For eutrophication, CML92 assumes that the organic materials discharged to surface water indirectly contribute to eutrophication by oxygen depletion due to biodegradation. That is, in addition to classical limiting

Table 4: 'Cradle-to-gate' LCI input and output for 1 kg of 1988-regular, 1992-compact and 1998-super compact granular laundry detergent in The Netherlands and Sweden

		The Netherlands			Sweden		
		1988 regular	1992 compact	1998 super compact	1988 regular	1992 compact	1998 super compact
Energy							
Supplier	MJ	29.5	28.2	30.3	22.2	28.2	30.2
Manufacturer	MJ	2.46	2.38	2.38 ^a	2.46	2.38	2.38 ^a
Packaging	MJ	2.16	1.93	2.61	2.16	1.93	2.28
Total	MJ	34.1	32.5	35.3	26.8	32.5	34.9
Total solid waste							
Sludge	g	5.0	5.4	5.8	4.1	5.4	5.7
Other solids	kg	0.2	0.2	0.2	0.2	0.2	0.2
Total	kg	0.2	0.2	0.2	0.2	0.2	0.2
Total airborne emissions							
CO ₂	kg	1.5	1.5	1.6	1.4	1.5	1.6
CO	g	1.9	2.2	2.8	2.4	2.2	2.7
Sox	g	10.8	9.4	10.8	11.7	9.4	11.1
Nox	g	4.8	4.7	6.2	5.6	4.7	6.2
CH ₄	g	2.5	2.1	3.6	8.9	2.1	3.8
CxHy	g	8.7	6.5	8.0	5.2	6.5	8.4
Part./dust	g	4.2	6.0	5.3	3.0	6.0	5.9
metals	mg	10.5	15.3	13.2	18.4	15.3	16.2
Total waterborne emissions							
BOD	mg	377	1230	913	297	1230	1230
COD	g	0.9	2.0	1.5	0.7	2.0	2.1
Tot-P	g	0.01	0.5	0.2	0.01	0.5	0.4
Tot-N	g	0.2	0.2	0.3	0.2	0.2	0.2
Solids	g	11.4	14.6	17.4	695.0 ^b	14.6	16.5
Oil/grease	g	0.1	0.1	0.1	0.2	0.1	0.1
Phenol	mg	1.6	1.7	2.1	1.7	1.7	1.9
Ammonia	g	0.05	0.1	0.1	0.1	0.1	0.1
Metals	g	2.5	1.0	0.8	0.4	1.0	0.9

a) Energy requirement corresponds to the compact process (1992) as no inventory on super compact is available

b) These solid waste emissions are mainly determined by the phosphate inventory (2.89 kg of suspended solid per kg of STPP produced [17])

Table 5: Energy consumption and environmental emissions per 1000 wash cycles with 1988-regular, and 1998-super compact granular P&G detergents used under Dutch and Swedish conditions

Class	Unit	The Netherlands 1988						The Netherlands 1998					
		Supplier	Manu- facturer	Packag- ing	Transport	Use	Disposal	Supplier	Manu- facturer	Packag- ing	Transport	Use	Disposal
Process energy	MJ	2680	377	104	65	4650	320	1320	178	74	31	3660	160
Primary energy	MJ	4510	377	337	75	15000	878	2270	178	197	36	11800	439
CO ₂	kg	203.0	20.3	6.7	5.1	967	55.4	108.0	9.7	3.8	2.5	762	32.2
CO	g	273.0	9.2	5.6	28.1	235	7.1	205	4.7	4.2	13.5	185	3.6
SO _x	kg	1.50	0.11	0.05	0.008	2.5	0.16	0.71	0.05	0.014	0.004	1.9	0.08
NO _x	kg	0.66	0.05	0.03	0.09	2.1	0.07	0.42	0.02	0.017	0.04	1.7	0.03
CH ₄	kg	0.37	-	0.012	0.006	2.9	0.4	0.27	-	0.008	0.003	2.3	0.2
C ₂ H ₆	kg	1.14	0.17	0.02	0.03	0.23	0.020	0.50	0.08	0.023	0.02	0.18	0.010
Particles/dust	kg	0.61	0.026	0.004	0.002	0.8	0.04	0.37	0.016	0.003	0.001	0.6	0.02
Metals	g	1.41	-	0.20	0.021	36.7	1.6	0.81	-	0.05	0.010	28.9	0.8
BOD	kg	0.05	0.01	0.004	7E-06	1E-04	5.08	0.06	0.003	0.002	3E-06	8E-05	3.15
COD	kg	0.10	0.02	0.021	0.0002	0.002	11.1	0.09	0.006	0.010	0.0001	0.002	6.3
Tot-P	g	1.2	-	0.02	0.0005	6.8	0.19	15.0	-	0.02	0.0003	5.4	0.10
Tot-N	g	23.8	-	2.4	0.3	5.0	0.4	19.0	-	1.7	0.2	4.0	0.2
Solids	g	1750	-	5.5	0	0	0	1300	-	2.4	0	0	0
Oil/grease	g	13	-	1.6	2.1	27.6	3.0	6.1	-	0.4	1.0	21.7	1.5
Phenol	g	0.2	-	0.009	0.010	0.1	0.016	0.15	-	0.003	0.005	0.1	0.008
Ammonia	g	6.9	-	0.10	0.17	2.3	0.2	5.5	-	0.04	0.08	1.8	0.1
Metals	kg	0.4	-	0.002	0.0007	0.8	22.6	0.06	-	0.001	0.0004	0.6	11.3
Sludge	kg	0.50	-	0.28	0	0	48.5	0.40	-	0.20	0	0	22.8
Other solids	kg	26.4	1.1	1.4	0	116	13.11	13.4	0.6	1.3	0	91.4	6.07
Total solids	kg	26.9	1.1	1.6	0	116	61.7	13.8	0.6	1.5	0	91.4	28.9
Class	Unit	Sweden 1988						Sweden 1998					
		Supplier	Manu- facturer	Packag- ing	Transport	Use	Disposal	Supplier	Manu- facturer	Packag- ing	Transport	Use	Disposal
Process energy	MJ	1500	283	78	364	4140	77	661	89	71	123	3820	33
Primary energy	MJ	2550	283	253	423	9950	231	1130	89	231	143	9170	100
CO ₂	kg	140.0	15.3	5.0	28.8	73.3	23.1	54.1	4.8	5.3	9.8	67.6	11.3
CO	g	262	6.9	4.2	158.0	19.3	1.69	98	2.4	2.4	53.5	17.8	0.72
SO _x	kg	1.22	0.08	0.038	0.04	0.7	0.04	0.37	0.026	0.03	0.01	0.6	0.02
NO _x	kg	0.58	0.04	0.021	0.5	0.2	0.018	0.21	0.012	0.02	0.2	0.2	0.008
CH ₄	kg	1.01	-	0.009	0.04	0.1	0.2	0.14	-	0.01	0.01	0.1	0.1
C ₂ H ₆	kg	0.45	0.13	0.016	0.18	0.2	0.005	0.27	0.042	0.03	0.06	0.1	0.002
Particles/dust	kg	0.32	0.02	0.003	0.012	0.05	0.010	0.21	0.008	0.005	0.004	0.05	0.004
Metals	g	2.0	-	0.15	0.12	3.1	0.1	0.5	-	0.09	0.04	2.9	0.2
BOD	kg	0.03	0.006	0.003	4E-05	5E-5	1.4	0.043	0.002	0.002	1E-05	5E-05	0.7
COD	kg	0.05	0.011	0.016	0.0013	0.0008	3.5	0.067	0.003	0.009	0.0004	0.0008	1.4
Tot-P	g	1.4	-	0.02	0.003	0.2	1070 ^b	15.2	-	0.006	0.001	0.2	0.02
Tot-N	g	15.6	-	1.8	1.9	3.5	0.11	8.8	-	0.26	0.6	3.3	0.05
Solids	g	79900 ^a	-	4.1	0	0	0	617	-	1.7	0	0	0
Oil/grease	g	16.5	-	1.2	11.7	25.1	0.8	3.5	-	0.6	4.0	23.2	0.4
Phenol	g	0.2	-	0.007	0.06	0.1	0.004	0.07	-	0.006	0.02	0.1	0.002
Ammonia	g	8.6	-	0.07	1.0	2.9	0.07	2.5	-	0.05	0.3	2.7	0.03
Metals	kg	0.05	-	0.001	0.004	0.03	14.7	0.003	-	0.002	0.001	0.03	5.4
Sludge	kg	0.28	-	0.21	0	0	32.9	0.20	-	0.05	0	0	11.7
Other solids	kg	21.9	0.84	1.0	0	18.8	8.0	6.5	0.3	0.4	0	17.3	4.5
Total solids	kg	22.2	0.8	1.2	0	18.8	40.9	6.7	0.3	0.5	0	17.3	16.2

a) These solid waste emissions are mainly caused by the Phosphate inventory (2.89 kg of suspended solid per kg of STPP produced [17])

b) This is solely caused by phosphate in the product. Due to incomplete removal, some amounts of phosphate end in surface water (STPP removal, 5%, 40% and 90% for primary, secondary and tertiary removal, respectively)

nutrients, phosphorus and nitrogen. Therefore, residual detergent ingredients in wastewater treatment plant (WWTP) effluent are converted to chemical oxygen demand (COD).

- For ecotoxicity, characterization factors are applied to residual detergent ingredients in WWTP effluent. Each

ingredient is assigned a characterization factor (WF) that is the inverse of the aquatic effect concentration as listed in the Detergent Ingredient Database [30] and internal P&G database. The aquatic toxicity score of the product is the sum of the aquatic toxicity scores of the ingredients.

Table 6: 'Cradle-to-gate' life-cycle impact assessment results for 1 kg of traditional (1988), compact (1992) and super compact (1998) granular laundry detergent used in The Netherlands and Sweden

	Unit ^a	The Netherlands			Sweden		
		1988 regular	1992 compact	1998 super compact	1988 regular	1992 compact	1998 super compact
Acidification	g SO ₂	15	13.5	17.0	18	13.5	17.2
Aquatic toxicity	m ³ water polluted	22.1	20.9	22.3	218 ^b	20.9	21.9
Eutrophication	mg PO ₄ ³⁻	882	934	1380	1260	934	1360
Greenhouse	kg CO ₂	1.54	1.56	1.86	2.16	1.56	1.86
Human toxicity	kg body weight	0.0178	0.0158	0.0187	0.0218	0.0158	0.0191
Ozone depletion	ng CFC-11	550	317	276	454	317	318
Smog	mg C ₂ H ₄	3350	2620	3230	2130	2620	3400

a) Unit represents the contribution of emissions to an impact assessment category generally compared to reference compounds. See [27] for more information
b) Due to Cd released during the mining of phosphate rock according to [17]

Table 7: 'Cradle-to-grave' life-cycle impact assessment results per 1000 wash cycles with traditional, compact and super compact granular P&G detergents used under Dutch and Swedish conditions. Transportation between formulator's site and country of destination was excluded from the calculation

	Unit ^a	The Netherlands			Sweden		
		1988	1998	main driver	1988	1998	main driver
Acidification	Kg SO ₂	6.6	4.6	energy	3.3	1.4	energy
Aquatic toxicity	m ³ water polluted	50380	34630	dosage	35530	7430	dosage
Eutrophication	Kg PO ₄ ³⁻	693	487	energy	4448	107	Zeolite replaced STPP
Greenhouse effect	Kg CO ₂	1296	961	energy	379	155	energy
Human toxicity	kg body weight	8.14	5.51	energy	4.23	1.82	energy
Ozone depletion	Kg CFC-11	156	72	energy	161	81	energy
Smog	Kg C ₂ H ₄	641	344	energy	390	201	energy

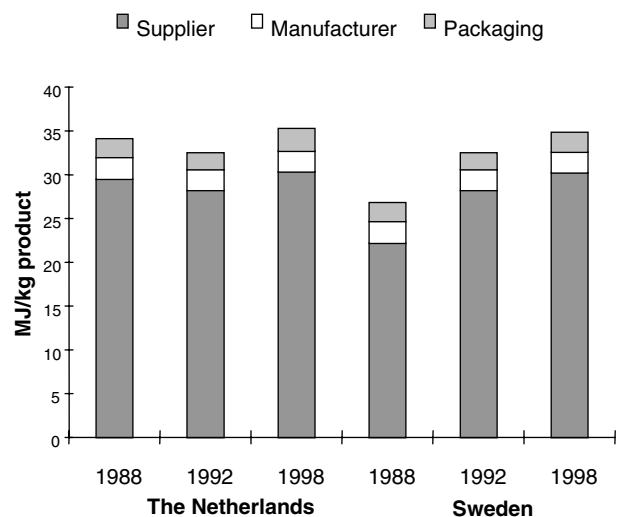
a) Unit represents the contribution of emissions to an impact assessment category generally compared to reference compounds. See [27] for more information

The results of our 'cradle-to-gate' impact assessments, reported on the basis of 1 kg of finished product, are shown in **Table 6**. The results of the 'cradle-to-grave' impact assessments, reported on the basis of 1000 wash cycles, are shown in **Table 7**. Our objective was to make the comparison of products over time and between countries, regardless of where the products were made and how far they would have to be transported. Therefore, transportation from the manufacturing site to the countries of destination was not included in the impact assessment of the 'cradle-to-grave' analysis. Including this stage would increase the Swedish impact scores as all products are produced in Belgium, however the contribution of transportation to the over-all impact assessment is expected to be minimal (Table 5).

4 Interpretation and Discussion

4.1 Product comparisons or 'cradle-to-gate' analyses

Energy consumption. The primary energy (which includes process energy and feedstock energy) required to produce 1 kg of 1988-regular, 1992-compact and 1998-super compact P&G granular laundry detergent is quite similar and ranges from 26 to 35 MJ (**Fig. 1**). The majority of the primary energy (>80%) is associated with the raw material supply stage. The formulation of the product represents less than 9% of the total energy requirement and the packaging raw material around 6-8%. Between 1992 and 1998, an increase in overall energy requirements of up to 10% was observed due to the increased number of ingredients in the 1998-products (Table 2).

**Fig. 1:** Energy requirement to manufacture 1 kg of 1988-regular, 1992-compact or 1998-super compact granular laundry detergent including raw material supply (supplier), product formulation (manufacturer) and packaging

The energy required to formulate the finished products decreased only slightly between 1988-regular process and 1992-compact process (~3%). The manufacturing data was obtained from published LCIs for the production of regular and compact detergents during the early 90s [23]. This data represents an average of different manufacturing sites from different companies in Germany. The manufacture of a regular detergent starts with a hot slurry (~100°C) which is spray-dried in a

'tower' at temperatures up to 300°C. The first generation of compact granules (1992 product) was produced using a combination of spray-drying and dry mixing, leading only to a small decrease in energy consumption from regular to compact processes. The new generation of super compact granules, however, is produced only by dry mixing, starting with a warm paste (~50°C) that is fed into a fluid-bed dryer at about 80°C. Due to the lower temperatures, this process requires much less energy and allows a higher compaction of the granule [31,32]. For lack of an LCI for the super compact process, LCI data for the compact processes of 1992 was used to describe the 1998 super compact process. This clearly caused an overestimation of the energy requirements at the product formulation stage for the super compact products of 1998. The benefits obtained with the super compact formulation process are therefore not represented in this analysis.

Impact assessment. The 'cradle-to-gate' Life-Cycle Impact assessment reveals that the products for The Netherlands and for Sweden were very similar in 1988, 1992 and 1998 (Table 6). These environmental impacts are solely based on the environmental emissions listed in the chemical raw materials, formulation of finished product and packaging LCIs. Few significant differences in the calculated scores, however, can be observed between products:

- The aquatic toxicity impact category for the Swedish formula of 1988 was 10-fold higher when compared to the other products (Table 6). This difference was solely due to the release of cadmium from mining phosphate rock as listed in the LCI of tripolyphosphate [17]. This ingredient was only used in the 1988 Swedish formula.
- Products formulated for The Netherlands and Sweden in 1992 had the same chemical composition (Table 2), leading to identical impact assessments.
- Impact assessment scores for products formulated in 1998 are also very similar³, despite a different chemical com-

³ A difference of less than 20% is not considered significant due to the uncertainties associated with LCA

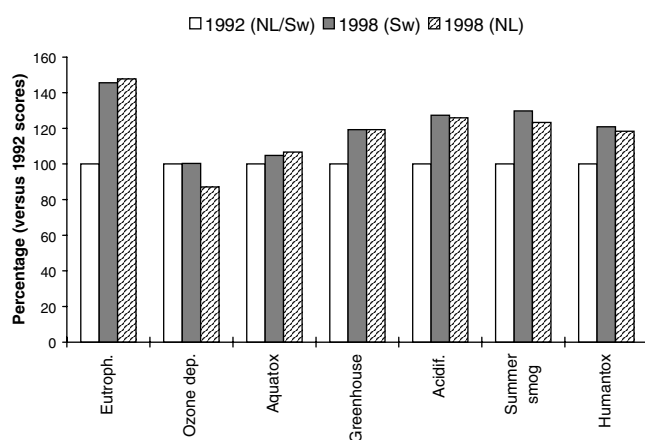


Fig. 2: Normalized assessment scores for environmental impact categories (CML92 method) on the basis of 1 kg of finished product formulated for the Dutch and Swedish markets in 1992 and 1998. All scores were normalized against 1992 scores. The difference between scores must be ≥ 20% in order to be considered significant

position of the Swedish product which had to comply with the Nordic Swan Ecolabel scheme (Fig. 2).

- Between 1992 and 1998, an increase in eutrophication, acidification and smog environmental impact scores was apparent, driven by the increase in the number of ingredients used to formulate the 1998-products (Fig. 2).

4.2 Product life-cycle comparison or 'cradle-to-grave' analyses

When all stages of a life-cycle are taken into account, the results are representative of the function as a whole (in this case, cleaning clothes) rather than of the individual products. Factors such as consumer habits and practices (product dosage per load, whether or not to pre-treat or pre-wash, choice of washing machine settings) and washing machine characteristics (water use, energy use, options for water level, spin speed, number of rinses, type of wash), all play a role.

Energy consumption. A decrease in energy usage was observed between 1988 and 1998 in both countries (Table 5). This correlated with the introduction of compact detergents, resulting in lower detergent consumption due to lower recommended dosages and lower wash temperatures made possible by better low-temperature performance (Table 3) [33].

It is important to note here that the washing machine energy efficiency evolution between 1988 and 1998 has not been taken into account in this analysis because of the lack of adequate publicly available data. The same heating efficiency was used for both periods. The European Committee of Manufacturers of Domestic Equipment (CECED, Belgium), however, have reported in their annual report a decrease in energy consumption of up to 19% between 1994 and 1997. This saving has not been taken into account in our analysis.

The relative contributions of the different stages to the overall energy consumption remained stable between 1988-regular and 1998-super compact for both countries (Fig. 3). In all cases, the bulk of the energy consumption occurs during

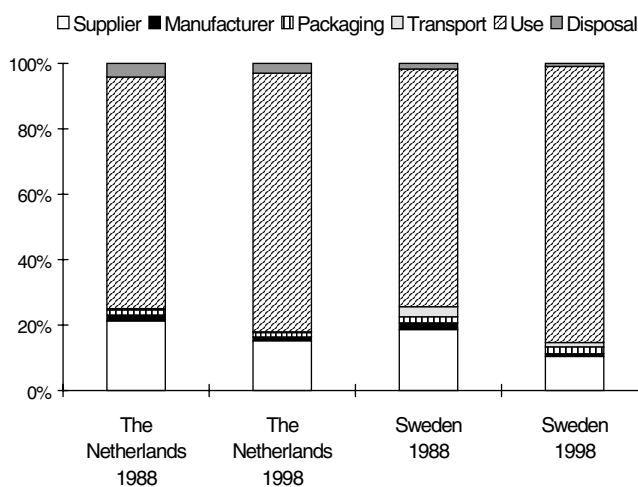


Fig. 3: Relative energy consumption during raw material supply, product formulation, packaging, transportation, use and disposal stages for P&G laundry detergents used in Sweden and The Netherlands in 1988 and 1998

consumer use, accounting for 70-85% of the total energy requirements due to heating of the water and the operation of the washing machine. The second largest contributor is raw material supply, which accounts for 10-21% of total energy consumption. Formulation of finished product, packaging, transportation and disposal together account for only a small percentage of total energy consumed.

Total energy consumption between 1988-regular and 1998-super compact decreased by approximately 30% and 20% in The Netherlands and Sweden, respectively. Most of these energy savings occurred during raw material supply and during consumer use, the latter driven by a substantial decrease in average wash temperature (a shift to 30°C and 40°C with fewer washes at $\geq 60^\circ\text{C}$) and a lower recommended dosage. The total primary energy requirement, however, was higher in The Netherlands (21039 MJ in 1988 and 14864 MJ in 1998) than in Sweden (13452 MJ in 1988 and 10831 MJ in 1998) due to a different electricity generation process in Sweden [10]. The electricity production process in The Netherlands maintains an overall efficiency of 31%, while Sweden does considerably better at 41%. Process energy, which corresponds to the energy consumption of the washing machines in the consumer's homes, was actually quite similar in both countries in 1998 (3660 MJ and 3820 MJ for The Netherlands and Sweden, respectively).

Carbon dioxide emissions. For the most part, the environmental emissions to air followed the same distribution pattern between the life-cycle stages as the energy consumption. This is because most of these emissions are energy-related. In The Netherlands, more than 80% of CO₂ emissions occurred during consumer use and were related to electricity generation from fossil fuel (Fig. 4). The second largest contributor to CO₂ was raw material supply, which accounted for 11-16% of the total CO₂ emitted, mostly from the generation of energy to drive manufacturing processes. The picture was quite different in Sweden, where total CO₂ emissions were 6-fold lower than in The Netherlands. This can be explained

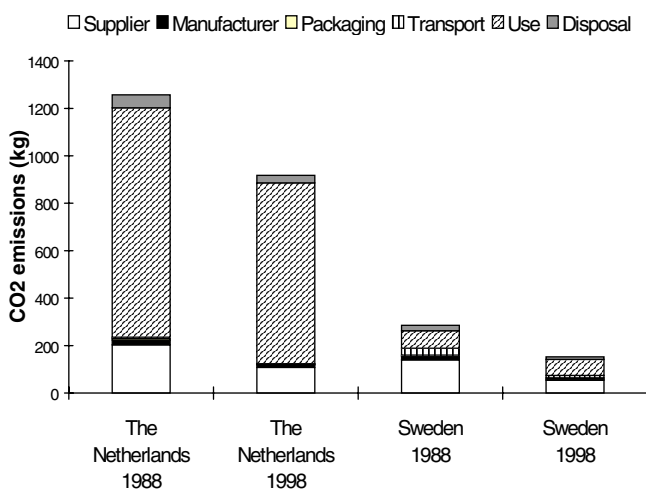


Fig. 4: Estimated CO₂ emissions (kg/1000 washes) for different life-cycle stages of P&G 1988-regular and 1998-super compact granular detergents used in Sweden and The Netherlands

by the use of hydroelectric and nuclear power as the main sources of energy generation in Sweden, versus fossil fuels in the Netherlands. The distribution of CO₂ emissions between the different life-cycle stages was also more balanced in Sweden: 26-45% was generated during consumer use, 36-49% was accounted for during raw material production and up to 8% was emitted mainly from biodegradation during the wastewater treatment process. Between 1988 and 1998, a clear decrease in CO₂ emissions is observed in both countries, mostly due to a decrease of emissions during consumer use (lower wash temperatures) with a smaller reduction due to energy savings at the WWTP (compacts are more weight efficient, so there is less material to be treated).

Biological oxygen demand emissions. The largest part of the total BOD emissions occurred during the disposal stage (Table 5), as is typical for products that are almost entirely discharged to sewers, and from there via WWTPs to the aquatic environment. The observed decrease of BOD emissions between 1988 and 1998 was consistent to the parallel decreases in COD and is attributable to the lower detergent usage per wash. One last interesting observation was that the relative decrease in BOD between 1988 and 1998 in The Netherlands (38.5% decrease) and Sweden (48.25% decrease) was smaller than the relative decrease in COD in these countries (42.9% and 60.4%, respectively). This points to an increase in biodegradable content of the laundry product components during this time period.

Solid waste emissions. Solid waste emissions are the summation of ashes from energy generation, sludges from the WWTP and packaging. The decrease of solid waste between 1988 and 1998 was attributable to the lower energy consumption as discussed earlier and less sludge generation (less BOD to be treated) (Table 5). The absolute quantities of solid waste generated in The Netherlands and Sweden proved to be quite different (131 kg and 39 kg, respectively), again due to the waste ash quantity from the differences in energy generation, as already discussed.

Impact assessment. The observed decreases for selected inventory endpoints were reflected by the impact assessment. The 1988-super compact products had lower impact scores for each of the considered impact categories than the 1988-regular powder products (Table 7). This observation correlated well with the observed decrease in energy consumption and the corresponding decrease in environmental emissions.

A number of observations can be drawn from this analysis:

- The lower eutrophication impact score of the 1998-super compact compared to the 1988-regular in Sweden is explained by the replacement of phosphate builders by Zeolite after 1988. A parallel decrease was not observed in The Netherlands, because the product there already contained zeolite in 1988 (Table 2).
- It is important to highlight that the increase in the number of ingredients in the 1998-super compact formula did not lead to a significant increase in the aquatic toxicity score, but to a significant decrease in both countries (Table 7). The environmental risk assessment performed

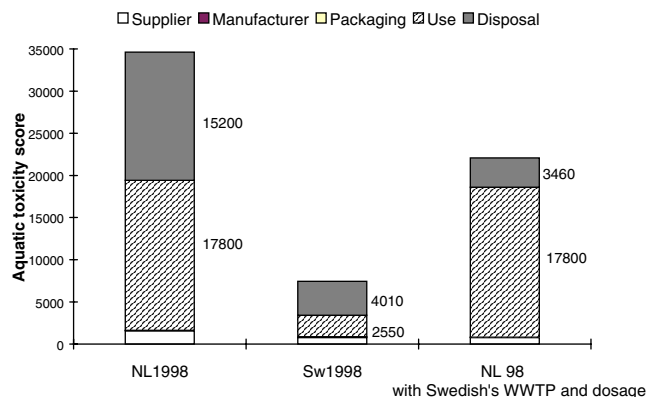


Fig. 5: Contribution of the different life cycle stages to the aquatic toxicity score for the 'cradle-to-grave' analysis results per 1000 wash cycles with 1998-super compact granular P&G detergents used under Dutch and Swedish conditions. Additionally, the scores for the Dutch product have been calculated assuming dosage and disposal are similar to those in Sewden

on the same products actually indicated that safety margins (assuming full additivity as performed in this impact assessment) have decreased by a factor of 3 to 5 between 1992 and 1998 [5].

- Three life-cycle stages were important contributors to the aquatic toxicity score (Fig. 5): consumer use (via energy related emissions), disposal (via emission of chemical after wastewater treatment) and raw material supply. Their ranking in terms of magnitude was different in The Netherlands (use > disposal > supply) when compared to Sweden (disposal > use > supply). Raw material supply was a relatively minor ($\leq 11\%$) contributor, whereas disposal and consumer use were of a similar importance (Fig. 5).
- The consistently lower aquatic toxicity impact scores in Sweden as compared to The Netherlands are attributable to different wastewater treatment infrastructures. In The Netherlands, the total volume of wastewater that is discharged untreated is twice as large as in Sweden (Table 3). We removed the variables of wastewater treatment infrastructure and product dosage from the equation by forcing them to be the same for the two countries. This resulted in the aquatic toxicity score associated with the disposal stage now lowest in The Netherlands (Fig. 5).
- A clear difference between all the calculated impact assessment scores was actually observed between The Netherlands and Sweden. The wash cycle performed in Sweden showed lower environmental impact scores across all impact categories, both in 1988 and 1992 (Table 7). This indicates that the laundry process in Sweden (in the 'cradle-to-grave' sense) generated less emissions over-all. As shown by the 'cradle-to-grate' analyses presented earlier, these differences were not product related. Rather, they were due to lower energy consumption in Sweden, sustained by the more efficient electricity grid based on nuclear and hydro-power, and to the lower laundry product dosage in a country with softer water. It is important to note that the radioactive wastes from nuclear energy were not taken into account in this analysis. This would have drastically changed the interpretation of this analysis.

4.3 Limitations of this analysis

- The cradle-to-gate LCA was based on identical raw material LCIs gathered in and applied to product formulas from 1988, 1992 and 1998. We do not claim, however, that the results presented here are fully representative of changes in raw material extraction and production occurring in this time frame or that its accurate reflections of current realities (2001). The objective was to reveal the effects of process changes, i.e. compaction, on the environmental profiles of the products. We assumed that the raw material inventories remained unchanged during the period studied. It is likely, though not certain, that raw material extraction and manufacture have reduced environmental emissions and the resulting environmental impact scores over time.
- For some ingredients, no LCI was available at all; whereas, for other ingredients, it was possible to use a closely related LCI on a similar ingredient. This is the case for a cationic surfactant used in our product [34], but for which no inventory data was available. The most closely related inventory was the study performed by EMPA [17]. This LCI was estimated from a variety of sources and was different from the one used in our product. Regardless, the LCI was the best available at the time, hence, to use it was the pragmatic thing to do, knowing that it could be improved in the future. Such pragmatism is common practice in LCI and a number of assumptions or hypotheses are always made; this has much to do with the enormous variety of products and processes out there, and the significant expense associated with conducting an actual LCI study. The use of this inventory, however, accounted for 16% of the eutrophication impact score in 1998 and was primarily responsible for the increase in the eutrophication impact scores between 1992 and 1998. Removing the nitrogen-containing cationic surfactant from the product would reduce the differences between the eutrophication impact scores to less than 20%, which would make the difference with the 1992 score insignificant.
- The decrease in energy usage by washing machines from 1988 until 1998 was not taken into account because of the lack of available data as discussed previously. However, it is a known fact that the energy consumption of washing machines has decreased significantly over the last 10 years. Therefore, the trend towards less energy consumption during the time period of this study is expected to be even steeper. We also have not distinguished between the different types of washing machines that may possibly be used by the Dutch and Swedish consumers. Without an understanding of the situation in each country, the impact of such simplifications is difficult to ascertain.
- While LCA characterizes emissions and waste over a product's life cycle, it does not allow for a complete assessment of a product's potential impacts, also sometimes referred to as its 'safety profile' or its 'risk assessment'. This is because LCA reports emissions on a chosen functional unit basis (i.e. 1000 wash cycles or 1 kg finished product). The exposure and hazard assessments,

required as input for the risk assessments, are not part of the LCA. For each type of emission, the probability of adverse impacts can be quantified by risk assessment, taking into account all sources of exposure. LCA was not designed to do that, but rather it was designed to understand the relative contribution of each stage of the life cycle to certain environmental impact categories. LCA also allows comparisons between equivalent stages between life cycles (i.e. the consumer stage of product A and the consumer stage of product B), provided that the LCIs rely on the same databases and the same assumptions. Thus, even though LCA cannot tell us whether or not the use of a product is 'safe', it does provide us with 'indicators' concerning impact assessment scores of the relative contributions of entire or partial product life cycles to specified impact categories [35]. As such, it can be a powerful aid for the risk manager in business or in government, which is needed to decide which exposures should be managed first and to communicate this effectively to diverse audiences.

5 Conclusion

The analysis presented here clearly indicates that the environmental profiles of compact granular detergents introduced in the early nineties were at least as good, if not better when compared to the regular granular detergents of the late eighties. LCA shows us that energy use, raw material consumption and environmental emissions decreased substantially. This was made possible by the development of the new, more weight-efficient formulations that resulted in the compaction of granular laundry detergents and improved cleaning performance at lower temperature, compared to the traditional granular detergents of 1988. The improvements shown would have been even greater, had we taken into account the higher energy-efficiency of newer laundry machines. This study highlights the importance of wash temperature selection and detergent dosage in the overall LCA using the principle of equivalent washing performance.

This analysis also shows that the activity of 'doing the laundry' results in lower emissions in Sweden, when compared to The Netherlands. It would be easy to arrive at the intuitive – however erroneous – conclusion that the Swedish product is therefore 'better for the environment' than the Dutch product. By making use of LCA, we unraveled the reasons for the observed differences in the emission spectra. The results of the 'cradle-to-gate' LCA show that the overall, lower environmental impact potential associated with doing the laundry in Sweden is unrelated to differences in product composition.

The 'cradle-to-grave' LCA shows that the difference is really due to (1) the more efficient energy production in Sweden, (2) the lower recommended dosage of laundry made possible by lower water hardness and (3) the difference in wastewater treatment infrastructure between Sweden and The Netherlands; in particular the larger fraction of untreated wastewater discharge in The Netherlands.

This example illustrates how LCA can be used to break down highly complex processes into their more easily understood

parts and how important it is to understand assumptions and limitations before conclusions are made on the apparent environmental benefit of products. LCA, probably more than any other analytical tools, requires a high level of transparency and expertise.

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The Effect of Compact Formulations on the Environmental Profile of Northern European Granular Laundry Detergents

Part I: Environmental Risk Assessment

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Abstract. Regular (1988) and compact granular (1992, 1998) laundry detergents were compared on the basis of two distinct, complementary approaches: Environmental Risk Assessment and Life Cycle Assessment. The results are presented in this paper and an accompanying paper in this volume (Part II: Life Cycle Assessment). Exposure data from The Netherlands and Sweden were used for this retrospective analysis. The time period studied (1988-1998) spans many innovations in laundry detergents, one of which was the introduction of compact detergents. The aquatic risk assessment resulted in risk quotients below 1 for all detergent ingredients in both countries over the period studied. Furthermore, it showed that risk quotients decrease two to five-fold between 1988 and 1998 in each country due to the introduction of compact detergents. Slightly lower risk quotients were observed in Sweden, when compared to The Netherlands, attributable to the lower water hardness resulting in lower detergent usage per wash cycle in that country. If water hardnesses were equal, the outcome of the product risk assessments would also be the same in the two countries.