European Commission

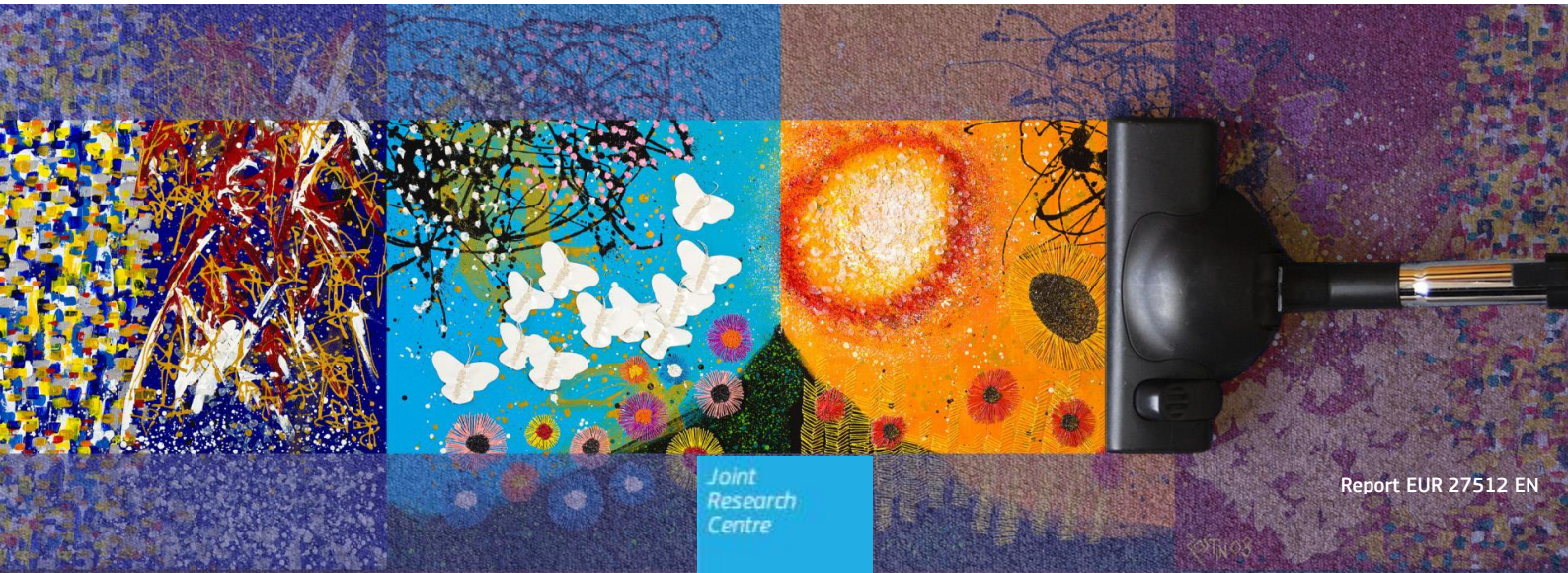
JRC SCIENCE AND POLICY REPORT

Technical support for Environmental Footprinting, material efficiency in product policy and the European Platform on LCA

Durability assessment of vacuum cleaners

Silvia Bobba, Fulvio Ardente, Fabrice Mathieux

November 2015



Report EUR 27512 EN

European Commission

Joint Research Centre

Institute for Environment and Sustainability

Contact information

Fulvio Ardente

Address: Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749 I-21027 Ispra (Italy)

E-mail: fulvio.ardente@jrc.ec.europa.eu

Tel.: +(39) 0332 785698

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JRC96942

EUR 27512 EN

ISBN 978-92-79-52710-4 (PDF)

ISSN 1831-9424 (online)

doi:10.2788/563222

Luxembourg: Publications Office of the European Union, 2015

Printed in Italy

Abstract:

The report aims to contribute to the review process of the specific ecodesign requirements on the durability of the hose and the operational motor lifetime of the vacuum cleaner (VC) product group. For this purpose a comprehensive method for the environmental and economic assessment of extending the lifetime of VCs has been developed and applied, based on the former indexes developed within the 'REAPro' method (Ardente and Mathieux, 2014). The starting point of the analysis was the performing of a Life Cycle Assessment of an exemplary VC, complemented with the analysis of the literature. The functional unit was a bagged canister VC with an operating time of 10 years. A sensitivity analysis has been implemented considering potential changes in the manufacturing, repair, maintenance and energy consumption. Successively, the potential extensions of the lifetime of the VC have been analysed through the application of Durability indexes. The report showed that extending the lifetime of VCs generally implies benefits, from both environmental and economic perspectives, for the large majority of scenarios considered. In general, these benefits already exist for small extensions of lifetime, and they become significant if the lifetime is extended further. These results could be used to promote the design of more durable products, e.g. via more ambitious policy measures. The report also highlighted the relevance of repairability of VCs from both environmental and economic points of view. Repairability could be promoted for instance through a proper 'design for repairing' of products but also the availability of information and tools for the repair and/or replacement of some components. Finally, the importance of the role of consumers has been confirmed, in terms of proper use of VCs during their operation phase and the proper maintenance/repair operations (e.g. to grant the energy efficiency of the product throughout the lifetime).

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Abbreviations

ABS	Acrylonitrile-butadiene-styrene
ADP	Abiotic Depletion Potential element
ANEC	European Association for the Co-ordination of Consumer Representation in Standardisation
BEUC	European Consumers' Organization
BMC-GF	Bulk moulding compound — Glass Fibre
CESA	Canadian Electrical Stewardship Association
ECCP	European Climate Change Programme
EEE	Electrical and Electronic Equipment
EoL	End-of-Life
EPEAT	Electronic Product Environmental Assessment Tool
ErP	Energy-related Product
EuP	Energy-using Product
GER	Global Energy Requirement
GPP	Green Public Procurement
GWP	Global Warming Potential
HD-PE	High-Density Polyethylene
HRS	'High repairing' scenario
ICRT	International Consumer Research & Testing
LCA	Life Cycle Assessment
LCI	Life Cycle inventory
LCIA	Life Cycle Impact Assessment
LD-PE	Low-Density Polyethylene
LLD-PE	Linear Low-Density Polyethylene
LRS	'Low repairing' scenario
MEErP	Methodology for the EcoDesign of Energy-related Products
MEEuP	Methodology for the EcoDesign of Energy-using Products
PCB	Printed Circuit Board
POM	Polyoxymethylene
POP	Persistent Organic Pollutants
PP	Polypropylene
SHA	Small household Appliances
SLCA	Simplified LCA
SMW	Small Mixed WEEE
VC	Vacuum cleaner
VOC	Volatile Organic Compounds
WEEE	Waste of Electrical and Electronic Equipment

Executive Summary

Context

This report is part of the project 'Technical support for Environmental Footprinting, material efficiency in product policy and the European Platform on LCA' ([1]) funded by DG Environment from 2013 until 2016. Material-efficiency criteria for products have become increasingly relevant in EU policy, as reflected in some of the latest communications in which the European Commission has manifested its interest in 'moving towards a more circular economy' ([2]). In particular, the Commission aims to go beyond its initial objectives (European Commission 2011; European Commission 2014) and support innovative actions at all stages of the lifecycle of products. The circular economy 'can promote competitiveness, innovation, a high level of protection for humans and the environment, […] and can provide consumers with more durable and innovative products that provide monetary savings and an increased quality of life' ([3]).

Promoting more durable products is also an objective of the EU Ecodesign Directive (2009/125/EC), which mentions the relevance for evaluating the potential for the extension of lifetime of products (as achieved through minimum guaranteed lifetime, minimum time for availability of spare parts, modularity, upgradeability, reparability). Ecodesign requirements on durability have been developed, in particular, for the 'vacuum cleaner' (VC) product group, setting that 'the hose, if any, shall be durable so that it is still useable after 40,000 oscillations under strain', and that 'the operational motor lifetime shall be greater than or equal to 500 hours' ([4]). EU Regulation No 666/2013 also established the need to 'review the specific ecodesign requirements on the durability of the hose and the operational motor lifetime […] by September 2016'.

This report aims at contributing to this review by putting together results obtained when applying a comprehensive method for the assessment of environmental and economic benefits of extending the lifetime of VCs. The method has been built upon the method REAPro (Resource Efficiency of Products) ([5]) ([6]), and based on a 'life-cycle thinking' approach. In particular, the environmental assessment method has been revised to capture new aspects of the durability (including the assessment of the impacts of auxiliary materials used during the operation, the impacts due to the manufacturing of a more durable product and the impacts of the potential substituting product). Moreover, the method has been enlarged to assess also the economic costs and benefits of extending the lifetime of product.

Life Cycle Assessment

The selected base-case product was a bagged VC with a lifetime of 500 hours ([7]), and a consumption of 25 [kWh/year] ([8]). The Bill of Materials has been derived by exemplary products disassembled complemented by data from the literature. Information about other life-cycle phases (manufacturing,

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([1]) Administrative Arrangement JRC № 33446 -2013-11 07.0307/ENV/2013/SI2.668694/A1
([2]) http://ec.europa.eu/environment/circular-economy/index_en.htm
([3]) http://ec.europa.eu/smart-regulation/impact/planned_ia/docs/2015_env_065_env+_032_circular_economy_en.pdf
([4]) Commission Regulation (EU) No 666/2013
([5]) http://bookshop.europa.eu/en/integration-of-resource-efficiency-and-waste-management-criteria-in-european-product-policies-second-phase-pbLBNA25656/
([6]) Ardente and Mathieux (2014), Journal of Cleaner Production 74(1),62–73.
([7]) This corresponds to 10 years, assuming 50 hours of operation per year.
([8]) This value corresponds to a product of Energy class 'A'.

transports, end-of-life) have been derived by various references, including the 'Work on Preparatory Studies for Eco-Design Requirements of EuPs (II) Lot 17 Vacuum Cleaners' (2009).

The environmental impacts estimated through the Life Cycle Assessment methodology proved to be largely influenced by the use-phase, especially for impacts as the Global Warming Potential (GWP) and the Acidification. The impact due to the production of materials and components was always relevant (above 15 %) for all the considered impact categories, and it resulted dominant for some of them. Particularly relevant is the contribution of the manufacturing of the printed circuit board (PCB), of copper and steel parts, and of large plastic parts.

Durability Assessment

The environmental assessment of durability compared the two different scenarios: prolonging the lifetime of the VC beyond 10 years versus the replacement of the VC with a more energy efficient one. The analysis proved that the benefits are mainly depending on the energy efficiency of the potential replacing product and the considered impact category. Higher benefits are estimated for those impact categories more influenced by the manufacturing. Considering the GWP indicator, extending the lifetime of the VC by 100 h (i.e. 2 years) saves around 1.5 % of GWP compared to its replacement with a 15 % more efficient product. Alternatively, the same lifetime extension generates higher benefits (up to 20 %) for other impact category (as the 'Abiotic Depletion Potential' (ADP)). The analysis proves also that higher benefits can be obtained for higher extension of the lifetime. For instance, in comparison to the replacement of the VC with a new one 15 % more efficient, a lifetime extension of 300 hours (i.e. 6 years) can reduce the GWP impact by 5 %. It was observed that there are also environmental benefits even when extra impacts are accounted due to the manufacturing of more durable products.

In order to perform a comprehensive assessment of durability, the environmental analysis has been also performed using the Ecoreport tool *2013* ([9]). The life-cycle impacts of the base-case VC and the environmental assessment of extending the lifetime have been calculated based on the same assumptions of the previous analysis. This study demonstrated the applicability of the proposed method also through the use of the Ecoreport tool, although some limitations occurred (mainly related to the inclusion of new materials and components, the adoption of different impact categories and the modelling of aspects as the transport, repair and maintenance). The results provided via the Ecoreport tool proved to be similar for the GWP impact category. For instance, compared to the replacement of the VC with a new one 15 % more efficient, the lifetime extension of 100 h reduces the GWP by 3.7 % (compared to the 1.7 % previously calculated). The analysis based on other impact categories has been not reported due to higher uncertainties and lower comparability.

Similarly to the environmental analysis, the economic assessment analysed the costs and benefits of prolonging the lifetime of VC versus its replacement, taking a life-cycle perspective. The outcomes proved that the lifetime extension of 100 h brings a saving of about 11-13 € ([10]), depending on assumed the energy efficiency class of a potential replacing VC. Moreover, the higher lifetime extension, the higher are the economic benefits achieved. Also the repair costs have been included in the economic assessment and revealed to be relevant. For example, for repair costs lower than 20 % than the purchasing price of the

([9]) The 'Ecoreport tool' is the tool used to run the environmental assessment within the preparatory study for Ecodesign implementing measures for energy related product. The version considered for this analysis was the v.3.06 as modified in 2013 to take into account the lifetime parameter [BIO Intelligence Service (2013a)]

([10]) This scenario did not include costs for repair.

VC, it is always convenient to extend the lifetime than replacing a product with one 15 % more energy efficient. For repair costs up to 40 % of the purchasing price, the economic benefits occur when the lifetime is extended for more than 200 h.

The environmental and economic assessments have been also complemented by a detailed sensitivity analysis of the assumptions, to increase the robustness of the results. Also in this case, the extension of the lifetime resulted to be environmentally beneficial in the large majority of the considered scenarios.

Conclusions

In conclusion, the study showed that extending the lifetime of VC generally implies benefits, from both environmental and economic perspectives, for the large majority of scenarios considered. In general, these benefits already exist for small extension of the lifetime and they become significant if the lifetime is extended further. These results could be used to promote the design of more durable products, e.g. via more ambitious policy measures.

The report also highlighted the relevance of reparability of VCs from both environmental and economic points of view. Reparability could be promoted for instance through a proper 'design for repairing' of products but also the availability of information and tools for the repair and/or replacement of some components.

Finally, the importance of the role of consumers has been confirmed. This is particularly important in terms of proper use of VCs during their operation phase and the proper maintenance/repair operations (e.g. to grant the energy efficiency of the product throughout the lifetime).

The results presented in this report should be considered during the review of EU Regulation No 666/2013 of 8 July 2013 on ecodesign requirements for vacuum cleaners.

Introduction

Durability is often seen as one of the most important criteria for resource efficiency of products. The relevance of durability was mentioned in some major European policy documents (EC 2011a; EC 2011b) and included for several years in some European and non-European voluntary instruments (e.g. criteria for Green Public Procurement and for various eco-labelling schemes as the EU Ecolabel, Nordic Ecolabel, Blaue Engel, and Electronic Product Environmental Assessment Tool — EPEAT).

Durability is a cross-cutting requirement of different aspects of resource efficiency requirements (waste reduction, reparability, design for disassemblability, remanufacturing, refurbishment and reuse), and it should be carefully assessed to evaluate potential benefits associated to the lifetime extension (Bundgaard et al. 2014).

In the last year there were some examples of durability aspects introduced into mandatory European policies (e.g. Ecodesign implementing measures for some Energy-related Products — ErP). However, there are several difficulties in implementing durability requirements, as for example the strict relationship with the user behaviour or the lack of measurement methods. Moreover, the extension of the lifetime of ErP can produce conflicting environmental effects, since it can produce some advantages (in terms of lower use of resources and waste reduction), but it can also cause some impacts (in terms of higher energy consumption during the operation). Also the assessment of the durability of products and of the associated benefits/impacts is more difficult compared to energy efficiency aspects. Standardised tests for the durability are missing for a large number of products and this has been representing an obstacle to the implementation and verification of durability measures into policies.

Some authors also emphasized that the technological improvement due to ecodesign policy measures had also positive impacts for the durability (Bundgaard et al. 2014). Nonetheless, resource efficiency aspects and, in particular, durability, are still considered as crucial factors to be implemented into product policies. For instance, in order to stress these aspects, the Austrian 'Sustainability label for electric and electronic appliances designed for easy repair (white and brown goods)' underlines the importance of the 'repair services' within the context of the EU legislation, with particular reference to the WEEE Directive (Österreichisches Normungsinstitut 2006). Criteria on durability as implemented in some voluntary instruments can be divided into two main groups: direct criteria on durability of a specific product or component, or indirect criteria. These latter are mainly related to extended warranty, upgradability, repair, availability of spare parts and modularity (Bundgaard et al. 2014). Moreover, it should be noticed that the costs due to repairing/replacing spare parts or to higher operational costs can discourage the consumer in purchasing longer-lasting products (including also reused products) (Boulos et al. 2014).

Vacuum cleaner is one of the few product groups for which durability requirements have been introduced into Ecodesign measures (EC 2008). These requirements have been introduced because the relevance of lifetime issues for VC has been recognised during the preparatory phase due to the availability of a standardised method for the testing of the hose durability and operational motor lifetime. However, even if the potential benefit/cost of extending the lifetime of VC have been assessed within the preparatory study, it can represent a starting point for a more details and exhaustive analysis as some considerations about technology development, or increase of energy efficiency of replacing products or even higher options of lifetime extension are not included in such a study.

This report will analyse the environmental and economic benefits, in a life-cycle perspective, due to the extension of the lifetime of VCs. The first part will analyse durability issues, focusing on EU policies and the scientific literature. Successively, a case-study VC is analysed through the Life Cycle Assessment (LCA) methodology. Results are used to assess the potential environmental and economic costs and benefits due to the extension of its lifetime. The analysis will be also be complemented with results obtained with the Ecoreport tool ([11]).

This report has been developed within the study 'Technical support for Environmental Footprint, material efficiency in product policy and the European Platform on LCA' funded by DG Environment (AA JRC No 33446 — 2013-11 07.0307/ENV/2013/SI2.668694/A1).

([11]) Based on the 'Methodology for the Ecodesign of Energy-related Products' (MEErP)

CHAPTER 1
Review of durability aspects in policies and standards

Chapter 1 analyses the available policies and standards relevant to durability of the VCs product group. In this context, the Ecodesign directive and the corresponding implementing measures have introduced some durability criteria especially for non-directional household lamps (EU 2009a) and vacuum cleaners (EU 2013a).

Concerning the Ecodesign directive and the energy labelling regulation for VCs, section 1.1 and 1.2 report the significant information about durability and VCs. Section 1.3 analyses the durability issue as discussed in the Preparatory study for ecodesign requirements of Energy-using Products and in the Impact Assessment report accompanying the ecodesign directive and the energy label of VCs. Finally, the international standards concerning vacuum cleaners have been investigated: section 1.4 illustrates the durability criteria proposed in the EN and ISO standards regarding durability of vacuum cleaners (in particular for the hose durability and the operational motor lifetime).

1.1. Ecodesign Directive

In 2009 Directive 2009/125/EC was adopted by the European Union for establishing a 'framework for the setting of ecodesign requirements for energy-related products', i.e. those products having an impact on energy consumption ([12]). This section collects the most significant information included in the Ecodesign Directive that are propaedeutic for this study.

The background information of Directive 2009/125/EC highlight that, within the European Community, a large portion of natural resources and energy is consumed for production and use of the Energy-related Products (ErPs); furthermore, the electricity demand in EU is fasting growing (and it is projected to grow within the next 20 to 30 years in the absence of any policy action to counteract this trend) (EU 2009b). The Commission, in its European Climate Change Programme (ECCP) ([13]), suggested that lower energy consumption is feasible, notably in terms of preventive approach. In this framework, energy savings can represent the most cost-effective way to both increase the supply security and decrease the import dependency. It should be also acknowledged that certain ErPs have significant improvement potentials through better design and a more environmentally friendly use. The integration between the environmental aspects and the product design (EcoDesign ([14])) is recognised as a crucial factor in the Community strategy on Integrated Product Policy (EC 2001), where the purpose is the optimisation of environmental performances of products along their life-cycle, without negatively affecting their functional qualities.

In this perspective, the EcoDesign directive establishes a framework for setting up EcoDesign requirements for Energy-related Products, and so it contributes to Sustainable Development improving both energy and resource efficiency of products.

([12]) Energy-related products include both Energy-using Products (EuPs) and products which not use energy but having an impact on energy
([13]) http://ec.europa.eu/clima/policies/eccp/second/index_en.htm (accessed April 2015)
([14]) 'Ecodesign' means the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life-cycle (EU 2009b)

It should be noticed that the EcoDesign directive focuses on ErPs with a considerable sales volume within the Community (higher than 200 000 units/year), with a significant impact but also with a high potential of improvement concerning their environmental impacts, without excessive costs.

In order to achieve the improvement of the environmental performances of products, the 'EcoDesign parameters for products' related to all the phases of the products life-cycle have been identified (Annex I of the Ecodesign Directive). Among others, the extension of lifetime is one these key criteria and is stated in terms of:

- minimum guaranteed lifetime;
- minimum time for availability of spare parts;
- modularity;
- upgradeability;
- reparability.

This means that different aspects occurring during the life-cycle of products are related to the 'lifetime' parameter and should be taken into account for evaluating 'the potential for improving the environmental aspects' (EU 2009).

In this context, the communication factor plays a key role for maximising the environmental characteristics and performance (particularly from manufacturers to consumers), also through the sustainable use of products. Indeed, within the 'requirements relating to the supply of information' (Part 2 of Annex I of the Ecodesign Directive), there are listed the required information that should be supplied by manufacturers to the end users. These information refer to the environmental characteristics and performance of ErPs but also to their handling, for instance how to install, use, maintain and dispose those products in an environmentally friendly manner, the period of availability of spare parts and the possibility of upgrading products.

Finally, it is worth noting that the EcoDesign directive is complementary to other policy instruments including: energy labelling and standard product information of energy consumption (EU 1992; EU 2008), eco-label award schemes (EU 2000), waste electrical and electronic equipment (WEEE) (Directive 2002/96/EC), use of hazardous substances in electrical and electronic equipment (Directive 2002/95/EC, Directive 2006/121/EC).

1.2. Ecodesign Implementing measure (Regulation 666/2013) and Energy labelling of vacuum cleaners (Regulation 665/2013)

As previously mentioned, the Ecodesign directive introduced durability issues in particular for lamps and vacuum cleaners. Among the Ecodesign implementing measures, the EU Regulation No 666/2013 (EU 2013a) is about the ecodesign of vacuum cleaners. In such a document, some significant elements are identified, such as energy consumption in the use phase, dust pick-up on carpet and on hard floor, dust re-emission, noise (sound power level) and durability (particularly about hose and operational motor lifetime).

In Table 1 the details of the ecodesign requirements are illustrated. The application of these requirements is scheduled in two different steps in order to allow manufacturers enough time for product re-design. Note that when this Regulation entered into force in 2013, the benchmark between domestic vacuum cleaners available in the market was 'an upright vacuum cleaner of 650 W at a cleaning head width

of 0.28 m, which translates into a specific energy consumption of 1.29 Wh/m^2, although with sound power level rated at over 83 dB'.

Table 1: Specific Ecodesign requirements for vacuum cleaners

Parameter	From 1 September 2014	From 1 September 2017	Unit of Measure
Annual energy requirement	65	43	[kWh/year]
Rated input power	1600	900	[W]
Dust pick-up on carpet	0.7	0.75	-
Dust pick-up on hard floor	0.95	0.98	-
Dust re-emission	-	1	[%]
Sound power level	-	80	[dB(A)]
Hose	Still useable after 40 000 oscillations under strain		
Operational motor	Greater than or equal to 500 hours		

This EU regulation highlights that the 'durability' parameter is strictly related to hose durability and the operational motor lifetime. The 'Measurements and calculation method' (Annex II of the 666/2013/EU) specify that the hoses 'shall be considered usable after 40 000 oscillations under strain if it is not visibly damaged after those oscillations, and strain shall be applied by means of a weight of 2.5 kilograms'; while concerning the operational motor, its lifetime should be greater or equal to 500 hours, and the test 'may be discontinued after 500 hours and shall be discontinued after 600 hours', as envisaged also by the existing standards about vacuum cleaners (chapter 1.4).

Together with the Ecodesign directive, other Union instruments contribute to create a legal framework in order to maximise the energy savings and the environmental performances of products. Among these instruments, Directive 30/2010 'on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products' (EU 2010) concerns the labelling and standard product information about energy consumption in order to allow end-users to choose more efficient products. In particular, Regulation 665/2013 (EU 2013b) supplements Directive 30/2010 with regard to energy labelling of vacuum cleaners.

Table 2: Energy efficiency classes

Energy Efficiency Class	Annual energy consumption (AE) [kWh/y]	
	From 1 September 2014	From 1 September 2017
A+++	n/a	AE ≤ 10.00
A++	n/a	10.00 < AE ≤ 16.00
A+	n/a	16.00 < AE ≤ 22.00
A	AE ≤ 28,00	22.00 < AE ≤ 28.00
B	28.00 < AE ≤ 34.00	28.00 < AE ≤ 34.00
C	34.00 < AE ≤ 40.00	34.00 < AE ≤ 40.00
D	40.00 < AE ≤ 4616.00	AE > 40.00
E	46.00 < AE ≤ 52.00	n/a
F	52.00 < AE ≤ 58.00	n/a
G	AE > 58.00	n/a

The Energy label of VCs also prescribes to label the annual energy consumption in kWh/year, as indicative annual energy consumption based on 50 cleaning tasks. Similarly the Ecodesign implementing measures assumes 50 one-hour cleaning tasks per year.

The energy-labelling directive identifies the information that must be provided on the label, on technical documentation, on any advertisement disclosing energy-related or price information, and any technical promotional materials including the technical parameter of a VC model. Table 2 illustrates the energy efficiency classes set for the VC product group. Starting from 1/9/2017 the worst energy class will include VCs with an annual energy consumption higher than 40 [kWh/y].

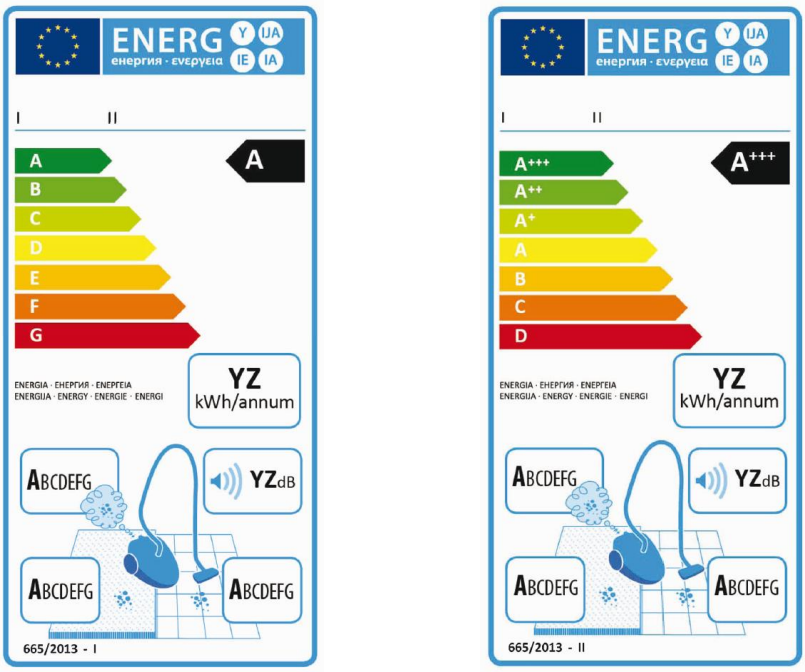

Figure 1: Energy label for vacuum cleaners placed on the market before (on the left) and after 1 September 2017 (on the right)

1.3. Analysis of Durability in the Ecodesign preparatory study and Impact assessment

An important source of information for the European policies about ecodesign of VCs is represented by the Preparatory study for ecodesign requirements of Energy-using Products (EuPs) about vacuum cleaners (in the following called 'Preparatory study') carried out by AEA Energy & Environment, Intertek, and Consumer Research Associates between November 2007 and January 2009. The available information of this document concerns technical, environmental and economic aspects of VCs; therefore, complemented by those included within the Impact Assessment report accompanying the ecodesign directive and the energy label of VCs (EC 2013), they were used as sources of information but also as basis for comparison with the results obtained by this study. Those compliant to such purpose are hereinafter illustrated.

As mentioned in section 1.1, products that should be covered by the implementing measures of the ecodesign directive must respect three criteria: large quantities of products placed on the EU market, significant environmental impact related to energy consumption, significant potential improvement without entailing excessive costs. According to the Preparatory study, VCs respect all these three criteria.

In 2006, the apparent consumption ([15]) of domestic VCs in EU-25 was around 45 million, most of them imported from China (only about 14 million produced in EU-27, particularly in Germany, Italy and UK). Note that the Preparatory study assumes that 85 % of the VCs on the market are canister VCs, while just 15 % are uprights. Trade data and PRODCOM statistics ([16]) proved that the sales growth rate between 2000 and 2005 was around 9 %, and most of the sold units are related to replacements, but during the crisis 2008-2010 the sales dropped to the level of around 2005, and afterwards started again to increase (EC 2013; AEA Energy & Environment 2009). As illustrated in the Preparatory study, the main reasons for the increase of the sales of VCs between 2000 and 2005 may be related to the VC lifetime: the assumed average lifetime for domestic VCs is equal to 8 years, but the Preparatory study forecasted that it is expected to decline from 8 years in 2010 to 5 years in 2020.

According to the available information of both the Preparatory study ([17]) and the Impact assessment report ([18]), the overall amount of electricity consumption associated to the operation of vacuum cleaners is very high: around 19 TWh per year in the EU-27 (about 25 % due to non-domestic VCs, and 75 % to domestic ones). Finally, an initial Methodology study for ecodesign of Energy-using Products (MEEuP), demonstrating that VCs environmental impact is 'use-phase' dominated, estimated the amount of potential savings deriving from the application of different design options.

The case-study of this report is therefore a domestic canister vacuum cleaner with a lifetime of 8 years, consistent with the above-mentioned market trends.

In order to evaluate the amount of energy use and the corresponding environmental impact, different aspects should be simultaneously taken into account, as the number of households ([19]), the dwelling sizes ([20]) and the power consumption of VCs (EC 2013; AEA Energy & Environment 2009). Especially concerning the latter, it is worth noting that this parameter plays a central role in potential energy consumption savings, as consumers' choices are often based on it: the higher the input power, the higher seems to be the performance of the VCs. Mainly for that reason, in the last decades the input power range of VCs has increased. On the contrary, the Preparatory study affirms that 'there is no correlation between input power and cleaning performance'. Moreover, the study depicts that the range of vacuum cleaners available in the market in 2005 includes products with an input power range from 1 000 W to 2 700 W, even if there are also examples of machines working in the range 650-900 W. This range is also related to the type of VC: the input power range is higher for canister than for upright VCs, but it is also higher for bagless than for bagged VCs (AEA Energy & Environment 2009).

In this framework, the lifetime of VCs is fundamental for assessing the environmental impact and the potential savings associated to the life-cycle of VCs, and it should be noted that lifetime is dependent on different aspects. In this perspective, the Preparatory study highlights that the potential increase of the environmental impact due to the VCs energy consumption within the European Union is not directly connected to more VCs sales; the essential parameter, in fact, is represented by the total number of operating hours per household ([21]), directly associated to the amount of energy demand.

([15]) The apparent consumption of VCs is given by the production and the imports of VC minus the exports of VCs
([16]) http://www.eea.europa.eu/data-and-maps/data/external/prodcom-database-eurostat
([17]) The environmental impact assessment of the EU-Stock 2005 highlights an electricity consumption of 3.7 TWh
([18]) In 2010 the EU-27 stock is of about 200 million units
([19]) The number of households is supposed to increase around 1-1.5 % per year (EC 2013)
([20]) The dwelling size is supposed to be incremented by 20 % in the period 2000-2020 (EC 2013)
([21]) This parameter is strongly affected by the consumer's behaviour as well as on the functions for which the VC is used (for instance use in a garage or wet and dry cleaning)

Moreover, the lifetime of an average VC is mainly related to some of its components, essentially the hose and the operational motors; this is confirmed if the principal reasons for breakdown are analysed (Table 3). Note that the breakdown of the motor usually corresponds to the substitution of the VC as the motor operating lifetime strictly depends on the wearing down of its carbon brushes and, in the domestic market, a worn-out carbon brush means the motor is unusable. This usually occurs after 500 hours of operating time of the motor (that corresponds to about 8 years of VC use) (AEA Energy & Environment 2009).

Hence, the lifetime adopted in the Preparatory study for assessing the environmental impact of a domestic vacuum cleaner is 500 hours, considering 62.5 hours per year of time spent cleaning and an electricity consumption of 1.5 kWh per hour (which means about 94 kWh per year).

Table 3: Main reasons for vacuum cleaner breakdowns (AEA Energy & Environment 2009)

Reason for breakdown	Upright	Cylinder
Split/broken hose	21 %	25 %
Suction	19 %	15 %
Motor	16 %	-
Broken casing	-	11 %
Power cable	-	11 %

Based on these hypotheses, the analysis performed by the Preparatory study proves that the canister VC life-cycle impacts are mainly related to the use-phase ([22]).

As previously mentioned, the Preparatory study assessed the 'improvement potential' through 8 different 'design options', which take into account both the environmental and the economic aspects. The technical design options adopted by the Preparatory study are the followings:

- maximisation of fan efficiency;
- improvement of efficiency airways;
- improvement of the nozzle;
- reduction of filtration energy losses;
- reduction of leakage losses;
- combination of the previous five options;
- reduction of materials (for instance considering best materials options);
- increase of the product lifetime.

Among these options, two are particularly relevant for the objective of this study. The first refers to the potential extension of VC lifetime (option 8 within the Preparatory study: 'Increased product lifetime'), while the second refers to the potential reduction of materials (option 7 within the Preparatory study: 'reduced materials/lightweighting'). For both of these options, the life-cycle impact has been calculated through the Ecoreport tool and a Life Cycle Cost analysis has been performed. The main outcomes of these analyses are illustrated in section 2.1.6.

([22]) For a domestic bagged canister vacuum cleaner with a lifetime of 8 years and an energy consumption of 1.5 kWh per hour, almost 90 % of the life-cycle Total Energy (GER) is to be associated to the use-phase, while less than 10 % is related to the manufacturing phase

Based on the Preparatory study results, the Impact Assessment report figures some policy options for implementing the ecodesign requirements and the energy labelling for VCs. These options concern the introduction of a power cap (sub-option 1 in the Impact Assessment report), the elimination of one or more energy efficiency classes in line with the 2010 industry proposal (sub-option 2 in the Impact Assessment report) and the combination of these two aspects (sub-option 3 in the Impact Assessment report). The sub-option 1 considers the introduction of a first power cap in 2014 (1 000 W) and a second one in 2017 (750 W). The sub-option 2, as illustrated in Figure 2, refers to the elimination of class F (during the first stage) and class G (during the second stage), without any power cap. Indeed, the second option proposes a first cap of 1 600 W together with the elimination of classes F and G, followed by a second step establishing a 1 200 W cap and the elimination of the D and E energy efficiency classes; in the meantime it is supposed to create three new classes: A+, A++ and A+++ (EU 2013a). All three sub-options can guarantee a reduction of the environmental impact within the EU, but sub-option 3 is considered to offer the optimal solution between fast savings and minimum strain for the industry (EU 2013a).

Finally, it is interesting to note that the Impact Assessment report affirms that the 'durability requirements addressing the hose and the motor can be introduced'. This is related to the not insignificant energy embedded in domestic VCs, to the top reasons for breakdowns (mainly due to the 'split or broken hose' and the 'motors') and to the existence of applicable test methods included in the IEC 60312 standard (EU 2013a).

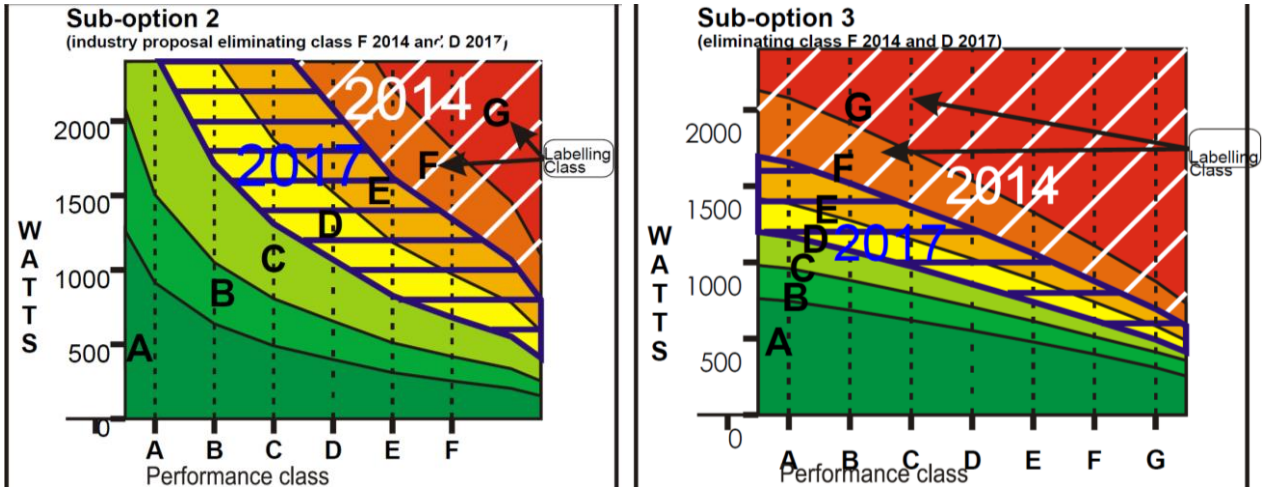

Figure 2: Graphic representation of the two sub-options proposed by (EU 2013a)

In conclusion, the relevant aspects coming to light from the Preparatory study and the Impact assessment report are hereinafter summarised:

- VC environmental impact is 'use-dominant', but it is worth noting that the manufacturing phase contribution, especially for domestic VCs, is lower than 10 %. Note that the energy consumption is higher than 90 kWh per year;
- the energy consumption during use and hence the environmental impacts of VCs depends on several factors, for instance time spent cleaning, dwelling size, number of households, power consumption;

- lifetime of VCs strictly depends on the consumer's behaviour in terms of frequency of maintenance, repair and substitution of VC ([23]);
- lifetime of VCs is dependent on the repair and maintenance potential of some of its components, especially the hose and the operational motor;
- the extension of VC lifetime has been assessed (from an environmental and economic point of view) but without taking into account the substitution of the VC with one that is more energy efficient;
- the policy options for the achievement of energy consumption savings and environmental impact reduction take into account the potential introduction of a power cap combined to the elimination of some energy efficiency classes.

1.4. Durability criteria in the EN and ISO Standards

Under the Union harmonization legislation, EN 60335.2.2 (CENELEC 2012) and EN 60312 (IEC 60312-1:2010, and A1:2011) are the two major standards applicable to vacuum cleaners (EC 2014a), and both of them are harmonised with the equivalent IEC standards (International Electrotechnical Commission, www.iec.ch/). Details of these standards are described in the following sections.

1.4.1. EN 60335

Within the family of standards EN 60335 ('Household and similar electrical appliances'), the EN 60335-2-2 deals with the specific requirements for vacuum cleaners and water-suction cleaning appliances for household and similar purposes, including vacuum cleaners for animal grooming, centrally sited vacuum cleaners and automatic battery-powered cleaners. Hazards associated with appliance usage are taken into account, as the standard is largely focused on safety issues.

The general conditions of the tests envisage that, for motor-operated appliances ([24]), 'the tests are carried out on the appliance as supplied' and with a power input corresponding to 'the power input at the most unfavourable voltage within the rated voltage range'. This standard also defines the maximum input power, the minimum airflow and the *nominal input power*. The maximum input power is measured when the airflow is at the highest (sometimes called *open airflow*); the minimum input power is measured when airflow is zero (sometimes called *sealed suction*); indeed, the *nominal input power* is the arithmetic average of maximum electric input power in W (at highest airflow) and the minimum input power in W (at zero airflow). Moreover, a 10 % tolerance is allowed by the standard in the nameplate-declaration of *nominal* and *maximum* value in W.

1.4.2. EN 60312-1:2013

The EN 60312-1:2013 aims at specifying essential performance of dry vacuum cleaners and to describe methods for measuring this performance. Thus, it describes various test methods dealing with the measurements relative to cleaning surfaces with different soiling types.

([23]) This VC substitution certainly depends on the cleaning performances of VC, but also by other non-technical aspects: the obsolescence of a product can be related primarily to the quality of the product but also to the desirability of the same (Cooper 2012).

([24]) Motor-operated appliances are defined as 'appliance incorporating motors but without any heating element'.

The measurements and the testing should be done in accordance with ISO554 ('Standard atmospheres for conditioning and/or testing'), and should be carried out under standard atmospheric conditions. Moreover, the floor on which the carpet for the test is placed must be flat, consisting in *a smooth untreated pine plywood or equivalent panel, at least 15mm thick and of a size appropriate for the test* in order to minimise the influence of electrostatic phenomena. The equipment and materials for measurements to be used in a test shall, prior to the test, be *kept hanging free or laying flat for at least 16 h at standard atmospheric conditions*. Finally, 1 % tolerance shall be allowed for carrying out measurements.

During the test, the vacuum cleaner and its accessories should be used in accordance with the instructions given by manufacturers about the normal operation. Note that before each test, both vacuum cleaner and its attachment shall be kept running for at least 10 minutes in order to permit their stabilisation.

As the conditions of the carpet (on which the dust removal ability is assessed) could change over time, a regular check should be done in order to verify the test results obtained ([25]).

The dry vacuum cleaner tests described in that standard are the following:

- dust removal from hard flat floors;
- dust removal from hard floors with crevices;
- dust removal from carpets;
- dust removal along walls;
- fibre removal from carpets and upholstery;
- thread removal from carpets;
- maximum usable volume of the dust receptacle;
- air data;
- performance with loaded dust receptacle;
- total emission while vacuum cleaning;
- filtration efficiency of the vacuum cleaner;
- miscellaneous tests.

Test on durability are included within the 'miscellaneous tests' section, with particular reference to the hose ('Deformation of hose and connecting tubes', 'Flexibility of the hose', 'Repeated bending of the hose') and the motor ('Life test'). Note that this standard never tests the motor as a stand-alone component, but the whole VC with all its electrical components.

([25]) Concerning the test carpet, a Wilson type is the 'preferred test carpet' that shall be used for international comparative testing.

BOX 1: Deformation of hose and connecting tubes

This test aims at determining the ability of the hose, the connecting tubes, the tube grip and the hose connection to sustain a certain load, equivalent to a moderately heavy person, without undergoing permanent deformations and so an impairment of the vacuum cleaner performances.

Through a screw press and a load indicator, a measured force shall be applied to the object: starting from 0 N, it is increased to 700 N and kept for 10 seconds before being reduced again to 0 N. Note that the hose shall not be stretched or compressed during the test.

Prior to the test, the cross-sectional diameter of the object being tested is measured. This operation will be repeated at least 1 minute after the end of the test procedure, in order to express the permanent deformation as a percentage reduction in the original diameter (adapted from EN 60312-1:2013).

BOX 2: Flexibility of the hose

In order to assess the hose's ability in not creasing under stress, the flexibility of the hose shall be tested.

The material required for this test is 1.5 m of the hose, bent in shape of a U; the free ends of the hose shall be clamped together. The tested hose shall be left suspended and, 1 minute after, the greatest distance between the centre lines of the two hose legs is measured. At this point, a load of 1 000 g shall be applied to the lowest point of the tested object and the same distance shall be measure after 1 minute.

The ratio between the difference of these two values and the original distance measure (before the load application) represents the flexibility of the hose (adapted from EN 60312-1:2013).

BOX 3: Repeated bending of the hose

As the repeated bending of the hose may cause leakages affecting vacuum cleaner performance, the hose's ability to be repeatedly bent shall be assessed.

Hence, the hose connector shall be attached to a pivoting lever with a clamping device so that the lever is operated by means of an oscillator performing a raising and lowering movement (frequency of 10 ± 1 periods per minute). The lever is initially positioned horizontally and then raised to form an angle of 40 ± 1 grades with the horizontal plane. The distance between the hose-fitting end of the connector and the pivot point shall be 300 mm ± 50 mm.

At this point, a load of 2.5 kg is attached to the hose pendent part so that is lifted to a height of 100 mm ± 10 mm above the mounting-bock and, during the remainder of the period, rests on the mounting-block to completely unload the hose.

A lateral deflection of maximum 3 grades is given in order to avoid the pendulation of the weight. The numbers of oscillations until the hose shall be considered unusable is recorded. Note that 'it is recommended that the test is discontinued after 40 000 oscillations' (adapted from EN 60312-1:2013).

BOX 4: Life test

The life test purpose is the determination of the vacuum cleaner's ability to maintain its air flow performances when the dust receptacle is partly filled.

Before loading the dust receptacle (50 % of dust required), some specific tests shall have been performed (air data measurements, dust emission, filtration measurements). Once the receptacle is loaded the vacuum cleaner is run intermittently with periods of 14.5 min on and 30 sec off (not in contact with the floor if there is an agitation device). After 50 h ± 5 h, the dust receptacle and filters should be substituted by new ones and, under these conditions, air measurements are repeated.

This cycle shall be repeated in steps of 50 h ± 5 h. Note that the recommendation is that the total time of the test shall be at least 500 h (adapted from EN 60312-1:2013).

CHAPTER 2
LCA and durability — Literature Review

2.1. Introduction

According to a review of the scientific literature, few studies have been identified concerning the LCA of VCs and the discussion of durability issues. Moreover, these studies were often not detailed in the analysis of durability or mainly based on qualitative judgements. In some cases, the study provided general considerations for EEE, including also VC.

Consistent with the goal of this study, the relevant studies in the literature have been summarised in Table 4 and further classified based on their topic. In particular, the classification focuses on the dissertation of specific features about the assessment of VC durability. Thus, the criteria for the classification of those studies deal with:

- considerations regarding the durability of EEE, and VCs in particular (quantitative and qualitative dissertations);
- considerations regarding the lifetime of EEE and its dependency on specific aspects;
- some specific LCA steps, with reference to the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) of EEE, and VCs in particular;
- economic considerations associated to the life-cycle of EEE and/or to the durability issue;
- considerations regarding the consumer's role affecting durability (for instance time spent cleaning, obsolescence of products, maintenance and repair operations);
- considerations regarding the existence and the applicability of standards and test methods about VCs.

Studies not directly addressed to VCs are highlighted through the acronym 'G.C.', meaning 'general considerations', while studies in which some specific information are related to VCs are highlighted through 'X'.

As mentioned previously, among the studies on VCs (11 of 18 studies), the majority discuss the lifetime of VCs, while a more detailed analysis of durability is generally missing. It is interesting to note that all the studies addressing durability of VCs provide information also about the VCs' lifetime and the consumer role.

The following sections analyse in detail some relevant outcomes of these studies.

Table 4: Literature review on studies of LCA and durability of ErPs.

N°	Authors	Article title	Durability	Lifetime indications	LCA		Economic aspects	Consumer role	Standards
					LCI	LCIA			
1	(Rose 2000)	Design for environment: a method for formulating product end-of-life strategies	—	X	—	—	—	X	—
2	(Ernzer & Birkhofer 2003)	How to carry out life cycle design? Methodical support for product developers	—	X	—	X	—	X	—
3	(Kobayashi et al. 2005)	A Practical Method for Quantifying Eco-efficiency Using Eco-design Support Tools	—	X	—	X	—	X	—
4	(Kemna et al. 2005)	Methodology Study Eco-design of Energy-using Products — MEEUP Product Cases Report	G.C.	X	—	G.C.	G.C.	G.C.	—
5	(Hur et al. 2005)	Simplified LCA and matrix methods in identifying the environmental aspects of a product system.	—	—	G.C.	X	—	—	—
6	(Cooper 2005)	Slower Consumption. Reflections on Product Life Spans and the 'Throwaway Society'	X	X	X	X	X	X	—
7	(Abele et al. 2005)	Environmentally Friendly Product Development Methods and Tools	—	X	—	X	X	X	—
8	(van Nes & Cramer 2006)	Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns	—	—	X (EoL)	—	—	—	X
9	(Allenby 2006)	Improvement Plan of Recycling rate of the Electronic & Electrical Equipment with Considering of Economics; Case study of Vacuum Cleaner	G.C.	G.C.	—	—	G.C.	G.C.	—
10	(Kota & Chakrabarti 2007)	Use of DFE methodologies and tools — major barriers and challenges	—	—	—	X	—	—	—
11	(Barba-Gutiérrez et al. 2008)	Eco-Efficiency of Electric and Electronic Appliances: A Data Envelopment Analysis (DEA)	—	—	X	X	X	X	—
12	(AEA Energy & Environment 2009)	Work on Preparatory Studies for Eco-Design Requirements of EuPs (II) Lot 17 Vacuum Cleaners	X	X	X	X	X	X	X
13	(WRAP 2010)	Environmental assessment of consumer electronic products	—	G.C.	—	—	—	G.C.	—
14	(WRAP 2011)	Specifying durability and repair in vacuum cleaners	G.C.	X	—	—	G.C.	G.C.	—
15	(DEFRA 2011)	Public understanding of product lifetimes and durability	X	X	—	—	—	X	—
16	(WRAP 2013b)	Product design review of a Vacuum Cleaner	—	—	X (packaging)	—	—	—	—
17	(Sam et al. 2014)	Resource efficiency indicators en case studies	G.C.	—	—	—	—	—	G.C.
18	(Boulos et al. 2014)	The Durability of Products: Task 1 Report. Standard assessment for the circular economy under the Eco-Innovation Action Plan	G.C.	—	G.C.	G.C.	—	—	—

G.C.: General Consideration; means that the study does not refer specifically to VCs but give some information about ErPs

X: This means that the information within the study refer to VCs

2.1.1. Simplified LCA and matrix methods in identifying the environmental aspects of a product system

A study by Hur et al. (2005) developed the Environmentally Responsible Product Assessment (ERPA) ([26]) method to identify how a simplified LCA (SLCA) could be applied for the assessment of Electrical and Electronic Equipment. In the study, several simplifications have been done in order to identify those life-cycle stages that could be omitted without significantly modifying the overall results.

Two case-studies have been analysed: vacuum cleaners and mobile phones. Their life-cycles have been divided in seven sub-stages (three levels for the pre-manufacturing, one level for manufacturing, one level for distribution and use and two levels for the end-of-life). Several assumptions about the reduction of the study scope (for instance excluding some levels of product system) and on data availability (for instance through the availability of databases or secondary data) have been introduced for each of these sub-stages (Table 5). Then, the obtained impact assessment results have been compared to a reference method ('Ref' in Table 5 and Figure 3) through the calculation of the ratio between the LCIA of a specific SLCA and the LCIA of the reference method.

The results of the ERPA method prove that for both the case-study products, the exclusion of the 'distribution and use' stage (i.e. SLCA 5, 9, 10 and 11 in Table 5) causes high differences between the LCIA results and those of the reference method. Focusing on the VC case-study, the comparison between the two SLCA which differ only in the 'distribution and use phase' (4 and 5 in Table 5) ([27]) points out that the potential environmental impact related to 'distribution and use' accounts for almost 60 % of the LC impact (Figure 3).

Table 5: Scope and data quality of 11 simplified methods (Hur et al. 2005)

SLCA method												
Life cycle stages	Level	Simplified methods										
		Ref	1	2	3	4	5	6	7	8	9	10	11
Pre-manufacturing													
Resource acquisition and materials production	Level −3	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
Sub-components manufacturing	Level −2	▤	□	□	□	▤	▤	□	□	□	□	□	□
Components manufacturing	Level −1	■	■	▤	□	■	■	■	▤	□	■	▤	□
Manufacturing	Level 0	■	■	■	■	■	■	■	■	■	■	■	■
Distribution and use	Level 1	■	■	■	■	■	□	■	■	■	□	□	□
End-of-life													
Components recycling	Level 2	■	■	■	■	□	□	□	□	□	□	□	□
Materials disposal	Level 3	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤

(▤) Substituted by database, (□) Excluded life cycle stage, (■) Gathering actual data.

([26]) The ERPA method is one of the matrix methods used for the identification of the key environmental performance of an examined product system.
([27]) Between method 4 and method 5, the only difference is about the use phase and the components recycling.

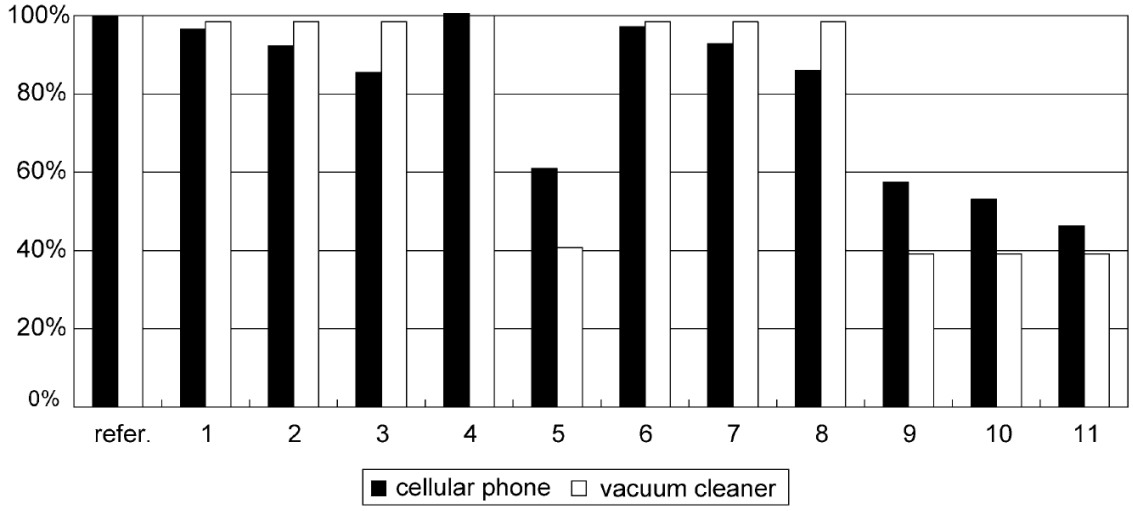

Figure 3: The results of the LC environmental impact obtained from the reference and each SLCA method (Hur et al. 2005). Impact categories considered refer to the eco-indicators developed by the Korean MOCIE (Ministry of Commerce, Industry and Energy).

Moreover, taking into account also the difficulty in data collection and calculation, the simplified methods have been grouped in 4 classes based on data accuracy and simplification.

So this study underlines that, in order to assess the environmental performance of VCs, the 'distribution and use phase' is the most important life-cycle stage in terms of environmental impact; therefore it should be modelled through actual data. Indeed, concerning other life-cycle stages ('resource acquisition and materials production', 'sub-components manufacturing' and 'materials disposal'), the availability of secondary data instead of actual data doesn't strongly affect the final result. Note that for the 'manufacturing' stage actual data have been considered for all the SLCA. Furthermore, the exclusion of some life-cycle stages, except for the use-phase, seems not to highly affect the LCIA results.

Finally, the VC environmental impact analysis ([28]) shows that the higher environmental burdens is attributable to the motor (almost 40 % of the life-cycle impact), followed by hose (about 20 % of the life-cycle impact) and printed board assembly (about 15 % of the life-cycle impact). Concerning the life-cycle stages, the pre-manufacturing and the use phase account for almost 90 % of the life-cycle impact.

2.1.2. A Practical Method for Quantifying Eco-efficiency Using Eco-design Support Tools

A study by Kobayashi et al. (2005) analysed two different case-studies of VC: a base-case manufactured in 1990 and a newer product manufactured in 2003. The main differences in the VC structure concern the dust collection system (the new one is a cyclone type, hence it doesn't need a paper dust bag), the weight (the new one weighs 5.3 kg, which means about 40 % less than the base-case) and the dust suction (the new one is more powerful). Both products are assumed to have the same lifetime (7 years). Note that, as the new VC has a more powerful dust suction, the study assumed that its electricity consumption during the use phase is higher than the energy consumption of the base-case VC.

([28]) The selected SLCA for the environmental assessment of VC is method 2 in Table 5, which means: actual data for 'manufacturing', 'distribution and use' and components recycling' stages; database data for 'Resource acquisition and materials production', components manufacturing' and 'materials disposal' stages; exclusion of the 'sub-components manufacturing' stage data.

The environmental impact of the two VC models is assessed with Life-cycle Impact assessment Method based on Endpoint modelling (LIME). From these results, it is possible to conclude that the main contribution is due to the use phase, even if the contribution of materials to the impact is relevant. Note that the EoL modelling assumes a direct landfill disposal for the base-case VC and the recycling of ABS, PP, PE, PVC, iron, copper and aluminium and incineration or disposal of the other materials for the new VC (the LCIA highlights that some environmental credits are associated to the End-of-Life of the new VC). The comparison between the base-case model and the new VC points out that the impact of the new one is the highest (4 % more than the base-case); this means that, even if there is a reduction of materials related to the non-use of dust bags, the VC has an overall higher impact due to the higher energy consumption in the use phase. This is confirmed by the contribution analysis: emissions of CO_2, SO_X, and NO_X are mainly related to the electricity consumption.

Kobayashi et al. (2005) also analysed the eco-efficiency of products defined as the 'product value per unit of environmental impact'. Authors then realised the 'Factor X chart' where the horizontal axis represents the product value factor, which means an improvement of the product value, and the vertical axis represents the environmental impact reduction factor, which means a reduction of the environmental impact (Figure 4). The resulting chart shows that the product value of the new VC was about 1.6 times the product value of the base-case VC, while the environmental impact of the base-case VC was about 0.9 times the new VC impact (thus the new VC had a higher environmental impact than the old one). The chart also illustrates the so-called Factor 4, meaning the curve of Factor X obtained doubling the product value without increasing the environmental burdens. Kobayashi et al. (2005) concluded that for the new VC the improvement of the product value was the main contributor to the improvement of eco-efficiency, while in the future it will be necessary to achieve further reductions in environmental impacts.

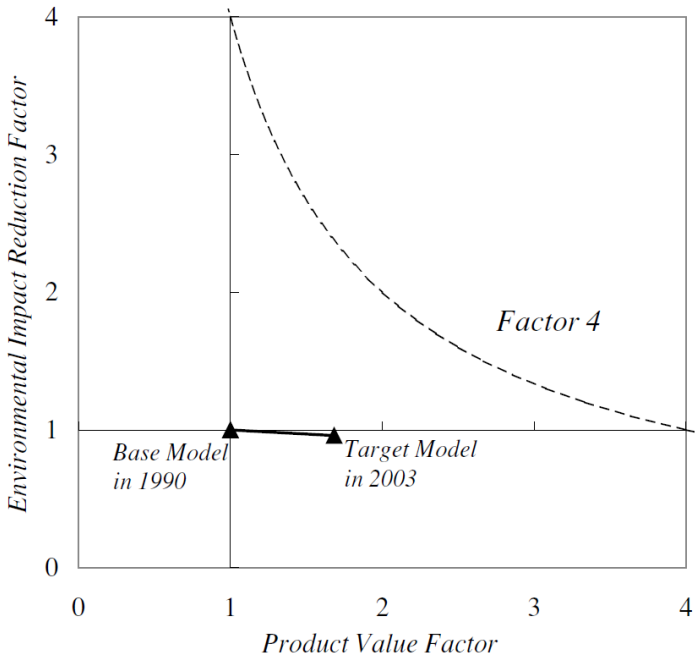

Figure 4: Factor X chart for two vacuum cleaners (Kobayashi et al. 2005)

2.1.3. Eco-design for Energy-using Products: the vacuum cleaners product case

Vacuum cleaners are included among the 10 product cases assessed through the Methodology for the Ecodesign of Energy-using products (MEEuP) (Kemna et al. 2005).

This methodology study performed a LCA of a base-case bagged VC with an average power of 90.5 kW and a mass of 8 kg (including packaging). Concerning the use phase, the time spent cleaning is assumed to be about 70 minutes per week and the replacement of bags and filters is supposed to be 5 bags and 1 filter per year.

It is interesting to note that Kemna et al. (2005) consider not economically convenient to repair the VC outside the warranty period, due to the 'relative modest product price for most models'. The maintenance of VCs substantially consists in the filters replacement (Kemna et al. 2005). The main characteristics of the base-case VC are summarised in Table 6.

The life-cycle impact of one canister VC (Table 7 and Figure 5) depicts the high contribution of the use-phase for several categories, but also a not negligible contribution of the manufacturing phase.

Table 6: Base case VC characteristics considered by Kemna et al. 2005

LCA	**Manufacturing phase**	Total mass (including packaging)	[g]	8 000
		VC bags	[g/year]	550
	Use Phase	Lifetime	[years]	8 (= 480 hours)
		Electricity consumption per hour	[kWh/h]	1.55
		Number of hour per year in use	[hours]	60
LCC	**LCC data**	Product price	[€]	125
		Electricity price	[€]	90
		VC bags price	[€]	78
		Repair & maintenance costs	[€]	40

Table 7: MEEuP study results of the Life-cycle impact of a domestic VC

Nr	Life cycle Impact per product: Vacuum Cleaners										
								Date	Author		
								0	vhk		
	Life Cycle phases -->		PRODUCTION			DISTRI-BUTION	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total			Disp.	Recycl.	Total	
	Materials	**unit**									
1	Bulk Plastics	g			**3875**			3488	388	**3875**	**0**
2	TecPlastics	g			**125**			113	13	**125**	**0**
3	Ferro	g			**2100**			105	1995	**2100**	**0**
4	Non-ferro	g			**1400**			70	1330	**1400**	**0**
5	Coating	g			**0**			0	0	**0**	**0**
6	Electronics	g			**0**			0	0	**0**	**0**
7	Misc.	g			**500**			25	475	**500**	**0**
	Total weight	g			**8000**			3800	4200	**8000**	**0**
	Other Resources & Waste							see note! debet	credit		
8	Total Energy (GER)	MJ	565	205	**770**	**119**	**7917**	272	211	**61**	**8867**
9	of which, electricity (primary MJ)	MJ	37	122	**159**	**0**	**7818**	0	2	**-2**	**7976**
10	Water (process)	ltr	84	2	**86**	**0**	**653**	0	1	**-1**	**738**
11	Water (cooling)	ltr	259	56	315	0	20835	0	8	-8	21142
12	Waste, non-haz./ landfill	g	22993	717	**23710**	**84**	**9465**	492	6	**486**	**33744**
13	Waste, hazardous/ incinerated	g	22	0	**22**	**2**	**180**	3600	1	**3599**	**3803**
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq.	25	11	**37**	**9**	**347**	20	15	**6**	**398**
15	Ozone Depletion, emissions	mg R-11 eq	negligible								
16	Acidification, emissions	g SO2 eq.	325	49	**374**	**24**	**2032**	41	19	**22**	**2453**
17	Volatile Org. Compounds (VOC)	g	1	0	**1**	**1**	**3**	1	0	**0**	**5**
18	Persistent Org. Pollutants (POP)	ng i-Teq	95	6	**100**	**0**	**52**	3	0	**3**	**157**
19	Heavy Metals	mg Ni eq.	104	13	**118**	**4**	**140**	73	0	**73**	**336**
20	PAHs	mg Ni eq.	32	0	**32**	**5**	**21**	0	0	**0**	**57**
21	Particulate Matter (PM, dust)	g	17	8	**25**	**171**	**131**	353	0	**352**	**680**
	Emissions (Water)										
22	Heavy Metals	mg Hg/20	47	0	**47**	**0**	**51**	23	0	**23**	**120**
23	Eutrophication	g PO4	1	0	**1**	**0**	**2**	1	0	**1**	**4**
24	Persistent Org. Pollutants (POP)	ng i-Teq	negligible								

***=Note: Recycling credits only relate to recycling of plastics and electronics (excl. LCD/CRT). Recycling credits for metals and other fractions are already taken into account in the production phase.**

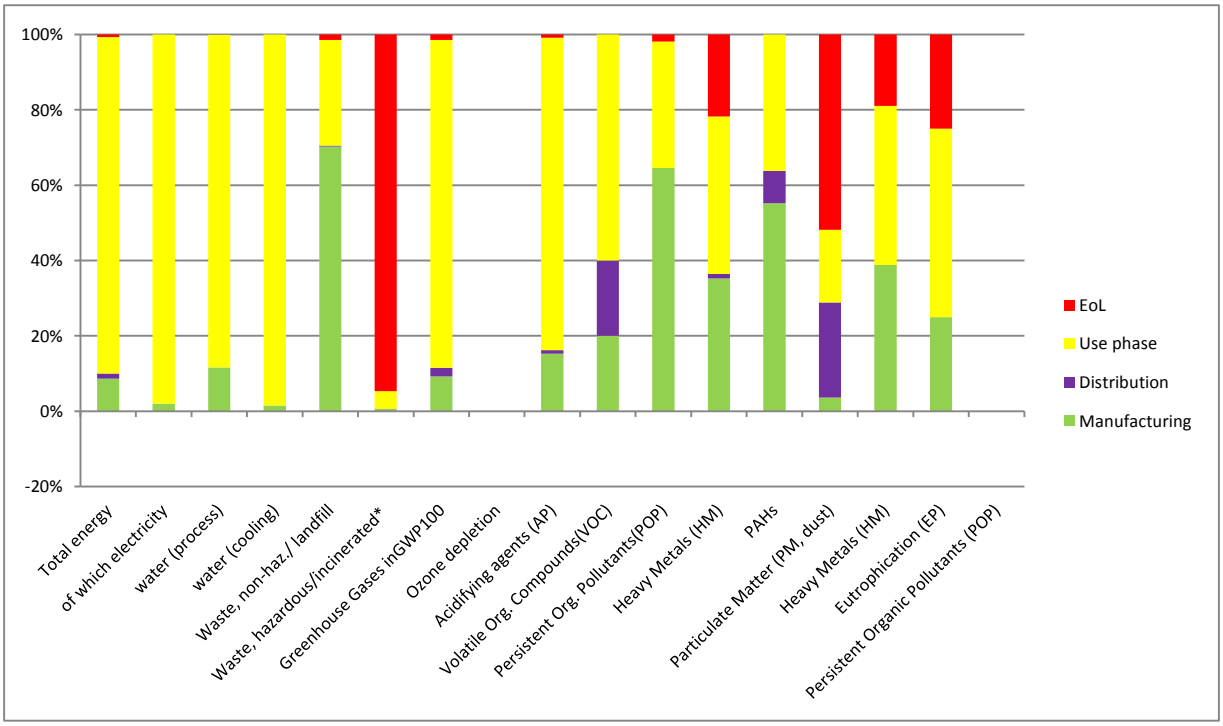

Figure 5: Percentage contribution to the overall impact of a domestic VC based on the MEEuP study

2.1.4. Product lifetime optimisation: a challenging strategy towards more sustainable consumption patterns

An interesting study on the durability of EEE has been proposed by van Nes and Cramer (2006). In the framework of the lifetime optimisation, the advantages related to the early replacement of products consuming energy during their lifetime have been assessed in order to evaluate the environmental desirability of longer-lasting products and to analyse the dualism existing between the lengthening and shortening of the lifetime.

According to the authors, the concept of 'product life' can be approached from different points of view, such as technical and economic, but also aesthetical and psychological. The substitution of a good can be associated to many reasons that are dependent by users, by market and by technical issues. In this perspective, product lifetime can be considered a part of a broader process, which aims at striving for a new utilisation-focused service economy.

Through a simple model, the environmental impacts of two products with a different lifetime have been evaluated. Noticeably, the longer-lasting product has a higher energy consumption than the shorter-lasting product, and so the environmental impacts reduction decreases (E_{gain} in Figure 6).

The critical issue is then represented by the replacement with a more energy-efficiency product. In this case, a *payback period* (T_p) has been defined to represent the time range between the replacement and the break-even point (BEP), after which the new product is more convenient in terms of environmental performance. The analysis of the 'early replacement scenario' demonstrates that the environmental benefits depend on the time range between the early replacement and the replacement due to the end of the lifetime product. This means that an early replacement is environmentally desirable when the payback period is shorter than the more efficient product's lifetime (Figure 6).

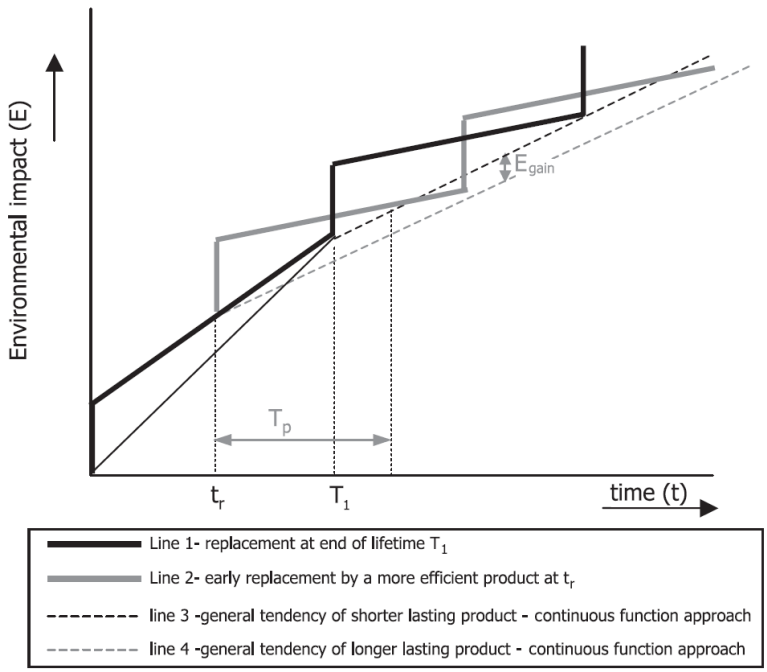

Figure 6: Environmental effect of lifetime extension versus early replacement for product with lower energy consumption

Therefore, this study highlights that the environmental desirability of an early replacement of a product is connected to the initial environmental impact of the replacing product, but also to the lower energy consumption and the lifetime of the new product.

2.1.5. Eco-Efficiency of Electric and Electronic Appliances: a Data Envelopment Analysis (DEA)

A study by Barba-Gutiérrez et al. (2008) compares the eco-efficiency of some household electric appliances. Authors developed a standard Data Envelopment Analysis (DEA) method, which uses LCA 'ecoipoints' ([29]) (as unit of measure of the environmental impact of products) and the retail price (as unit of measure of their economic value). Therefore, the increase of the eco-efficiency is associated to the increase of the economic value of the product and/or to the reduction of its environmental impact.

A wide spectrum of appliances has been considered in this study, including VCs. The bill of materials for VCs is illustrated in Table 8; note that its mass amounted to 4.5 kg.

The Eco-Indicator99 method has been used for the Life Cycle Impact Assessment (software SimaPro6.0). Results prove that the major impact is related to the 'Resources' damage ([30]) (1.79 ecopoints per VC, or 397.78 ecopoints per ton), similarly to the other assessed products. More specifically the major contribution is due to the presence of copper and aluminium, which contribute to the total impact respectively 47 % and 25 %.

Because the product is eco-efficiency, through the DEA model the necessary reduction of the environmental impact has been calculated for all the three assessed impact categories (Human Health, Ecosystem Quality and Resources). Thus, DEA results depict that the VCs product group exhibits *decreasing returns to scale* ([31]): this means that, the environmental impact reduction will not correspond to a proportional reduction of the product price. It is therefore suggested that for these products the more desirable design option should consider 'less functionality and complexity and a lower value but with less environmental impact'.

Finally, the future efforts of the DEA approach are focused on including the lifetime of products in the calculation of their eco-efficiency.

([29]) Ecoipoints are used to calculate the difference between the impact in a specific area and the quality target value (Barba-Gutiérrez et al., 2008).
([30]) The 'damages to resources are expressed as surplus energy for the future mining of resources' (Barba-Gutiérrez et al., 2008).
([31]) In economy, the *return to scale* refers to the trend of the increase in production in respect to the increase of the factors of production (land, labour and capital). A decrease in return to scale occurs when an increase of the factors of production corresponds to a less than proportional increase in the production outputs.

Table 8: Bill of materials of a vacuum cleaner (mass and percentages of total mass between brackets)

Components	Vacuum cleaner[g] (4.5 kg)
ABS	0.27 (6.00)
Aluminium	0.81 (18.00)
Bronze	
Cardboard	
Concrete	
Copper	0.675 (15.00)
Epoxy resin	
Glass	
Iron	
Lead	
Magnesium	
Nickel	
Oil and CFC	
Other Materials	
Paper	0.045 (1.00)
Phosphorus	
Plastic	
Polypropylene	0.9 (20.00)
Polycarbonates	
Polystyrene	0.45 (10.00)
Polyurethane	
PVC	0.45 (10.00)
Rubber	0.09 (2.00)
Silicon	
Steel (stainless)	0.765 (17.00)
Textile	0.045 (1.00)
Tin plate	
Water with R11	
Wood	
Zinc	

2.1.6. The preparatory study for Eco-Design requirements of EuPs — Vacuum cleaners

The Preparatory study for ecodesign requirements of Energy-using Products (EuPs) about vacuum cleaners was carried out by AEA Energy & Environment, Intertek and Consumer Research Associates between November 2007 and January 2009. In this section, the most relevant information for the durability assessment of VCs are reported.

As mentioned in section 1.3, the Preparatory study assessed the environmental performance of different types of VCs: canister (domestic and commercial), upright (domestic and commercial) and battery/cordless VCs) as well as their Life-Cycle Cost (LCC). Moreover, some improvement potential options have been assessed in order to highlight the potential improvement in terms of environmental benefits.

As this report assesses the durability of a canister VC, the information hereinafter reported refers to this type of VC.

The base-case VC is a bagged VC with a mass of about 8.5 kg (including packaging). Indeed, about the use phase of the VC, the Preparatory study underlines the importance of taking into account the operating hours of the appliance for evaluating the energy consumption during its lifetime. In this perspective, the average amount of time spent cleaning is assumed to be 1 hour per week, as the average between a 'light' pattern (15 minutes per week) and a 'heavy' pattern (4 hours per week). Note that in order to 'equate 500

hours (domestic)', the total hours in use for domestic VCs considered for the analysis are 62.5 per year. The characteristics of the canister VC considered by the Preparatory study are illustrated in Table 9.

Table 9: Canister VC characteristics considered by the Preparatory study

LCA	**Manufacturing phase**	Bulk Plastic	[g]	4 188
		Tec Plastics	[g]	695
		Ferro	[g]	1 467
		Non-Ferro	[g]	478
		Coating	[g]	8
		Electronics	[g]	29
		Misc.	[g]	1 612
		Volume of packaged product	[m^3]	0.08
	Use phase	Lifetime	[years]	8 (= 500 hours)
		Electricity consumption per hour	[kWh/h]	1.5
		Number of hour per year in use	[hours]	62.5
	EoL	'All EoL vacuum cleaners are separately collected in accordance with the WEEE Directive'		
		'70 % of separately collected EoL vacuum cleaners are recovered, complying with the WEEE Directive'		
		'50 % of separately collected EoL vacuum cleaners undergo reuse and recycling, also complying with the WEEE Directive'		
		'Metals — 95 % recycling is assumed'		
		'Plastics — 1 % reuse, closed loop recycling assumed. The percentage of material recycling is calculated so that an overall 50 % reuse and recycling rate for vacuum cleaners is achieved. The percentage of thermal recycling is such as to achieve an overall recovery rate for vacuum cleaners of 70 %'		
		'Landfill — 30 % of products are not recovered'		
LCC	**LCC data**	Product price	[€]	110
		Electricity price	[€]	91
		VC bags price	[€]	52
		Office paper (~filters, instruction manuals, etc.)	[€]	2
		Repair & maintenance costs	[€]	8

The life-cycle impact of one canister VC (Table 10 and Figure 7) depicts the high contribution of the use-phase for several categories, but also a not negligible contribution of the manufacturing phase.

Table 10: Preparatory study results of the Life-cycle impact of a domestic VC

	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Total	
	Materials	**unit**									
1	Bulk Plastics	g			4334			1461	2873	4334	0
2	TecPlastics	g			695			234	461	695	0
3	Ferro	g			1467			440	1027	1467	0
4	Non-ferro	g			478			143	334	478	0
5	Coating	g			8			2	5	8	0
6	Electronics	g			29			14	14	29	0
7	Misc.	g			1612			483	1128	1612	0
	Total weight	g			8621			2779	5843	8621	0
	Other Resources & Waste							debet	see note! credit		
8	Total Energy (GER)	MJ	592	219	811	125	7965	297	133	164	9065
9	of which, electricity (in primary MJ)	MJ	59	129	188	0	7881	0	5	-5	8065
10	Water (process)	ltr	101	2	103	0	631	0	4	-4	730
11	Water (cooling)	ltr	573	62	635	0	21006	0	18	-18	21623
12	Waste, non-haz./ landfill	g	9141	696	9837	87	9356	3174	17	3156	22436
13	Waste, hazardous/ incinerated	g	86	0	86	2	182	1709	4	1706	1976
	Emissions (Air)										
14	Greenhouse Gases in GWP100	kg CO2 eq.	23	12	36	9	349	22	8	15	408
15	Ozone Depletion, emissions	mg R-11 eq	negligible								
16	Acidification, emissions	g SO2 eq.	213	53	266	25	2043	45	12	33	2368
17	Volatile Organic Compounds (VOC)	g	0	0	0	1	3	1	0	1	6
18	Persistent Organic Pollutants (POP)	ng i-Teq	20	1	22	0	52	22	0	22	96
19	Heavy Metals	mg Ni eq.	79	3	82	4	141	84	0	84	311
	PAHs	mg Ni eq.	38	0	38	5	21	0	0	0	64
20	Particulate Matter (PM, dust)	g	20	8	28	185	132	401	1	400	745
	Emissions (Water)										
21	Heavy Metals	mg Hg/20	64	0	64	0	51	24	1	23	139
22	Eutrophication	g PO4	4	0	5	0	3	1	0	1	9
23	Persistent Organic Pollutants (POP)	ng i-Teq	negligible								

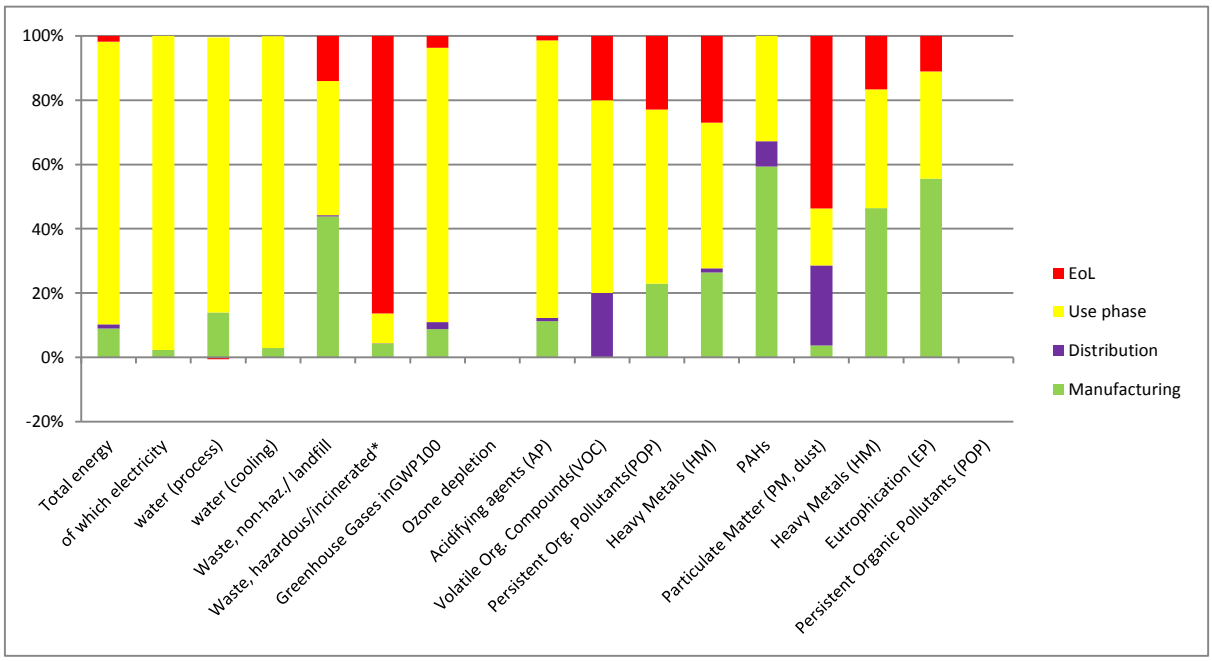

Figure 7: Percentage contribution to the overall impact of a domestic VC based on the Preparatory study LCIA.

As previously mentioned (section 1.3), the Preparatory study considered 8 'design options' and, among them, option 7 and option 8 are those more compliant with the goal of this study.

In option 8, the fundamental assumption is an increase of the VC lifetime of 50 %, which means from 8 years (average lifetime considered) to 12 years. It is worth noting that 'the question of whether or not it is better to replace more quickly an inefficient vacuum cleaner with an efficient vacuum cleaner' was not considered in this option. Therefore, the Preparatory study presents the results of the environmental

impact of a base-case VC in comparison to a VC with a longer lifetime ([32]). It is to be noticed that the description of this scenario suggested that the longer-lasting VC has a higher impact associated to the manufacturing phase due to the employment of more or different materials in order to guarantee the higher lifetime of the product. However, no further details are provided. The results depict a lower impact for the option 8 respect to the base-case VC, particularly the domestic one ([33]). Available results are aggregated and a contribution analysis in order to evaluate the potential decrease of the use-phase impact and the potential increase of manufacturing impact in option 8 is not immediate. Moreover, the comparison between the impacts of option 8 and the base-case does not take into account that the temporal system boundaries are different and the related function provided by the two alternatives (8 years for the life-cycle impacts of the base-case and 12 years for those regarding option 8) (Table 11). The corresponding economic analysis highlights that the extension of the VC lifetime corresponds to higher life-cycle costs, particularly due to the increase of the 'repair & maintenance costs' item: the base-case assessed in the Preparatory study assumes that the repair and maintenance costs represent about 3 % of the overall life-cycle cost ([34]), while for the VC with an 'increased product lifetime', this value rises until 10 %. Indeed, the contribution of the other cost items in respect to the LCC remains almost the same. Note also that the purchase price of the longer-lasting product is assumed to be higher than the purchase price of the base-case VC (Table 12).

In option 7, the main assumption is that the environmental impact of the VC could be reduced 'by reducing the amount of materials used in its construction', for instance through the employment of new materials. Hence, a mass of 50 % of the base-case VC mass is considered, and it is interesting to see that this reduction can be even higher: in fact, there are canister VCs even lighter than 4.5 kg ([35]). The results depict a reduction of all the impact categories considered ([36]). Similarly to the aforementioned, it is not possible to disaggregate the information in order to understand to what life-cycle phase (and/or used material) the savings are associated. It is interesting to note that the decrease of the 'Total Energy (GER)' used in option 7 in respect to the base-case is higher than the decrease of the 'Total Energy (GER)' used in option 8 in respect to the base-case (Table 11). Indeed, in the 'reduced materials/lightweighting' option, the values adopted by the Preparatory study don't affect the VC life-cycle costs; thus, the variation of the manufacturing materials seems not to affect the purchase price of the product (Table 12).

([32]) The environmental assessment is performed through the MEEuP eco-report.

([33]) The life-cycle impact assessment proves that the most relevant benefits are related to the emission of particulate matter (lower impact of more than 30 %), waste generation (-26 % of 'waste, hazardous/incinerated' and -17 % of 'waste, non-haz/landfill') and heavy metals emissions (-18 % of 'Heavy metals' emitted in air and -20 % of those emitted in water), while the savings about the total energy requirement are lower (less than 5 %).

([34]) The LCC is comprehensive of product purchase, electricity, dust bag and filter costs.

([35]) http://www.miele.co.uk/vacuum-cleaners/ 4.3kg — MIELE; http://www.currys.co.uk/gbuk/home-appliances/vacuum-cleaners/cylinder-vacuum-cleaners/337_3169_30257_xx_xx/xx-criteria.html 4.5kg — HOOVER; http://www.allergybuyersclub.com/all-canister-vacuum-cleaners.html#top 4.9 — ELECTROLUX; http://www.betterlifeuae.com/media/73364/vsz3180gb %20ss.pdf 4.3kg (cylinder only) — SIEMENS (ACCESS: 30/01/2015).

([36]) The life-cycle impact assessment proves that the most relevant benefits are related to the waste generation (-45 % of 'waste, hazardous/incinerated' and -28 % of 'waste, non-haz/landfill') and heavy metal emissions (-27 % of 'Heavy metals' emitted in air and -40 % of those emitted in water).

Table 11: EU stock 2005 environmental impacts for the base-case canister VC, the durable option and the light-weight option (AEA Energy & Environment 2009)

Main life-cycle indicators	Unit of Measure	Canister VC base-case	Option 8: Increased Product Lifetime		Option 7: Reduced Materials/ Lightweight	
			LCIA	Variation+	LCIA	Variationº
Total Energy (GER)	[PJ]	316.00	303.00	-4.11 %	299.00	-5.38 %
of which electricity	[TWh]	26.30	26.10	-0.76 %	26.00	-1.14 %
Water (process)*	[mln m3]	29.00	28.00	-3.45 %	27.00	-6.90 %
Waste, non-haz./ landfill*	[kton]	803.00	663.00	-17.43 %	577.00	-28.14 %
Waste, hazardous/incinerated*	[kton]	72.00	53.00	-26.39 %	39.00	-45.83 %
Greenhouse Gases inGWP100	[mt CO2eq]	14.00	14.00	0.00 %	13.00	-7.14 %
Acidifying agents (AP)	[kt SO2eq]	82.00	79.00	-3.66 %	77.00	-6.10 %
Volatile Org. Compounds (VOC)	[kt]	0.00	0.00	0.00 %	0.00	
Persistent Org. Pollutants (POP)	[g i-Tec]	3.00	3.00	0.00 %	3.00	0.00 %
Heavy Metals (HM)	[ton Ni eq]	11.00	9.00	-18.18 %	8.00	-27.27 %
PAHs	[ton Ni eq]	2.00	2.00	0.00 %	2.00	0.00 %
Particulate Matter (PM, dust)	[kt]	30.00	21.00	-30.00 %	23.00	-23.33 %
Heavy Metals (HM)	[ton Hg/20]	5.00	4.00	-20.00 %	3.00	-40.00 %
Eutrophication (EP)	[kt PO4]	0.00	0.00	-4.11 %	0.00	0.00 %

*=caution: low accuracy for production phase
+Calculated as: (Option8 — Base-Case)/ Base-Case [%]
ºCalculated as: (Option7 — Base-Case)/ Base-Case [%]

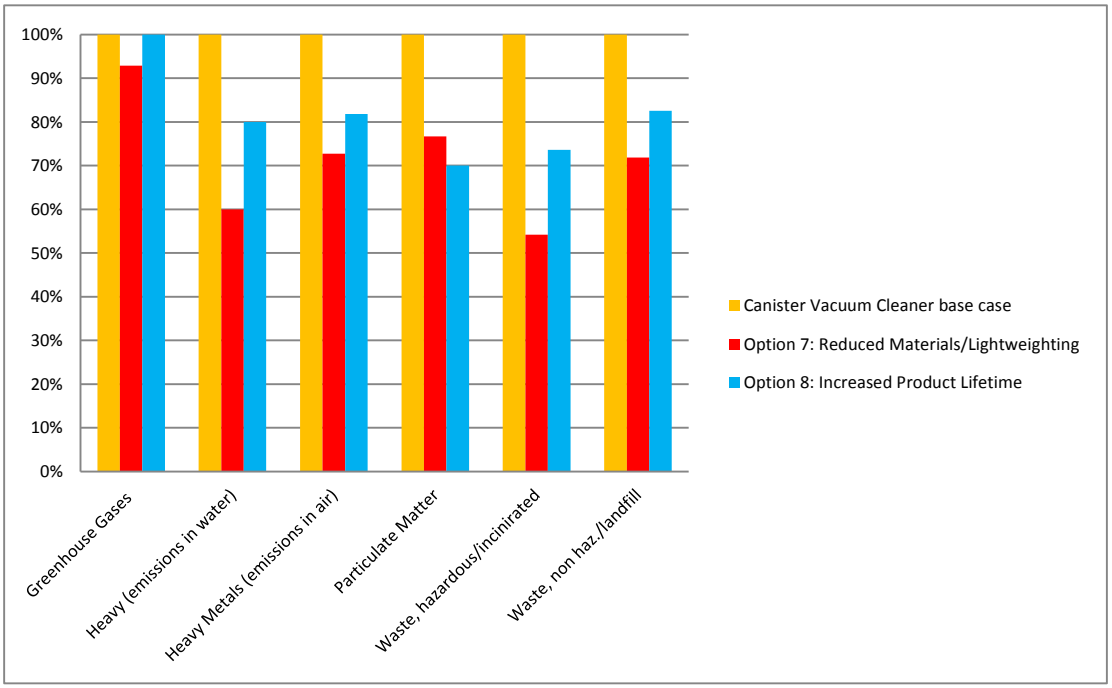

Figure 8: Comparison between the environmental impacts of the base-case canister vacuum cleaner, option 8 (increased lifetime) and option 7 (new materials/lightweight) assessed in the Preparatory study

Table 12: Life Cycle Costs per Product — Domestic Canisters (AEA Energy & Environment 2009)

Cost item	Canister VC base case [€]	Option 8: Increased Product Lifetime		Option 7: Reduced Materials/ Lightweight	
		LCC [€]	Variation+	LCC [€]	Variationº
Product price	110.00	121.00	10.00 %	110.00	0.00 %
Installation/ acquisition costs	0.00	0.00	0.00 %	0.00	0.00 %
Fuel (gas, oil, wood)	0.00	0.00	0.00 %	0.00	0.00 %
Electricity	91.00	125.00	37.36 %	91.00	0.00 %
Bags	52.00	71.00	36.54 %	52.00	0.00 %
Filters	2.00	3.00	50.00 %	2.00	0.00 %
Repair & maintenance costs	8.00	37.00	362.50 %	8.00	0.00 %
Total	263.00	357.00	35.74 %	263.00	0.00 %
+Calculated as: (Option8 — Base-Case)/ Base-Case [%] ºCalculated as: (Option7 — Base-Case)/ Base-Case [%]					

2.1.7. WRAP's Environmental assessment of consumer electronic products

A study by (WRAP 2010) classified electronic products into 'use phase dominant' or 'materials/process dominant' depending of such key factors as: the amount of material used for the product manufacturing, the amount of electronic components (37) in products, the power demand, the use frequency and the lifetime of the product. As depicted in Figure 9, VCs belongs to the first category, i.e. among products with a dominant use phase. In fact, the energy requirement for the manufacturing phase ('materials and process' in the following figures) turns out to be less than 15 % of the total life-cycle energy, much lower than the energy requirement during the use phase (about 80 %) (Figure 10).

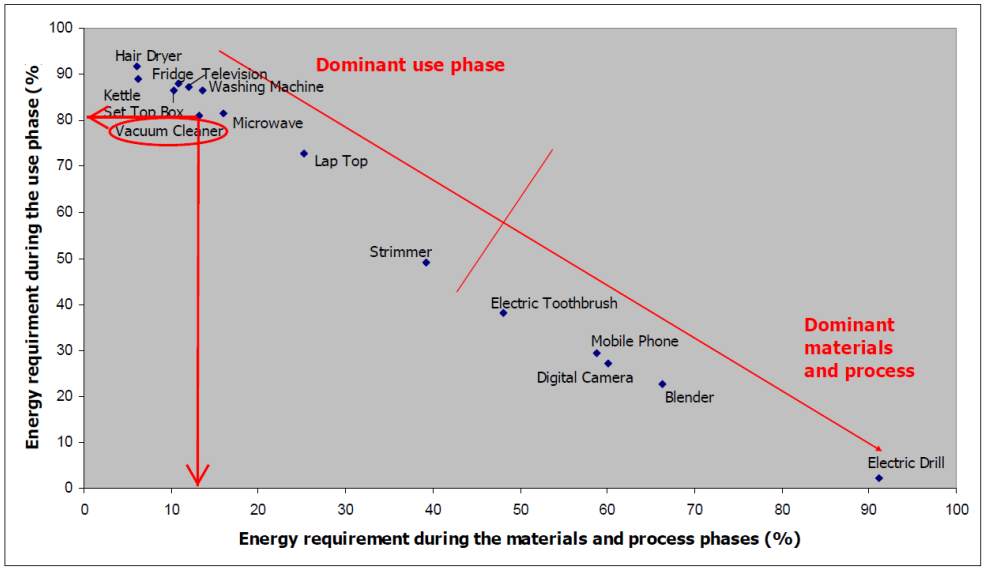

Figure 9: Classification of products by energy requirement in the use phase VS materials and process phase

Moreover, the study identifies the consumer's behaviour as a key aspect influencing significantly the energy savings, mainly during the use phase. Therefore it is always important to inform the final user about

(37) 'Electronic components such as large integrated circuits can require 140 times more energy to be produced than plastics such as PVC' (WRAP 2010).

the consumption profile of products in order to permit a conscious choice among differently performing goods. In this framework, the WRAP assessment highlights the need of more and specific information in order to quantify the frequency of use and the lifetime of products.

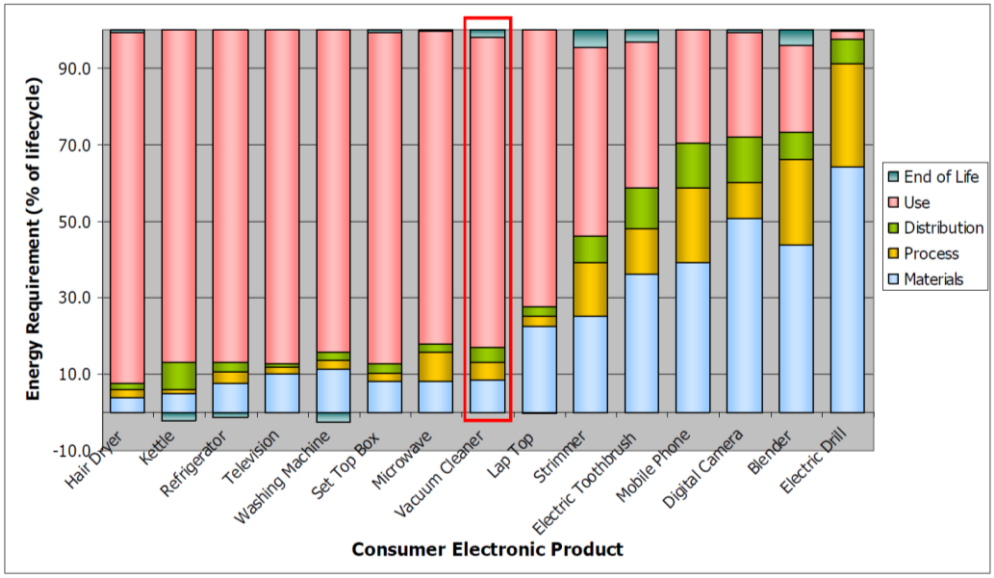

Figure 10: Energy consumption per product (% of the lifecycle)

2.1.8. Material-efficiency EcoDesign report and module to the Methodology for the EcoDesign of Energy-related Products (MEErP)

A study by BioIS (BIO Intelligence Service 2013a) analysed the MEErP methodology with the purpose of analysing and integrating Material Efficiency aspects, including the product's lifetime. The study observed that the Ecoreport tool already uses this parameter to calculate the life-cycle impact of a product. In any case, some general recommendations are proposed to enhance its use.

The study provides guidance on:

- the definition of 'performance and durability parameters' ([38]), in order to correctly define the lifetime of products;
- the definition of lifetime, in order to clearly distinguish between the technical lifetime, the service lifetime ([39]), the years of use plus storage period at the consumer (lifetime to disposal);
- the calculation of the impact per year of use, which allows assessment of the benefits of the lifetime extension of products.

Moreover, the study highlights the essential need to grant a sufficient level of performance of the product throughout its lifetime in order to satisfy the expectations of the consumers, and in this perspective some performance parameters have been analysed.

([38]) These parameters refer to the performance and the functionality of a specific product after a certain amount of lifetime. For instance, performance parameters refer to the start-up time, the cleaning/sucking ability, or to environmental aspects such as energy efficiency, noise emissions and so on.

([39]) The technical lifetime is the time that a product is designed to last to fulfil its primary function; the actual time in service is the time the product is used by the consumer (after which a product it is discarded due to replacement, poor functionality, change of needs or to other reasons related, or not, to the product).

Together with the 'performance and durability parameters', also 'lifetime', 'warranty' as well as 'availability of spare parts' and 'easiness of reparation and upgrade' have been included in those parameters useful for assessing the durability of components/products. Note that the last two are not considered as 'quantifiable parameters' and, contrary to the others, they are also considered as not related to product design. Moreover, 'performance and durability parameters', 'lifetime', and 'warranty' shouldn't be related only to the component design, but to the entire product design stage.

The RACER analysis ([40]) (Relevance, Acceptance, Credibility, Easiness and Robustness) performed in this study shows that 'lifetime and warranty' are included among the parameters with high relevance for Ecodesign, while the 'performance and durability parameters' is among those with medium relevance. It is also interesting to note that the weight of a product is not evaluated as 'potentially useful for implementation in the Methodology for Ecodesign of Energy-related Products' (BIO Intelligence Service 2013d; BIO Intelligence Service 2013a).

Finally, consistent with the Ecodesign Directive (2009/125/EC), in this study some 'information parameters' contributing to material efficiency are defined in order to set the ecodesign requirements. Among them, 'information on product lifetime or appropriate use/maintenance to optimise life expectancy' is highlighted as having both direct and indirect impacts on the environmental impacts of the products, particularly during the use phase. Even if the study points out the difficulty in quantitatively estimating the contribution of the information parameters for improving material savings, it should be noted that highly credible and unambiguous (even if only basic) information can contribute to the appropriate use/maintenance of products and their durability.

2.1.9. The Durability of Products

A study performed by the global sustainability consultancy Ricardo-AEA (Boulos et al. 2014) ([41]) deals with durability of products.

The definition proposed by (Boulos et al. 2014) is the following:

'*Durability is the ability of a product to perform its function at the anticipated performance level over a given period (number of cycles — uses — hours in use), under the expected conditions of use and under foreseeable actions. Performing the recommended regular servicing, maintenance, and replacement activities as specified by the manufacturer will help to ensure that a product achieves its intended lifetime.*'

Many factors should be considered in order to better assess the benefits related to the extension of a product's lifetime, for instance: production costs of materials; components and manufacturing processes; innovation rates; the role of key components in some products (such as the motor in VCs); potential impacts in the product's second life; the availability of appropriate standards for testing longer-lasting products. Moreover, it is worth noting that the replacement of a specific product could be caused by the failure of the product (or one of its components), or by the technology development (high rate of innovation) or by fashion (obsolescence designed by an economic driver).

The study selected two case-study products to be analysed: refrigerators and ovens. These have been selected based on criteria dealing with the existence of an improvement potential in extending the lifetime

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([40]) The RACER criteria have been set by the European Commission in the Impact Assessment Guidelines (SEC(2005)791) for evaluating the sustainability of indicators (EC 2005).

([41]) http://www.ricardo-aea.com/cms/

of products, but also with consumer perception. It is worth noting that the 'durable alternative' in both cases takes into account the potential changes concerning design or technology of the components; the tests proposed in this study are substantially based on existing test methodologies, even if more test conditions are suggested. Furthermore, the study focuses on potential improvements related to key components for product durability.

The study also highlights the relevance of the design of products, as this can influence such material efficiency aspects as maintenance, reparability and remanufacturing. Moreover, it considers the two concepts of 'product lifetime' and 'product durability' as inextricably linked (and often also interchangeable).

Moreover, some procedures to evaluate durability of products are identified based on:

- the comparison of the target life ([42]);
- the Failure Mode Verification Testing — FMVT: used for comparing two or more products under different stress conditions;
- the comparison to degradation (for products in which degradation over time is measurable) ([43]);
- the comparison to design iterations (FMVT for comparing different design options);
- the key component testing.

Finally, EU Ecolabel and GPP instruments are identified as opportunities in the framework of product durability. They can strengthen the role of durability, design for repair and remanufacturing into product requirements.

2.1.10. Bagless VC

Starting from the early 1990s, a new type of vacuum cleaners appeared in the European market: the cyclonic filtration bagless cleaners. This innovating option predominated the UK market, while the bagged options still dominated many other EU countries. According to Kemna et al. (2005) in 2001 the market share of bagless system was 14 %, while it rose to 28 % in 2004.

The Preparatory study points out that bagless vacuum cleaners have higher input power ranges than bagged VCs, but despite these higher values, the market trends highlight a development of bagless VCs due to their lower selling prices (AEA Energy & Environment 2009). This is confirmed also by consumer websites ([44]).

In some other studies, the bagless option is not always considered. For instance, Ernzer and Birkhofer (2003) and Abele et al. (2005) perform a Life Cycle Assessment of 'a standard vacuum cleaner using filter bags', and they both consider a consumption of 6 dust bags per year. Moreover, the considerations about the dust bags refer also to the potential loss of suction: the results of these studies prove that the higher losses of suction correspond to the conventional VC with filter bags, while they are lower than 15 % for other developed filter systems (i.e. cyclone with specific filter systems).

([42]) This represents the most common durability test: the device/product is exposed to specific conditions in order to establish whether or not the product achieves the requirements.

([43]) Through a portion of a life test, the time of failure of the product is estimated; thus it is possible to determine the rate of degradation of key parameters of the specific product.

([44]) For instance http://www.vacuumcleanersdigest.com/bagless.html (accessed April, 2015).

An exception is represented by Kobayashi et al. (2005). This case study examines two different VCs manufactured respectively in 1990 and 2003, and one of the main differences concerns the dust collection option (the new one is a cyclone type, and hence it doesn't need a paper dust bag) (for details see section 2.1.2).

2.2. Final Remarks

Nowadays, few studies are available on the environmental assessment of VCs, and these do not provide a detailed assessment of durability aspects. Moreover, the majority of these studies are not transparent enough in the discussion of the assumptions and input data used. The Preparatory Study on Ecodesign of VCs (AEA Energy & Environment 2009) resulted in the study which discussed more in detail apsects related to the extension of the lifetime of VCs. However, this study is not fully transparent in the discussion of the assumptions adopted to perform the analysis.

In general, vacuum cleaners can be considered as a product with a balanced relation between its product value and its environmental impact, thus an eco-efficient ([45]) product category. Considering its potential technological development, the same studies highlight that the environmental impact reduction is lower than the improvement of the VCs' product value (Barba-Gutiérrez et al. 2008; Kobayashi et al. 2005). The available LCA point out that VCs are 'use-phase dominant' products (Abele et al. 2005; Hur et al. 2005; Kobayashi et al. 2005; Kemna et al. 2005; van Nes & Cramer 2006; Kota & Chakrabarti 2007; AEA Energy & Environment 2009; Gandy et al. 2012;), stressing the relevance of the energy consumption during operation. It is also noted that manufacturing is always relevant, especially due to the impacts of motors and PCBs (Abele et al. 2005; Barba-Gutiérrez et al. 2008; Hur et al. 2005; Kobayashi et al. 2005; Kota & Chakrabarti 2007; WRAP 2010; Gandy et al. 2012; van Nes & Cramer 2006).

Taking into account the potential improvements on these products related to the technological development, several options have been explored in order to evaluate the potential benefits related to the extension of VC lifetime and to the employment of less (for instance bagless VC) or new materials (AEA Energy & Environment 2009; Kobayashi et al. 2005). Moreover, some studies assume that the economic value (i.e. the price) will increase in the next decades, and that there is the possibility that this could be related to higher environmental impacts, occurring especially in the manufacturing phase. More focus should be addressed to the reduction of the environmental impacts in order to encourage the use of more environmentally friendly products, even when more expensive (Barba-Gutiérrez et al. 2008; Hur et al. 2005; Kobayashi et al. 2005).

According to the analysis of the literature, the improvement of product durability is one of the possible strategies that allow the strengthening of the relation between more environmentally and economically convenient products. Doubtless, the durability of vacuum cleaners (and of EEEs in general) is strictly influenced by several factors, such as consumer behaviour, costs, repairability and reusability and existence of testing methods for assessing the longer-lasting products' performance (Boulos et al. 2014; BIO Intelligence Service 2013d; BIO Intelligence Service 2013b; BIO Intelligence Service 2013c; Abele et al. 2005). Hence, both the industry and the consumers have a key role for many of these aspects. For instance the replacement of a product is not always due to its breakdown or lower performance but due to a user choice; the lifetime of a product depends on the use condition during the operation (e.g. proper

([45]) Eco-efficiency is defined as 'product value per unit of environmental impact' (Kobayashi et al. 2005).

maintenance according to manufacturer's instructions); the repairing of the product is related to the ease of disassemblability and availability of spare parts. On such purpose, the SCOPE project on durability of household appliances, based on interviews undertaken in the United Kingdom, observed that over two-thirds of users considered the EEE repairing cost discouraging (Cooper 2005).

The relevance of lifetime for most purchased products strengthens the need of highly credible and unambiguous information and communication to consumers, in order to increase the acceptability and penetration rates of durable products on the market (BIO Intelligence Service 2013b; BIO Intelligence Service 2013c; BIO Intelligence Service 2013a; Cooper 2005; van Nes & Cramer 2006).

CHAPTER 3
Presentation of the case-study product

The method for the assessment of durability (Ardente et al. 2012) has been reviewed and applied to a specific ErP — i.e. to a vacuum cleaner. The aim is the identification of the potential environmental benefits associated to the lifetime extension of an average vacuum cleaner (VC) placed in the market, taking into account the current energy label and Ecodesign regulations (chapter 1.1).

The analysis of durability is based on the setting of two scenarios. The first is the base-case *scenario*, in which a standard product (product (A)) is supposed to reach its forecasted end of operating life and, at this moment, to be substituted by a new product (product (B)) with the same functionalities. Indeed, the second scenario is the *Durable scenario*, wherein the product (A) is supposed to have an extended lifetime, so that the substitution with a new product will occur later compared to the base-case scenario.

The main assumptions for assessment of durability of the vacuum cleaner are depicted in chapter 3. A canister vacuum cleaner has been dismantled and all its components have been categorised by weight and materials. Thus, considerations about the manufacturing phase (section 3.2) are exposed, with particular attention to the hose and the operational motor (sections 3.2.1 and 3.2.2), while all the other components are included in the same group (section 3.2.3). Also the packaging enters into the manufacturing phase considerations (section 3.2.4).

The use phase (section 3.3) focuses on the lifetime considerations about vacuum cleaners (section 3.3.1), but also on the energy efficiency of this products group (section 3.3.2) and on the materials and operation necessaries for the VCs' maintenance and correct functioning (sections 3.3.3 and 3.3.4).

Finally, section 3.4 deals with the end-of-life considerations about vacuum cleaners, and section 3.5 exposes the main assumptions concerning the transports during the whole VC life-cycle (for raw materials procurement, delivery and EoL).

3.1. Characteristics of the case-study product

Based on available market information, 85 % of vacuum cleaners sold in 2005 were canister models, while 15 % were upright (AEA Energy & Environment 2009). Canisters are preferred because they are handier and in general more reliable than the uprights (AEA Energy & Environment 2009).

Consistent with this information and the literature review (chapter 2) we selected as case-study a canister vacuum cleaner. It has been dismantled in order to classify its components (by mass and materials). The main characteristics of the canister vacuum cleaner are illustrated in Table 13.

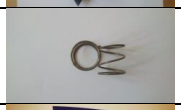
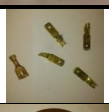
Figure 11: Case-study canister vacuum cleaner

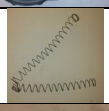
The main phases considered for both the LCA and the Durability assessment are:

- manufacturing, including transport for raw materials and the final delivery of the product (section 3.2);
- use phase, including the consumption of electricity during the operation, the use of auxiliary components (periodical changes of dust-bags) and maintenance (periodical filter replacements) (section 3.3);
- end-of-life (EoL), including transport and impact of waste treatment in a WEEE recycling plant. Potential credits related to recycling and recovery of materials have not been considered in the analysis in order to avoid calculating environmental benefits of both recyclability and durability (Ardente et al. 2014) (section 3.3.4).

The sections that follow illustrate the main considerations and assumptions of the study. A LCA of the case-study product has been performed through GaBi 6 software; this represents the starting point of the following assessment of durability.

Table 13: Components of the dismantled canister vacuum cleaner

N	Component	Description	Sub-category	LCA model category	N	Component	Description	Sub-category	LCA model category
1		Hose terminal	Hose	Hose	26		Pedal	Canister case	"Other components"
2		Hose handle	Hose	Hose	27		Pedal spring	Canister case	"Other components"
3		Tube extension	Hose	Hose	28		release lid	Canister case	"Other components"
4		Tube extension	Hose	Hose	29		Grip-handle	Canister case	"Other components"
5		Seal	Hose	Hose	30		Canister case, lower part	Canister case	"Other components"
6		Hose	Hose	Hose	31		Hose Air Regulator	Canister case	"Other components"
7		Connector	Motor	Motor	32		Canister case, upper part	Canister case	"Other components"
8		Fan housing	Motor	Motor	33		Padding indicator	Canister case	"Other components"
9		Seal	Motor	Motor	34		Filter	Filter	"Other components"
10		Stator assy	Motor	Motor	35		Filter	Filter	"Other components"
11		Fan	Motor	Motor	36		Filter	Filter	"Other components"
12		Carbon brushes	Motor	Motor	37		Nozzle	Nozzle	"Other components"
13		Rotor	Motor	Motor	38		Plastic components	Nozzle	"Other components"
14		Connectors	Motor	Motor	39		Wheels	Nozzle	"Other components"
15		Seal	Motor	Motor	40		Wheels axle	Nozzle	"Other components"
16		Washer	Motor	Motor	41		Nuts and springs	Nozzle	"Other components"
17		Motor cover	Motor	Motor	42		PCB	PCB	"Other components"

18		Guard motor	Motor	Motor	43		PCB	PCB	"Other components"
19		Springs	Motor	Motor	44		Power cord	Power cord reel	"Other components"
20		Nuts			45		Body	Power cord reel	"Other components"
21		Seal	Motor	Motor	46		Spring and Keeper	Power cord reel	"Other components"
22		Cable parts	Cables	"Other components"	47		Contact	Power cord reel	"Other components"
23		Cable parts	Cables	"Other components"	48		Seal	Power cord reel	"Other components"
24		Power button	Canister case	"Other components"	49		Canister wheels	Wheels	"Other components"
25		Canister case, middle part	Canister case	"Other components"	50		Canister wheel	Wheels	"Other components"

3.2. Manufacturing a canister vacuum cleaner

In order to perform the environmental analysis, the main components of the vacuum cleaner have been taken into account, with particular attention to the hose and the operational motor.

The case-study product (with a mass of 5.721 kg) was dismantled so that each part could be measured and the corresponding material identified. Figure 12 shows the exploded diagram of some vacuum cleaner parts, as derived from online manuals ([46]).

Figure 13 shows the mass contribution of the vacuum cleaner's components. As depicted in the previous chapters, the critical parts for durability requirements for vacuum cleaners are the hose and the operational motor. Therefore these parts have been investigated in detail.

Note that detailed data about the energy consumption for the manufacturing of vacuum cleaners are missing in literature, as well as in the Preparatory study. Based on some studies on the manufacturing of various electrical and electronic equipment (vacuum cleaners, clothes washers, refrigerators, dishwashers), 10 [kWh] of electricity were assumed for the assembly of the VC (Horie 2004; Olivetti et al. 2012; Wong 2009; WRAP 2010; Boustani et al. 2010).

([46]) http://www.manualowl.com/m/Hoover/S3332/Manual/380541 (accessed March 2015), http://www.manualowl.com/m/Hoover/S3332/Manual/182503?page=1 (accessed March 2015)

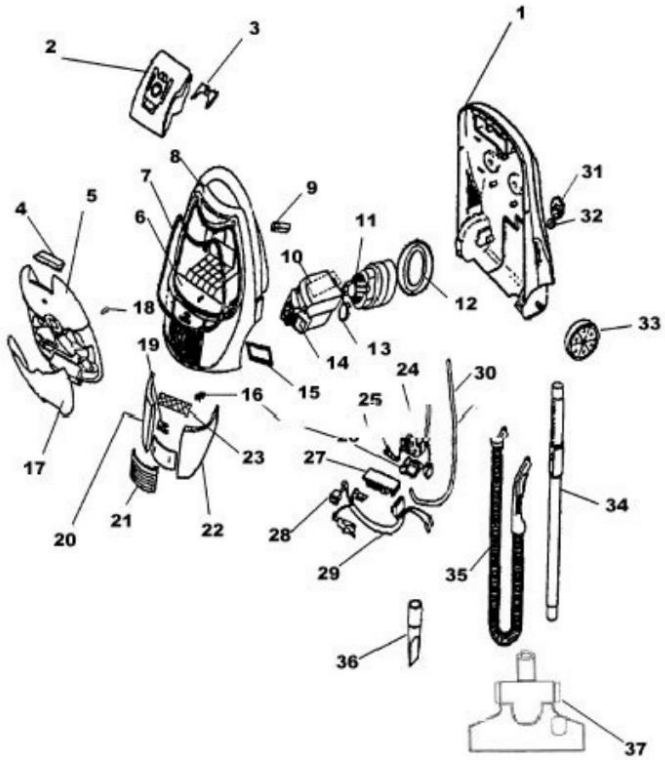


Figure 12: Exploded drawing and spare parts listing for the canister vacuum cleaner

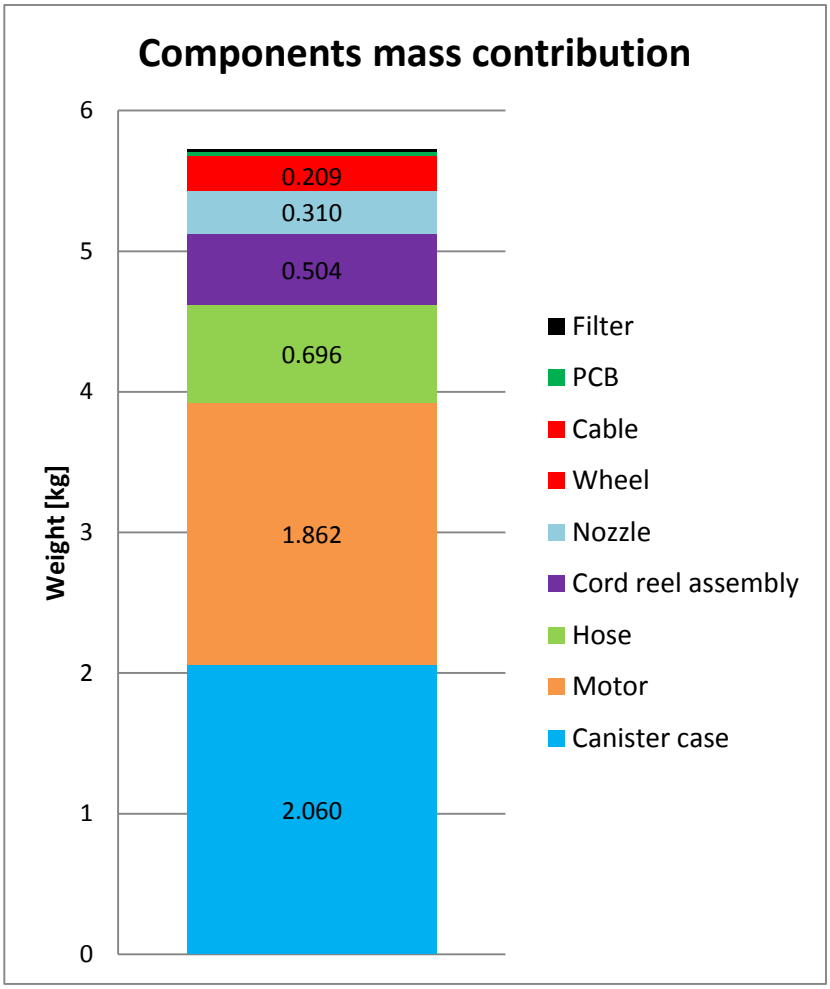


Figure 13: Mass contribution of the canister vacuum cleaner's components

3.2.1. Hose

The hose of the canister vacuum cleaner is mainly composed of plastics. More specifically, the rigid part is made of acrylonitrile-butadiene-styrene (ABS — more than 66 % of the total hose mass), while the flexible part is made of high-density polyethylene (HDPE — about 30 % in mass) (Figure 14).

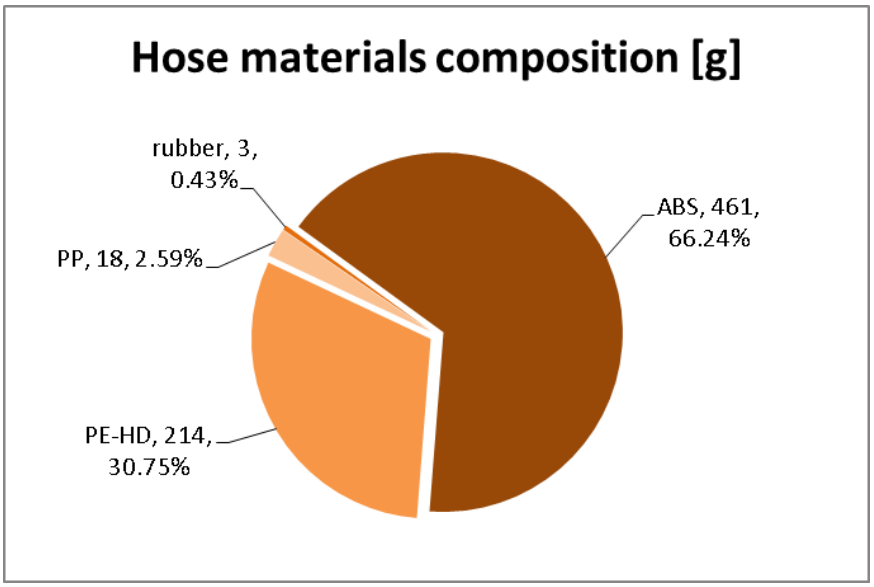


Figure 14: Mass contribution of the hose's materials

3.2.2. Motor

The vacuum cleaner motor is one of the most important components. It represents more than 30 % of the total mass (1 862 g) and mainly contains steel and various plastics (Figure 15).

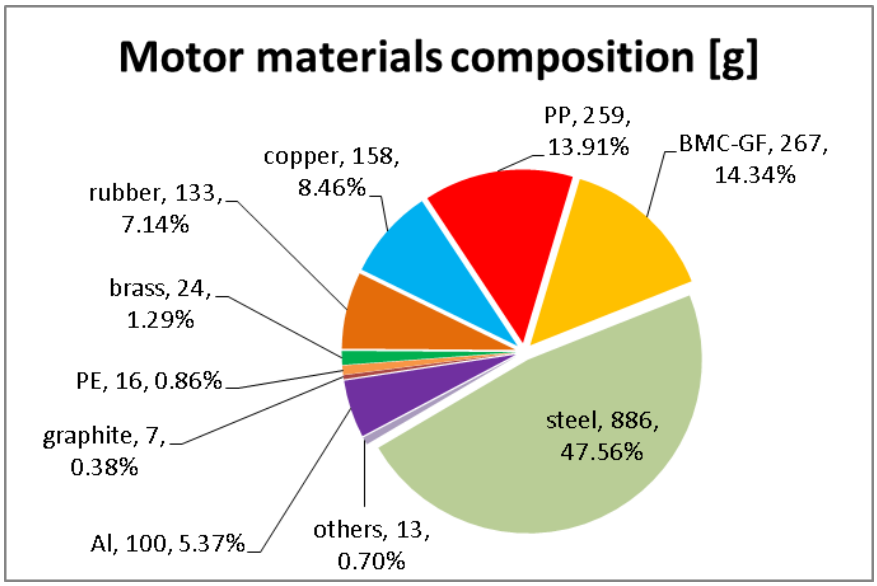


Figure 15: Mass contribution of the motor's materials

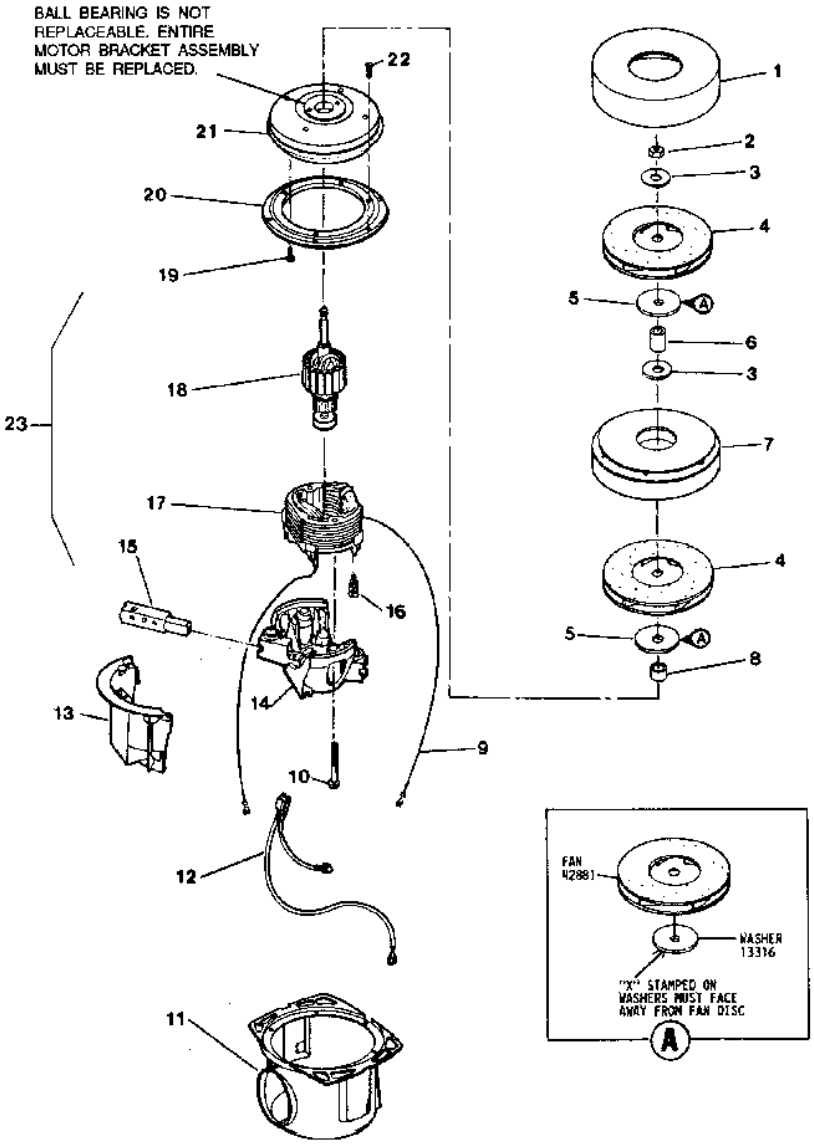


Figure 16: Example of motor assembly — exploded diagram

A motor settled into a vacuum cleaner consists of different components, all placed into a motor case (Figure 16).

Almost all the steel contained in the motor is associated to the rotor and the stator. The same holds true for copper, with which the stator and rotor windings are composed. Plastic parts in the motor case and the fan were made of polyester fiberglass resins (BMC-GF) ([47]).

Note that motor manufacturing requires energy in order to be assembled. Few data are available in the literature concerning the motor assembly, particularly in relation to appliance motors. Based on studies about the environmental impacts of appliances, the energy consumption for the motor assembly is negligible in respect to the overall impact of the life-cycle.

([47]) Bulk moulding compound or bulk moulding compounds (BMC) glass fibre is a ready-to-mould material usually used in injection moulding and compression moulding.

3.2.3. 'Other components'

All the other components of the vacuum cleaner were individually modelled, but according to chapter 0, they were grouped in prospect of the Impact Assessment. Other components of the VC are:

- canister case;
- cord reel assembly;
- nozzle;
- filters;
- wheels;
- cables;
- printed circuit board (PCB).

These components are separately analysed, but according to chapter 0, they were all grouped together in the Life Cycle Impact Assessment.

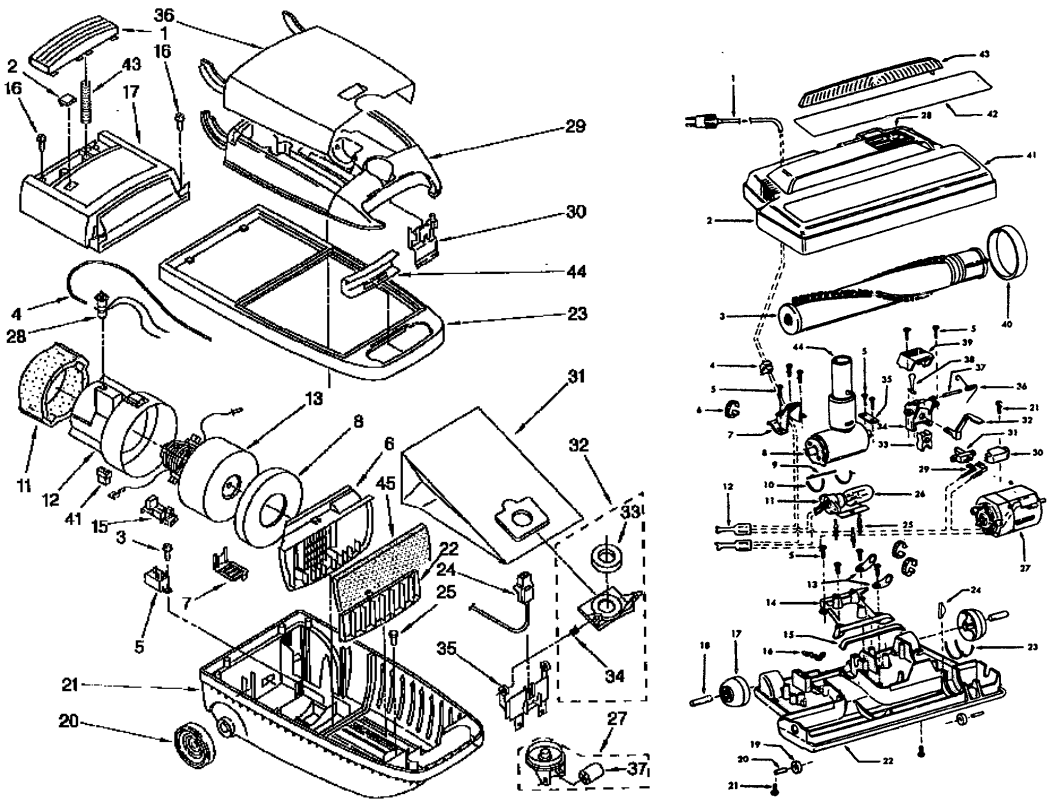


Figure 17: Example of an exploded drawing and spare parts listing for the canister and the nozzle plate ([48])

All these parts are made up of different materials, with ABS being the most-used material (in mass). Due to its mechanical properties (mainly impact resistance and toughness), ABS is used for the canister, the cord reel and the nozzle plate. Other materials used are polypropylene (PP) (in the nozzle plate and wheels), polyvinylchloride (PVC) (in the cables as insulation material and copper, in the cables).

([48]) http://www.searspartsdirect.com/Kenmore-Vacuum-Parts/Model-1162561290/0582/0642000/10042604/00001.html (accessed March 2015) http://www.searspartsdirect.com/Hoover-Vacuum-Parts/Model-S3281/0517/0642000/P0011218/00002.html (accessed March 2015)

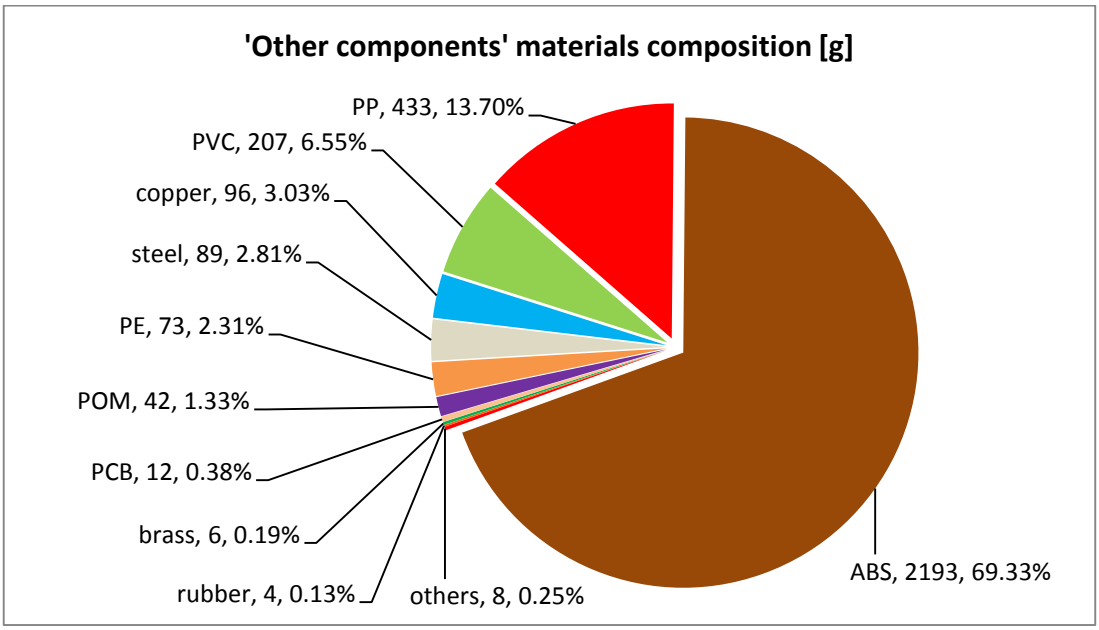


Figure 18: Mass contribution of the 'other components' materials

Figure 19: Overview of the canister and some of its components

The canister case represents the main part of the vacuum cleaner, wherein all the components (except for the hose and the nozzle) are contained. It is mainly constituted by ABS (about 2 kg, corresponding to

97 % of the mass of the canister case and about 35 % of the vacuum cleaner). Polyoxymethylene (POM), rubber and steel constitute the remaining 3 % of the canister case. The forepart of the canister is allocated for the dust-bag, where is also placed the hose module connecting the canister with the hose. The cord assembly is set next to the motor and the fan cases in the rear part of the canister case. On the opposite side of the cord reel, a simple PCB is placed (

Figure 19).

In canisters, there are three different kinds of filters ([49]): pre-motor filter, air clean filter and dust-bag. The pre-motor filter aims at protecting the vacuum cleaner motor from collecting dirt and dust particles; the air clean filter is a three-layer exhaust filter, made of electrostatically charged fibres, whose objective is to capture 99.95 % of microscopic particles bigger than 0.5 microns and 94 % of particles bigger than 0.3 microns ([50]). The dust bags collect dirt and dust until their fulfilment and, depending on their efficiency; there are many types available on the market. These kinds of filters are usually composed of various materials, such as borosilicate glass fibres or plastic fibres (e.g. PP and PE), bound together with binders. The efficiency of the barrier filter could be measured consistently with the European Standards (EN 1822). One of the more effective filter medias used for vacuum cleaners is the HEPA filter (High Efficiency Particulate Airflow); there are different grades of HEPA (H13-H14), and ULPA filters are even more well-performing (U15-U17). The Preparatory study affirmed that the most used is HEPA12 (overall efficiency: 99.5 %).

Figure 20: Overview of filters within the canister

The power cord assembly consists of the attachment cord and the cord reel. The latter is substantially composed by a mix of plastics (ABS and PE) and steel, while the former is a cable (composed of copper and PVC) (Baitz et al. 2004) (Figure 21).

([49]) http://www.sylvane.com/miele-s2121-olympus-vacuum.html (accessed March 2015), http://chinarayi.en.alibaba.com/product/1557977374-219940969/Hoover_Vacuum_Cleaner_HEPA_Pre_Motor_Filter.html (accessed March 2015), http://web.extension.illinois.edu/healthyair/vacuums.cfm (accessed March 2015), http://www.sopgreenklean.com/how-a-vacuum-bag-works (accessed March 2015)

([50]) http://web.extension.illinois.edu/healthyair/vacuums.cfm (accessed March 2015), http://www.sopgreenklean.com/how-a-vacuum-bag-works (accessed March 2015)

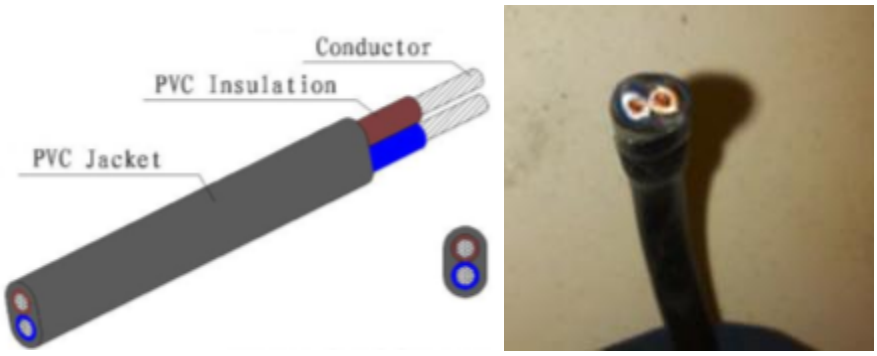


Figure 21: Overview of the cord assembly (schematic representation ([51]) and the case-study cable)

A very simple PCB is installed on the opposite side of the cord reel. However, as with other EEE, it is expected that more recent and advanced VCs will require more complex electronic circuits. The potential use of more complex PCB has been investigated during the LCIA and the durability assessment (section 4.4.1 and Figure 27).

Finally, the nozzle plate is made of different plastics (ABS, PP and PE), but it embodies also a small percentage of steel used for the wheels shaft.

3.2.4. Packaging

The preparatory study on VC assumed that cardboard packaging accounts for about 10-20 % of the mass product, and it sets the average volume of a packaged product as 0.08 m^3 (AEA Energy & Environment 2009). These figures are also in line with other products on the market (Table 14).

According to the Preparatory study, packaging includes cardboard, instruction manuals (paper) and polybag (plastic bags for holding manuals and parts of the vacuum cleaner). The presence of these materials for the vacuum cleaner packaging is confirmed by (WRAP 2013b): usually, the canister vacuum cleaner is packed into a corrugated carton board, and PE-LD clear sleeves are generally used for packaging the main body and the product components. Moreover, paper manuals are usually included in the packaging, with a full gloss cover and a guarantee slip.

([51]) http://dashing.en.ecplaza.net/h05vvh2-f-wire—219614-1440078.html (accessed March 2015)

Table 14: Examples of packaging options

Product		Size [cm]	Volume [m³]	Packaging	
				[kg]	[%] on the packaged product
1		50 X 31 X 30	0.048	1.26	20 %
2		46 X 28.5 X 29.5	0.040	1.30	21 %
3		46 X 29.5 X 27.5	0.037	1.70	28 %
4		40 X 31 X 30	0.037	0.70	13 %

1 — http://www.philips.com.sg/c-p/FC9172_67/performer-vacuum-cleaner-with-bag-with-triactive-nozzle/specifications (accessed March 2015)
2 — http://benheng.en.alibaba.com/product/1150692626-218724616/Very_Cheap_Price_Bag_Canister_Vacuum_Cleaner_Daewoo_Cylinder_Bagged_Suction_Vacuum_Cleaner.html (accessed March 2015)
3 — http://www.globalsources.com/si/AS/Suzhou-KVC/6008828688906/pdtl/Canister-Vacuum-Cleaner/1049456623.htm (accessed March 2015)
4 — http://tianer.en.alibaba.com/product/1096311200-200037747/Bagged_Canister_Vacuum_Cleaner_with_Dust_Bag_with_Big_Dust_Capacity_TE_806E.html (accessed March 2015)

3.3. Use phase

Based on literature review, the use phase represents the most important phase in terms of environmental loads for the ErP (Boustani et al. 2010; Gandy et al. 2012; Kota & Chakrabarti 2007; Hur et al. 2005; Abele et al. 2005; Kobayashi et al. 2005).

In order to analyse the impact of the consumption of energy and auxiliary materials, the lifetime of an average canister vacuum cleaner has to be evaluated (chapter 3.3.1), as well as maintenance and repairs required during its lifetime (chapter 3.3.3).

3.3.1. Lifetime

As mentioned previously, the lifetime depends on several aspects, not all related to the functioning of the vacuum cleaner. In fact subjective issues could occur in the decision of the final user to replace a vacuum cleaner (chapter 3/3.10). In this perspective, the repair operations should also be taken into account. Clearly, depending on the damage and on the breakdowns that could occur to the considered ErP (repair of one or more essential components or minor repair actions), the repair may or may not be convenient; this convenience should be evaluated on an economical point of view, but also on the length of time necessary for the repair operations (i.e. when the product is unable to accomplish its functions).

Generally speaking, studies on WEEE trends implemented by Huisman et al. (2012) and Monier et al. (2013) prove that the residential time of EEE is shortened in the decade 2000-2010 (-12 % for Small Household Appliances), where 'residential time' means the age of products including the time of non-functioning or unused appliances in stock (Murakami et al. 2010; Oguchi et al. 2010).

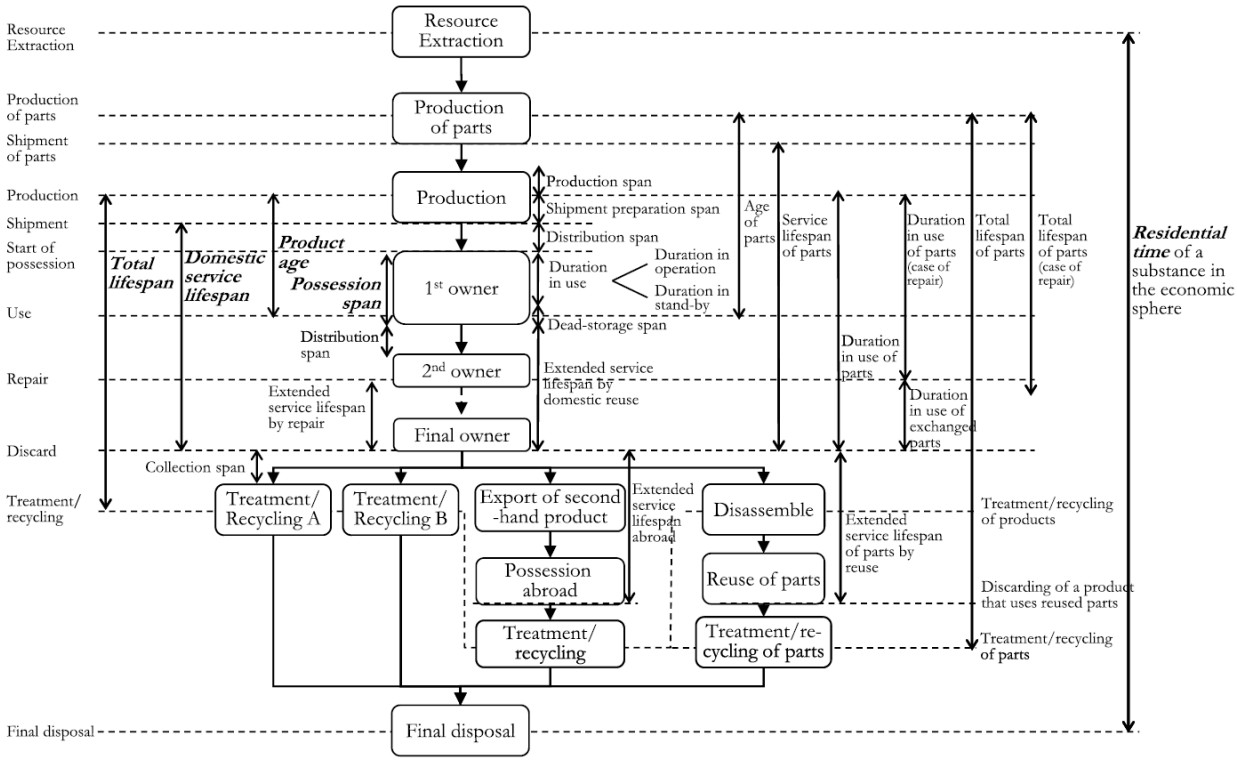


Figure 22: Definitions of various 'life' terminologies for consumer durables and other machinery (Murakami et al. 2010)

Considerations about vacuum cleaner lifetimes collected from the literature review are illustrated and summarised in Table 15. These are based on the average lifetime and the residential time of products, but also on their wear-out life, meaning the length of time after which the product can't meet its original functions.

Different sources confirm that the life expectancy of a canister vacuum cleaner is between 5 and 9 years, but some others point out longer periods. The Canadian Electrical Stewardship Association (CESA) indicates a range of lifetime between 6 and 9 years (Canadian Electrical Stewardship Association 2011), as well as DEFRA (2011) (5-7 years), Kobayashi et al. (2005) (7 years) and Rose (2000) (wear-out life of 8 years, whereas the vacuum cleaner technology cycle is 7 years); nevertheless in some consumer websites the life expectancy rises to 12 years.

The average lifetime considered in the Preparatory study for vacuum cleaners is 8 years, ranging from 6.3 to 10 years. The Preparatory study also considers the potential extension of the product lifetime up to 12 years. Both the energy label and the Ecodesign implementing measures for VCs assume 50 one-hour cleaning tasks per year. Assuming 500 hours of lifetime of the motor, this corresponds to a 10-year lifetime of the product.

In some cases, the lifetime is expressed in operating hours, as for the European Association for the Co-ordination of Consumer Representation in Standardisation (ANEC) and the European Consumers' Organisation (BEUC). They affirmed that comparative tests performed by International Consumer

Research & Testing (ICRT) members for vacuum cleaners prove a life expectancy higher than 550 hours (Maurer 2010).

Some manufacturers tested their vacuum cleaners to last **1 000 operating hours** or an average of 20 years of residential use, and prove that the motor achieved between 800 and 950 hours and, if used consistently to the manual instruction, it can last up 1 200 hours ([52]).

Finally, an interesting indicator can be the warranty offered by manufacturers and the availability of spare parts: the manufacturer's warranty constitutes an element on which consumers assess a product lifetime, as they infer that it's connected to the reliability of products evaluated by the manufacturer itself (Boulos et al. 2014). Note that warranty is considered one of the parameters for evaluating the repairability and the durability of the product by the MEErP (Bundgaard et al. 2014; BIO Intelligence Service 2013d). Depending on the manufacturer and on the vacuum cleaner components, the years of warranty can assume different values, for instance 7-10 years on the motor and body casing ([53]), 5 years ([54]) or 2 years ([55]) for the vacuum cleaner and its components.

([52]) http://www.which.co.uk/news/2009/10/miele-ads-banned-for-vacuum-cleaner-claims-186889/ (accessed march 2015)
([53]) http://www.achooallergy.com/miele.asp (accessed march 2015)
([54]) http://www.dyson.com/vacuums/browsetherange.aspx (accessed march 2015)
([55]) http://www.electrolux.com.au/Global-pages/Page-Footer-Menu/Top/Changes-to-Consumer-Law/ (accessed march 2015)

Table 15: Considerations about vacuum cleaners lifetime in literature

Product	Lifetime	Note	Source	Year
Vacuum cleaner	5-7 years	'5-7 years lifespan. Clean the filters after every few uses to make sure nothing is blocking the nozzle, hose or entry to the bag.'	http://classiccleaners.net/2013/09/03/whats-the-life-expectancy-of-these-5-appliances-part-1/ (accessed March 2015)	2013
Vacuum cleaner	8 years		'Okala Practitioner: Integrating Ecological Design'	2013
Vacuum cleaner	5-7 years	'After every few uses, clean the filters to make sure nothing is blocking the nozzle, hose or entry to the bag or the dirt container.'	(Johnston 2013)	2013
Vacuum (canister, stick, upright, handheld)	6-12 years (average = 9 years)	'Some models of vacuum cleaners have been demonstrated to have life spans in excess of 12 years.'	Canadian Electrical Stewardship Association (CESA)	2011
Vacuum cleaner	5-7 years		Department for Environment, Food and Rural Affairs by brook Lyndhurst	2011
Vacuum cleaner	550 hours	'Most consumers replace a vacuum cleaner due to a decrease in the cleaning performance of the product over time but only rarely because the motor is broken.'	The European Association for the Co-ordination of Consumer Representation in Standardisation (ANEC) & the European Consumers' Organisation (BEUC)	2010
Vacuum cleaner	more than 1,200 hours	'Miele said its vacuum cleaner motors achieved between 800 and 950 hours on the highest setting, which was 300-450 hours above standard test regulations, and when the S7 was used on variable power settings, as recommended in the instruction manual, the motor lasted up to 1 200 hours'	http://www.which.co.uk/news/2009/10/miele-ads-banned-for-vacuum-cleaner-claims-186889/ (accessed March 2015)	2009
Vacuum cleaner	7 years		A Practical Method for Quantifying Eco-efficiency Using Eco-design Support Tools	2005
Vacuum cleaner	up to 10 or 12 years		http://www.vacuumcleanerrepair.org/ (accessed March 2015)	n.a.
Vacuum cleaner	15-20 years		(Lee n.d.)	n.a.
Vacuum cleaner	more than 1 000 operating hours or 20 years		http://www.achooallergy.com/miele-callisto-s5280-vacuum-cleaners.asp (accessed March 2015)	n.a.

3.3.2. Energy efficiency class

Based on European web shops and manufacturers' websites, the majority of vacuum cleaners placed on the market belong to classes A and B. It is expected that future products will progressively move towards higher energy efficiency classes (EU 2013b).

For the current analysis it was decided to study a VC belonging to energy class A (section 1.2) with a yearly energy consumption of 25 [kWh/y] ([56]).

3.3.3. Maintenance and Repairs

The maintenance of vacuum cleaners includes all those aspects aiming at the correct household functioning (in terms of performance) and at guaranteeing the proper lifetime of the product. Typically, vacuum problems are related to the stress of some elements and to the frequency of the appliance usage. In particular, the most common malfunctions are associated to hose, suction issues, belt, agitator brush, canister case or power cable (section 1.3). In any case, a constant check of the vacuum cleaner might limit possible breakdowns ([57]).

When buying a vacuum cleaner, simple maintenance instructions are provided in the user guide included in the box. That manual permits the user to correctly use the appliance maximising its performances and minimising early failures, as well as to diagnose the main problems could be occurred and to do simple repairs on its own. Note in some cases, there are available online user guides containing an exploded view of all the key parts, the parts catalogue, the electrical fault diagnosis and wiring scheme, and a step-by-step guide to disassemblability, with photographs illustrating parts, locations and fasteners (WRAP 2011). Moreover, often it's possible to find a catalogue of all the spare parts on the company website.

Doubtless, when some breakdowns occur but the product replacement is not considered as the first option, the repair of the vacuum cleaner (or one of its components) takes place. The MEEuP Product Cases Report (Kemna et al. 2005) assumed that about 50 % of vacuum cleaners undergo a repair during the product lifetime of 8 years, with an estimated repair cost of EUR 50. On the other hand, the 'Which?' survey (AEA Energy & Environment 2009) assumes a lower percentage of repairs (10-20 %) in the first 6 years of the product life. The same survey reports that canister vacuum cleaners seem to be more reliable than the uprights: just 1 in 10 of canister models require repairs in those 6 years, contra 1 in 5 of upright vacuum cleaners (WRAP 2011). The Consumer Report 2004 ([58]) depicts a repair rate of 13 % for upright vacuum cleaners (excluding belt replacement, which represent one of the most common reasons of breakdowns for upright VCs — AEA Energy & Environment 2009), and of 23 % for canister vacuum cleaners; this means the repair could be a minor or major repair, but it doesn't necessarily mean a total failure of the vacuum cleaner.

Clearly, some components of the vacuum cleaner are easier to repair and/or replace, while others could require a professional intervention (WRAP 2013a). This is the case of motor or some electrical components, that can critically influence the reliability of the internal operating mechanisms and, ultimately, the product durability (Cooper 2005). In effect, universal motors used in the vacuum cleaners (with carbon brushes) are usually not considered as serviceable (meaning not repairable), because if the brushes wear out, it is not convenient to replace them, and it is necessary to replace the whole motor (AEA Energy & Environment 2009).

There are several maintenance guidelines and instruments available online. Usually they give general recommendations to preserve the correct operation of the vacuum cleaner, with particularly focus to the

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([56]) The energy class A is enclosed between 22 and 28 [kWh/year].
([57]) http://www.vacuumcleanerrepair.org/, (AEA Energy & Environment 2009)
([58]) www.cunsomereport.org

motor (for example periodically substitution of pre- and post-motor filters, or precautions to extend vacuum cleaners' lifetimes) ([59]). Moreover, most of these guidelines notice that motor replacement is quite costly, and for that reason they are generally not convenient to replace. It is to be noted that there is available information online explaining how it's possible to manually replace the motor directly by the user (this is possible in those products specifically designed for the purpose ([60])), while in other cases the substitution is not possible without breaking motor or canister components.

The maintenance can be classified as ordinary maintenance (chapter 3.3.3.1) and extraordinary maintenance (chapter 3.3.3.2).

3.3.3.1. Ordinary maintenance

Ordinary maintenance should be carried out according to the effective running time of the system in order to ensure an efficient performance and avoid serious mechanical damage. Concerning vacuum cleaners, this involves primarily the substitution and the cleaning of filters ([61]).

To ensure the correct operation of a vacuum cleaner during its lifetime, filters should be regularly replaced (where applicable), as should dust bags (Kemna et al. 2005). Note that the substitution of full dust bags is not included in 'maintenance', but is part of the normal operation activities (i.e. consumption of auxiliary materials necessary to accomplish the vacuum cleaner functions).

The Preparatory study suggests that the typical replacement frequency for filters is one set of filters per vacuum cleaner per year. Some manufacturers recommend changing the filter every six months or once a year ([62]). Other manufacturers recommend changing filters at least once a year, but in the meanwhile to wash them every 30 days ([63]).

As mentioned above, almost all the spare parts can be found on the market with minor effort. In the case-study realised by WRAP (WRAP 2011) it is confirmed that most of the components are quick and easy to access in order to permit the maintenance of vacuum cleaners. However, access to certain specific components is restricted to professional service engineers, particularly for mechanical or electrical components.

([59]) The main recommendations are related to: cleaning of vacuum cleaner filters, proper usage of the cord (untangled all the time, prevention of kinks), regular checking of the bags and substitution when it is only half full (for suction performances), the monitoring of noise and performance (refer to the instruction manuals). (http://www.cleanipedia.co.uk/en/floor-carpets/vacuum-cleaner-maintenance-how-to-keep-your-hoover-in-good-condition (accessed 2015), http://homeguides.sfgate.com/preserve-life-vacuum-cleaner-motor-49266.html (accessed 2015), http://www.doityourself.com/stry/cleaning-a-vacuum-filter (accessed March 2015), http://www.airfilters.com/blog/vacuum-cleaner-maintenance/ (accessed March 2015), http://www.mrappliance.com.au/Appliance-Spare-Parts/Manufacturers/Dyson-Vacuum-Cleaner-Parts/Dyson-Motors (accessed March 2015).

([60]) https://it.ifixit.com/Guide/Dyson+DC14+Motor+Replacement/11532 (accessed March 2015), http://www.dysonmedic.com/DC07 %20Folder/DC07 %20Motor %20change.html (accessed March 2015), https://it.ifixit.com/Guide/Repairing+Dyson+DC08+Motor+ %28Fran %C3 %A7ais %29/9773 (accessed March 2015)

([61]) (BigGreen Commercial n.d.), http://www.achooallergy.com/vacuum-cleaner-maintenance-guide.asp (accessed 2015), http://www.vacuumcleaneronline.com/vacuum-cleaner-maintenance-quick-tips-to-avoid-unnecessary-service-calls/ (accessed 2015), http://www.svcvacuum.com/bagless_mant.html) (accessed March 2015),

([62]) http://www.achooallergy.com/miele-freshair-s8390-canister-vacuum-cleaner.asp (accessed March 2015), http://www.manualowl.com/m/Miele/S-8390-Kona/Manual/322606 (accessed March 2015), http://www.amazon.com/203-1073-Bissell-Cleaner-Replacement-Pre-Motor/dp/B0054SN33Y (accessed March 2015), http://service.hoover.co.uk/advice-centre/how-to-maintain-your-vacuum-cleaner/ (accessed March 2015), http://evacuumstore.com/c-1726-dyson-vacuum-filters.aspx (accessed March 2015), http://www.miele.co.uk/Resources/OperatingInstructions/S %206210_S %206390.pdf (accessed March 2015)

([63]) http://www.ebay.com/bhp/dyson-vacuum-cleaner-filters (accessed March 2015)

3.3.3.2. Extraordinary maintenance

Extraordinary maintenance includes those operations that are not constantly carried out, and deals with failure of specific components. Replacing some parts, such as the motor, can be expensive. Induction motors, which are mainly used in household appliances, have a short lifetime and a low number of operating hours (De Almeida 2007; De Almeida et al. 2008). Moreover, they require very little maintenance (Brook Crompton 2009). The brushes are the most critical elements of the motor for failure, because of wear ([64]). In order to avoid replacing brushes, longer carbon brushes can be used, expressly designed for the whole life of the product (WRAP 2011). The Preparatory study highlighted that the tendency of brushes to wear down is related to the life of the motor: their substitution is not considered a common practice, so that when the brushes wear down, the motor cannot be repaired and need to be substituted. Mainly for that reason, in the Preparatory study the motor lifetime is considered not lower than 500 hours.

Figure 23: Motor brushes and their abrasion (ABB group n.d.)

3.3.4. Auxiliaries components

During the use phase, some ErPs need auxiliaries' materials for the operation. Among the canister vacuum cleaners, there are two main options: bagged and bagless vacuum cleaners.

The bagless option is becoming quite common in Europe, particularly in the UK market. In this kind of vacuum cleaner, reusable containers are used for storage dirt particles, saving the use of bags.

Bagged vacuum cleaners employ a disposable dirt storage container that is disposed of once it is full, while the bagless vacuum cleaners use a reusable container permitting the saving of dust-bags. Consistent to the AEA Energy & Environment 2009, as bagged machines represent a large part of the market in most EU countries (except for UK), in this study a bagged product is considered. Hence, bagged vacuum cleaners for instance need the periodical replacement of dust-bags. These consumables should be taken into account in the analysis as they are part of the product life-cycle, and they contribute the final impact of vacuum cleaners.

For this study, consistent to what was illustrated in section 2.1.10 and to the analysis performed into the Preparatory study, the bagged option is selected. In any case, the dust bags are considered as a specific item within the analysis in order to check its influence to the life-cycle VC impacts and the life-cycle VC costs.

The Preparatory study considers a dust bag replacement of 10 bags per year, but it could rise to 15 bags per year depending on the operation conditions and user behaviour. On the other hand, both Abele et al.

([64]) https://www.anaheimautomation.com/manuals/forms/brush-dc-motor-guide.php (accessed March 2015), (De Almeida et al. 2008)

(2005) and Kemna et al. (2005) considered a lower number of bags replaced: respectively 6 dust bags per year and 5 dust bags per year.

3.4. End-of-Life

The recycling process of a WEEE has been regulated by the EU Directive (2002/96/EC) (EU 2012). It consists in sequence of different treatments to progressively separate recyclable/recoverable fractions (Johansson & Björklund 2010; Sam et al. 2014; Allenby 2006; Bundgaard et al. 2014; Monier et al. 2013). Note that the WEEE Directive specifies that, starting from 15 August 2015, the minimum rate for SHA recovery must be 75 %, while at least 55 % of SHA shall be prepared for re-use and recycled (2002/96/EC).

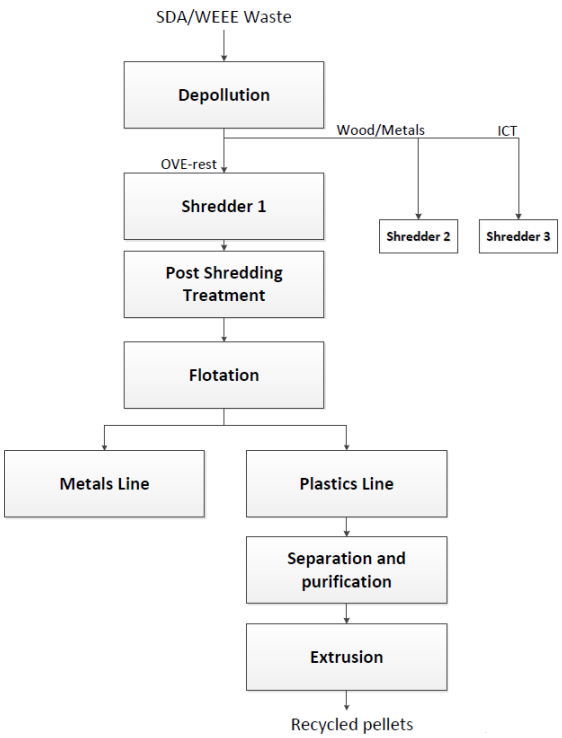


Figure 24: Example of EoL treatments for a vacuum cleaner (Sam et al. 2014)

Vacuum cleaners belong to the subcategory of WEEE within the category of 'Small household appliances' (SHA). In order to estimate the type and composition of WEEE treated into the civic amenity site ([65]), starting from this categorisation of WEEE, a study by the UK Department for Environment, Food and Rural Affairs (DEFRA 2007) highlighted that vacuum cleaners dominate the category 2 of Small Mixed WEEE ([66]) (SMW): they represent more than 60 % of the SMWs. Indeed, the Preparatory study suggests that average waste vacuum cleaners collected per year within the EU-27 is about 100 000 tonnes that, for an average weight of 7.2 [kg] per vacuum cleaner, corresponds to about 14 million tonnes of waste equipment.

([65]) Or a household waste recycling centre, where the household waste can be disposed in order to begin their EoL treatments.

([66]) 'Small mixed WEEE (SMW) refers to a wide range of waste electrical items which includes: small household appliances, IT and communications equipment, powered tools, toys and sports equipment, medical devices, control instruments, smoke detectors and dispensers.' http://www.complydirect.com/news/ea-issue-guidance-for-small-mixed-weee/#.VRE48eHLL0w (accessed March 2015)

The disposal of the VC occurs at the end of the product lifetime. During the operating time, VCs also produce waste due to the use of auxiliaries' components and ordinary maintenance (i.e. dust-bags and filters). Also extraordinary maintenance produces some waste, but this amount can be considered as negligible (EC 2013; AEA Energy & Environment 2009).The study by Kemna et al. (2005) assumes a high percentage of recycling rate of metals (95 %) and energy recovery of plastics (90 %), while the values in the Preparatory study are illustrated in Table 16.

Table 16: EoL assumptions in the Preparatory study

Material	Disposal	Recycling
Bulk Plastics	33.71 %	66.29 %
TecPlastics	33.67 %	66.33 %
Ferro	29.99 %	70.01 %
Non-ferro	29.92 %	69.87 %
Coating	25.00 %	62.50 %
Electronics	48.28 %	48.28 %
Misc.	29.96 %	69.98 %
Total mass	32.24 %	67.78 %

Based on this information, the EoL scenario considered in this study was modelled according to the IEC/TR 62635 (IEC 2012) and on (Huysman et al. n.d.). More specifically, it takes into account the environmental impact of the transport of wastes, as well as the shredding operations. The disposal, recycling and recovery options of the waste flows are not considered for the LCA as well as for the environmental assessment of durability. To be thorough in respect to the LCA model, the waste flows are defined based on the IEC/TR 62635, which provides some detailed figures on the recycling and recovery rates of WEEE components and materials undergoing different separation processes.

3.5. Transport

Transport related to raw materials as well as to product delivery has been also considered in the analysis to calculate life-cycle impacts of the case-study VC. The manufacturing factory is supposed to be settled within the European Union.

For the procurement of raw materials it is supposed that plastic parts are transported for about 100 km, while all the other raw materials, for 200 km. In regards to packaging, transport on a lorry for 100 km has been included. Concerning delivery, it was hypothesised that the vacuum cleaner travels in the EU for an overall distance of 1 000 km. Finally, the transports associated to the EoL are assumed to be about 100 km.

Table 17: Inventory data used for the LCA of canister vacuum cleaner's transports

Transported material	Life-cycle stage description	Distance [km]
Plastics	Raw material procurement	100
Metals	Raw material procurement	200
Packaging materials	Raw material procurement	100
VC	Delivery	1 000
VC	EoL	100

CHAPTER 4
LCA of the case-study product

4.1. Goal and scope

The overall aim of this LCA is to assess the potential environmental impact of an average canister vacuum cleaner. Moreover, the results represent the background data for the environmental assessment of vacuum cleaner durability. In this framework, the impact categories selected for this study are ILCD/PEF recommendation (Table 18). Note that the land use impact category has been excluded (due to limited life-cycle inventory data) and the Resource Depletion impacts have been subdivided into *Abiotic Depletion Potential, mineral resources* ([67]) and *Primary energy from non-renewable resources (net cal. value).*

Table 18: ILCD/PEF recommendation impact categories

Impact categories		Unit of Measure
Abiotic Depletion Potential, mineral resources	ADP-res	[kg Sb-Equiv.]
Acidification, accumulated exceedance	AP	[Mole of $H+_{eq.}$]
Ecotoxicity for aquatic fresh water, USEtox (recommended)	FET	[CTUe]
Freshwater eutrophication, EUTREND model, ReCiPe	EPf	[kg P_{eq}]
Human toxicity cancer effects, USEtox (recommended)	HT-C	[CTUh]
Human toxicity non-canc. effects, USEtox (recommended)	HT-nC	[CTUh]
Ionising radiation, human health effect model, ReCiPe]	IR	[kg $U235_{eq}$]
IPCC global warming, excl biogenic carbon	GWP	[kg $CO2_{Equiv.}$]
Marine eutrophication, EUTREND model, ReCiPe	Epm	[kg $N_{Equiv.}$]
Ozone depletion, WMO model, ReCiPe	ODP	[kg $CFC\text{-}11_{eq}$]
Particulate matter/Respiratory inorganics, RiskPoll	PMF	[kg $PM2,5_{Equiv.}$]
Photochemical ozone formation, LOTOS-EUROS model, ReCiPe	POCP	[kg NMVOC]
Primary energy from non-renewable resources (net cal. value)	PEn	[MJ_{Prim}]
Terrestrial eutrophication, accumulated exceedance	EPt	[Mole of $N_{eq.}$]
Total freshwater consumption, including rainwater, Swiss Ecoscarcity	FC	[UBP]

The functional unit of the study is a packaged canister vacuum cleaner (5.721 kg of mass for the vacuum cleaner and 1.26 kg for the packaging) with an operating lifetime of 10 years (corresponding to 50 hours per years of time spent vacuuming).

The system boundaries include the following phases:

- manufacturing phase (including transports for raw materials and the final delivery of the product);
- use phase, including consumption of electricity during the operation, use of auxiliaries components (periodical change of dust-bags) and maintenance (periodical filter replacements);
- end-of-life (EoL), including transport and impact of waste treatment in a WEEE recycling plant. Impacts related to further processing of recyclable and recoverable materials, and benefits related

([67]) The abiotic depletion potential — resources — is an impact category that account for the extraction rate of a certain resource (in relationship to the estimated world reserves), compared to a reference resource (antimony).

to secondary materials production were not considered in the analysis, because the EoL scenarios are strictly related to the materials and the technology potentiality in separating and treating the waste flow materials. So that, as many information about the manufacturing of the new product in the future, and the technological developments are complicated to model and they potentially increase the uncertainty of the final results, the comparison between the two scenarios excluded the EoL treatments.

The LCA of the case-study product is performed through GaBi 6 software and the database used is PE database for almost all the process units. Though, in some cases, due to lack of information, Ecoinvent v2.2, DKI/ECI ([68]) and PE/FEFCO ([69]) databases are used (ANNEX1).

Data used for the model realisation refer to a dismantled canister vacuum cleaner described in section 3.1: all the components have been weighted and categorised by material (thanks to the brands). Where the information was not available, data are based on literature.

4.2. Life Cycle Inventory

The Life Cycle Inventory (LCI) mainly refers to the case-study product described in section 3.1. This section depicts the specific hypotheses on which the LCA modelling is based on. Moreover, the detailed LCI (including tables and flowcharts) is available in ANNEX 1.

As underlined by Chiu & Chu (2012), the major difficulties about the LCI data collection should be associated to the availability of reliable database of both materials and processes.

Consistent with the goal of the study, except for the hose and the operational motor, all the other components of the vacuum cleaner have been grouped.

4.2.1. Manufacturing

4.2.1.1. Hose

The inventory data used for the hose model are showed in Table 19.

Table 19: Inventory data used for the LCA of canister vacuum cleaner's hose

Material	Unit of Measure	Mass
ABS	[kg]	0.461
PE	[kg]	0.214
PP	[kg]	0.018
Rubber	[kg]	0.003

([68]) German Copper Institute, http://www.kupferinstitut.de/
([69]) European Database for Corrugated Board Life Cycle Studies, (FEFCO 2011)

4.2.1.2. Motor

The total weight of the motor is 1.862 kg: more than 30 % of the vacuum cleaner weight. Note that in the inventory, 13 g were not defined.

For almost all the materials it was possible to find a correspondence in the PE database ([70]), but it's to be noted that for some others there is not a matching process within the database; for that reason, they have been modelled ad hoc. This is the case of the winding assembly: an average composition have been extrapolated based on literature data (De Almeida et al. 2008; De Almeida et al. 2013; Olivetti et al. 2012).

Concerning plastic elements, the material brand of plastics allowed the identification of the plastic typology. For instance, the brand on the motor case and on the fan shows that those plastics are polyester fiberglass resins (BMC-GF). The modelling was made according to Menzolit® BMC 1000, a bulk moulding compound based on unsaturated polyester resin ([71]) (>UP-(MD+GF)70<), made up of 25 % glass fibre (GF), 45 % mineral powder (MD) and 30 % unsaturated polyester (UP) (European Alliance for SMC/BMC 2011). The production process considered is injection moulding.

Note that motor manufacturing requires energy in order to be assembled. Few data were available in the literature concerning the motor assembly, particularly in relation to appliance motors. Based on selected studies about the environmental impacts of appliances, the energy consumption for the motor assembly has been neglected (Olivetti et al. 2012; Wong 2009; Horie 2004).

The inventory data used for the motor model are shown in Table 20.

Table 20: Inventory data used for the LCA of canister vacuum cleaner's motor

Material		Unit of Measure	Mass
Aluminium		[kg]	0.042
Brass		[kg]	0.025
Copper		[kg]	0.124
Copper windings	Copper Steel Aluminium	[kg]	0.0326 0.271 0.0579
BMC-GF		[kg]	0.267
Graphite		[kg]	0.007
Polyethylene granulate (PE)		[kg]	0.016
Polypropylene granulate (PP)		[kg]	0.259
Rubber sealing compound		[kg]	0.133
Steel		[kg]	0.614
Others		[kg]	0.013

([70]) http://www.gabi-software.com/databases/ (accessed March 2015)
([71]) http://plastics.ulprospector.com/datasheet/e92126/menzolit-bmc-1000 (accessed March 2015), http://www.matbase.com/material-categories/natural-and-synthetic-composites/polymer-matrix-composites-pmc/reinforced-polymers/material-properties-of-unsaturated-polyester-resin-15-percent-glass-fiber-reinforced-bulk-mouldin.html#properties (accessed March 2015)

4.2.1.3. 'Other components'

All other components of the vacuum cleaner were individually modelled, but as in chapter 3.2 they were all grouped in prospect of the Impact Assessment.

The inventory data used for the 'other components' model are showed in Table 21.

Table 21: Inventory data used for the LCA of canister vacuum cleaner's 'other components'

Component	Material	Unit of Measure	Mass
Canister case	ABS	[kg]	2
	POM	[kg]	0.042
	Rubber	[kg]	0.002
	Steel	[kg]	0.004
Hose Reel	Brass	[kg]	0.004
	ABS	[kg]	0.142
	PE	[kg]	0.021
	Rubber	[kg]	0.002
	Steel	[kg]	0.052
Attachment cord	PVC	[kg]	0.194
	Copper	[kg]	0.089
Nozzle plate	ABS.PP	[kg]	0.052
	PE-HD	[kg]	0.020
	PP	[kg]	0.219
	Steel	[kg]	0.019
Filter	PE-HD	[kg]	0.017
Wheels	PP	[kg]	0.209
Cables	Brass	[kg]	0.002
	PE	[kg]	0.015
	PVC	[kg]	0.011
	Wires	[kg]	0.005
Cables	Brass	[kg]	0.001
	PVC	[kg]	0.002
	Wires	[kg]	0.002
PCB	PCB	[kg]	0.012
	Steel	[kg]	0.014
Others		[kg]	0.008

4.2.1.1. Packaging

To model the packaging, both the cardboard for the box and the paper for the instruction manual have been considered. Moreover, a small percentage of plastic (PE-LD) has been included. Data are based on a waste material declaration of Philips' canister vacuum cleaner ([72]): 1.26 kg, about 20 % of the packaged product.

([72]) http://download.p4c.philips.com/files/f/fc9192_81/fc9192_81_wad_aen.pdf (accessed March 2015), Table 14

Table 22: Inventory data used for the LCA of canister vacuum cleaner's packaging

Material	Unit of Measure	Mass
PE-LD	[kg]	0.06
Paper	[kg]	0.10
Cardboard	[kg]	1.10

4.2.2. Use phase

The canister vacuum cleaner lifetime is assumed to be 10 years, consistent with the literature review. Moreover, concerning its energy consumption, the VC is supposed to belong to the energy class A in the energy labelling starting from September 2017 (EU 2013b), so that a yearly energy consumption of 25 [kWh/y] is adopted for the LCA.

As the case-study product is a bagged vacuum cleaner, the frequency of dust-bag replacement is assumed equal to 7 bags per year ([73]). Indeed, the estimate for ordinary maintenance for the present LCA is the use of 1 set of filters per year.

Finally, extraordinary maintenance is not considered in this specific LCA.

Table 23: Inventory data used for the LCA of canister vacuum cleaner use phase

Material	Unit of Measure	Mass
Bags	[kg/piece]	0.04
Set of filters	[kg/piece]	0.017
Electricity consumption	[kWh/year]	28

4.2.3. End-of-Life (EoL)

Consistent with the system boundaries of the LCA, the EoL is modelled up to final disposal of waste material flows, but only the environmental impacts associated to the EoL chain until the shredded products are considered. Note that, even if there are examples of vacuum cleaners for which high percentages of recycled material have been used in polymer contents (WRAP 2013b), the secondary material and the recycling content are not considered in the LCA. This means no environmental credits (or benefits) are associated to the EoL.

Therefore, based on Huysman et al., transports, energy and chemical elements necessary for the treatment processes have been included into the EoL scenario (Table 24). It's to be noticed that Huysman et al. includes also the styrene butadiene styrene (SBS) for the plastics separation; according to the system boundaries of this study, this has been not considered, as it is used after the shredding operations.

([73]) This is the average value of those available in literature (section 3.3.4).

Table 24: Inventory data used for the LCA of canister vacuum cleaner EoL (shredding process)

Material	Unit of Measure	Mass
Carbon black	[kg]	0.079
Limestone	[kg]	0.348
Electricity	[MJ]	10.298
Magnetite	[kg]	0.054
Transports	[kg*km]	9.029

Finally, the recycling and recovery rate of product parts is modelled according to IEC/TR 62635 (Table 25).

Table 25: Inventory data used for the LCA of canister vacuum cleaner EoL (waste flows)

Material	Recycling	Incineration	Disposal
ABS	74 %	26 %	0 %
ABS.PP	0 %	100 %	0 %
Aluminium	91 %	0 %	9 %
BMC-GF	0 %	100 %	0 %
Brass	100 %	0 %	0 %
Copper	100 %	0 %	0 %
Graphite	0 %	0 %	100 %
PCB	0 %	0 %	100 %
PE	90 %	10 %	0 %
POM	0 %	100 %	0 %
PP	90 %	10 %	0 %
PVC	0 %	100 %	0 %
Rubber	90 %	10 %	0 %
Steel	94 %	0 %	6 %
Cardboard	90 %	0 %	10 %
LDPE	90 %	10 %	0 %
Paper (Manual)	90 %	0 %	10 %

4.2.4. Transports

Consistent with the assumptions in section 3.5, the inventory data used for the motor model are showed in Table 26.

Table 26: Inventory data used for the LCA of canister vacuum cleaner's transports

Transported material	Life-cycle stage description	Distance [km]	Mass*Distance [kg*km]
Plastics	Raw material procurement	100	432.32
Metals	Raw material procurement	200	279.57
Packaging materials	Raw material procurement	100	126.00
VC	Delivery	1 000	6 981.00
VC	EoL	100	698.10

4.3. Impact assessment of an average canister vacuum cleaner

All the impacts hereinafter illustrated have been calculated for the considered functional unit (a canister vacuum cleaner with an operating lifetime of 10 years).

Table 27 and Figure 25 shows that the life-cycle overall environmental impacts of the canister vacuum cleaner and the percentage contribution of life-cycle phases: manufacturing, use (including consumption of energy and auxiliary materials and ordinary maintenance) and end-of-life.

Table 27: LC Impact Assessment of the canister vacuum cleaner

Impact category	Unit of measure	Vacuum Cleaner	Manufacturing	Use phase			EoL
				Auxiliaries components	Ordinary maintenance and dust-bags	Energy consumption	
ADP-res	[kg $Sb_{Equiv.}$]	1.27E-03	1.21E-03	9.76E-07	1.80E-07	6.09E-05	9.16E-07
AP	[Mole of $H+_{eq.}$]	8.04E-01	1.20E-01	4.06E-03	1.60E-03	6.70E-01	8.64E-03
FET	[CTUe]	7.78E+01	7.39E+01	2.21E-01	5.09E-02	3.52E+00	1.22E-01
EPf	[kg P_{eq}]	3.79E-04	1.61E-04	6.50E-05	5.42E-07	1.48E-04	4.17E-06
HT-C	[CTUh]	3.37E-07	2.11E-07	1.48E-08	3.92E-09	1.02E-07	4.99E-09
HT-nC	[CTUh]	9.18E-06	6.22E-06	2.70E-08	1.79E-08	2.86E-06	4.92E-08
IR	[kg $U235_{eq}$]	5.59E+01	2.77E+01	-1.27E-02	3.83E-02	2.44E+01	3.68E+00
GWP	[kg $CO2_{Equiv.}$]	1.49E+02	2.72E+01	1.80E+00	4.24E-01	1.18E+02	1.59E+00
Epm	[kg $N_{Equiv.}$]	1.06E-02	4.29E-03	8.04E-04	1.69E-05	5.19E-03	2.53E-04
ODP	[kg CFC-11 $_{eq}$]	1.11E-07	2.11E-08	-5.35E-11	1.39E-10	8.78E-08	1.82E-09
PMF	[kg $PM2,5_{Equiv.}$]	4.94E-02	8.17E-03	1.26E-04	8.75E-05	4.04E-02	5.71E-04
POCP	[kg NMVOC]	3.18E-01	6.39E-02	4.56E-03	1.03E-03	2.46E-01	3.10E-03
PEn	[MJ]	2.76E+03	5.84E+02	2.27E+01	1.46E+01	2.11E+03	3.01E+01
EPt	[Mole of $N_{eq.}$]	1.13E+00	2.37E-01	1.88E-02	2.74E-03	8.62E-01	1.25E-02
FC	[UBP]	1.60E+02	2.57E+01	8.94E+00	3.10E-01	1.24E+02	1.66E+00

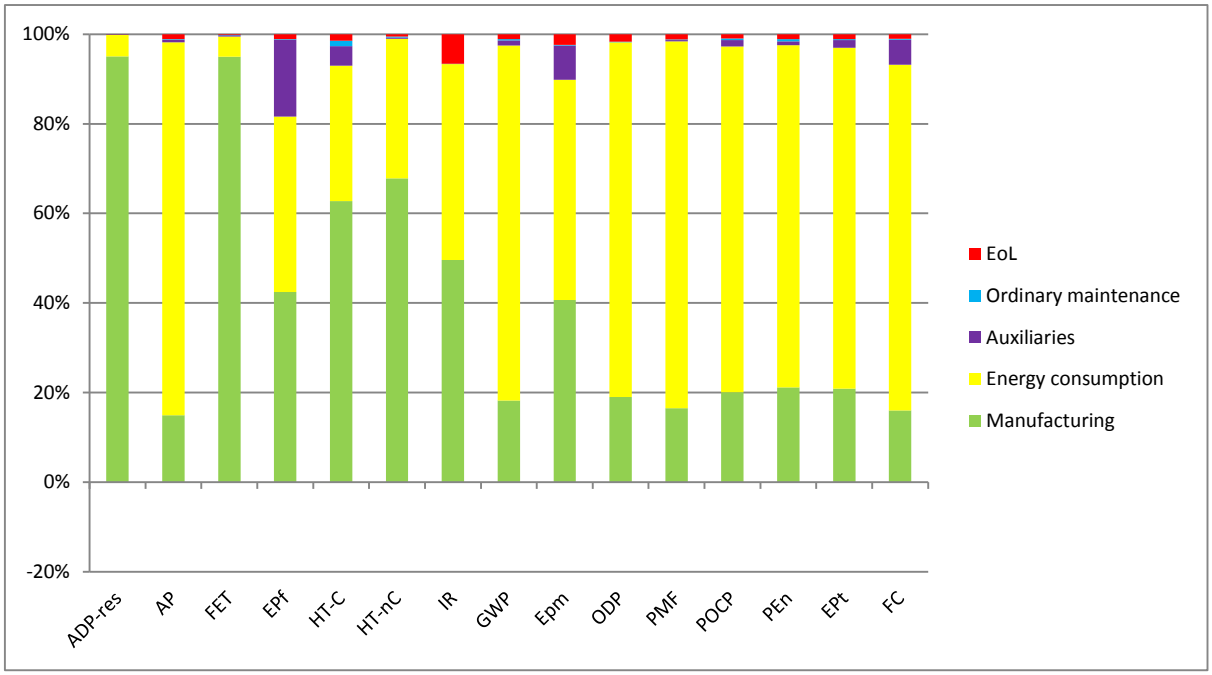


Figure 25: Percentage contribution to the overall impact of the canister vacuum cleaner LC phases

The results demonstrate that the major contributions in terms of environmental impacts are associated to use and manufacturing phases.

In particular, for the impact categories more related to the energy consumption (Acidification, GWP, Ozone Depletion and Particulate Matter) the energy consumption contribution is always higher than 79 %. In any case, except for Ecotoxicity for aquatic fresh water and Abiotic Depletion, the use phase can't be considered as negligible (less than 5 %).

The manufacturing phase is particularly relevant (more than 95 %) for Ecotoxicity for aquatic fresh water and Abiotic Depletion; in any case, it's never lower than 14.5 % for all 15 impact categories.

Concerning auxiliaries components and ordinary maintenance, note that on the whole they have an environmental impact higher than 15 % only for Freshwater eutrophication (6.55E-05 kg_{Peq}). The EoL phase contributes for less than 5 % for almost all the impact categories; an exception is represented by Ionising Radiation. Note that the system boundaries of the study have been set to include only the pre-processing of the VC waste, and do not include the further treatments of recyclable/recoverable materials, nor the potential environmental credits due to the energy and material recovery (section 3.4 and 0).

4.4. Life Cycle Interpretation

The impacts have been calculated for all the impact categories illustrated in tables and reported in ANNEX 2. This section illustrates a more detailed analysis performed for some exemplary impact categories as:

- GWP, being dominated by the energy consumption;
- Abiotic Depletion Potential, mineral resources, being dominated by the manufacturing phase;
- Human toxicity cancer effects, being equally influenced by both manufacturing and use phase.

4.4.1. Manufacturing phase

Consistent with the goal and scope of the study, hose and operational motor are modelled separately to all the 'other components' of the canister vacuum cleaner (i.e. canister case, PCB, nozzle plate, hose reel, attachment cord, cables, filter and wheels). Moreover, packaging and transports of raw materials are included in the manufacturing phase. Results are illustrated in Table 28.

Table 28: Environmental impact of the manufacturing phase components/processes

	IPCC global warming, excl biogenic carbon		**Human toxicity canc. effects, USEtox (recommended)**		**Abiotic Depletion Potential, mineral resources**	
	[kg $CO2_{Equiv.}$]	**[%] respect to the total**	**[CTUh]**	**[%] respect to the total**	**[kg $Sb_{Equiv.}$]**	**[%] respect to the total**
Hose	2.48	1.82 %	1.79E-08	5.56 %	8.71E-07	0.07 %
Motor	5.47	4.00 %	5.23E-08	16.24 %	1.04E-03	82.25 %
'Other components'	12.66	9.27 %	1.16E-07	36.01 %	1.62E-04	12.74 %
Energy consumption	4.73	3.46 %	4.07E-09	1.26 %	2.43E-06	0.19 %
Packaging	1.42	1.04 %	1.78E-08	5.52 %	3.75E-06	0.30 %
Transport	0.04	0.03 %	2.84E-10	0.09 %	6.46E-09	0.00 %

In line with results from the literature, the energy consumption for the manufacturing phase is negligible: it represents about 3.5 % of the GWP of the VC (4.73 kg CO_{2eq}) and is negligible for the other two impact categories. Focusing on the GWP manufacturing impact however, electricity represents one of the most important elements. Regarding materials, more than 35 % of the impact is associated to ABS (10.68 kg CO_{2eq}) used for the hose, the hose reel and the casing of the canister. Note that ABS is also the most relevant material of the VC in terms of mass (section 3.2). Other components having a GWP impact higher than 3 % in relation to the manufacturing are copper, steel and PCB.

The manufacturing phase dominates the Abiotic Depletion category, being responsible of more than 95 % of the overall impact (1.21 g Sb eq.). The most relevant components for the ADP are the motor and the printed circuit board. In particular, the greatest impact is due to the content of copper (in the rotor, stator and in the cables), even if the content of copper is less than 10 % of the motor mass — section 4.2.1.2. Indeed, note that the PCB mass contribution is lower than 0.5 %, and that the major contribution of its impact is to be associated to the printing wiring board (5.45E-05 kg Sb eq.) and transistor (2.84E-05 k g Sb eq.).Concerning the human toxicity (cancer effect), the major contribution is related to the life-cycle impact of the copper in the motor and the electric cables. Also in this case, ABS contribute to the Human Toxicity manufacturing impact for more than 30 %, while the steel and PCB contributions are higher than 5 %.

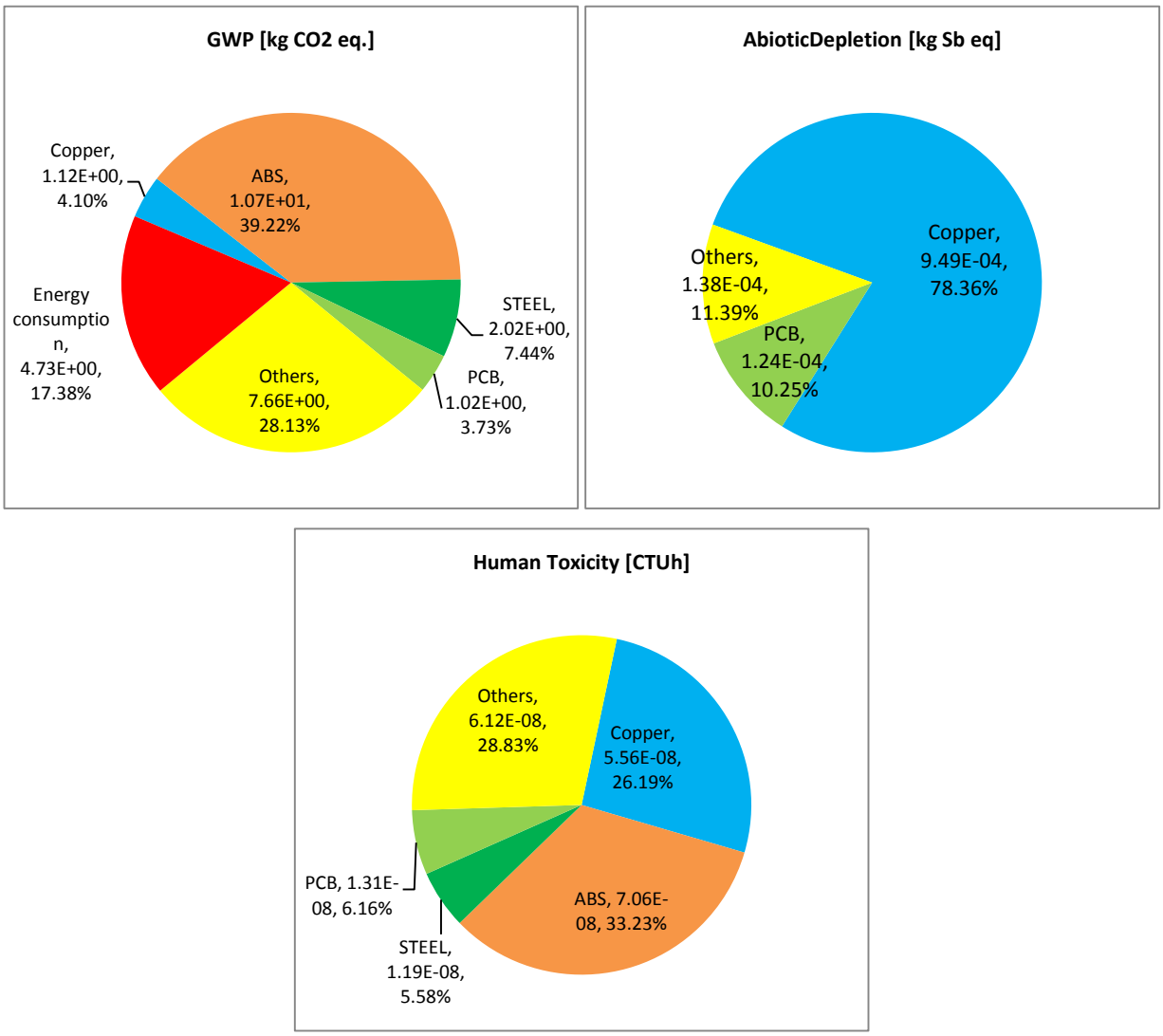


Figure 26: Contribution of the canister's materials to the overall impact of the canister vacuum cleaner

In order to take into account the technology development during the lifetime of VC, the environmental burdens associated to the production of a new and more technologically advanced product (B) have been considered. The main assumption is about the technological development of the printed circuit board as more complex PCB are already used in vacuum cleaners available on the market.

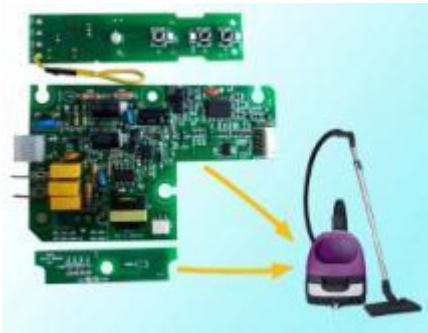


Figure 27: PCB of the dismantled vacuum cleaner and example of a more recent PCB (74)

Few data are available about the composition of PCB in VCs. However, even from a not detailed analysis it is possible to observe that modern VCs included much more complex PCB (see e.g. Figure 27). Therefore the sensitivity analysis was realised assuming a varied impact of the PCB, according to a parameter γ:

$$I_{PCB'} = \gamma \cdot I_{PCB} \qquad , \qquad 0 \leq \gamma$$

In order to define the range of γ variation, a more complex PCB is modelled (differences are substantially related to the amount of many components, ANNEX 1). Except for three impact categories (i.e. human toxicity non-cancer effects, ionising radiation and ozone depletion), the environmental impact of the more recent PCB is higher than that of the base-case VC. Substituting the new PCB into the LCA model, it's to be noted that higher variation of the overall impact is to be associated to the abiotic depletion (more than 10 %), while almost all the impact categories don't vary their environmental impact for more than 1 % (Figure 28).

Therefore, the γ parameter has been varied between 90 % and 140 %. Results are illustrated in Table 29. The LCIA results prove that the substitution of the PCB with a more complex one could cause variation for the life-cycle impacts that are generally lower than 5 %. Higher differences can be found just for abiotic depletion and human toxicity (cancer effects) but only in correspondence to high γ-values.

(74) http://longoodpcba.en.ec21.com/PCB_Assembly_for_Vacuum_Cleaner—5761729_5774978.html (accessed March 2015)

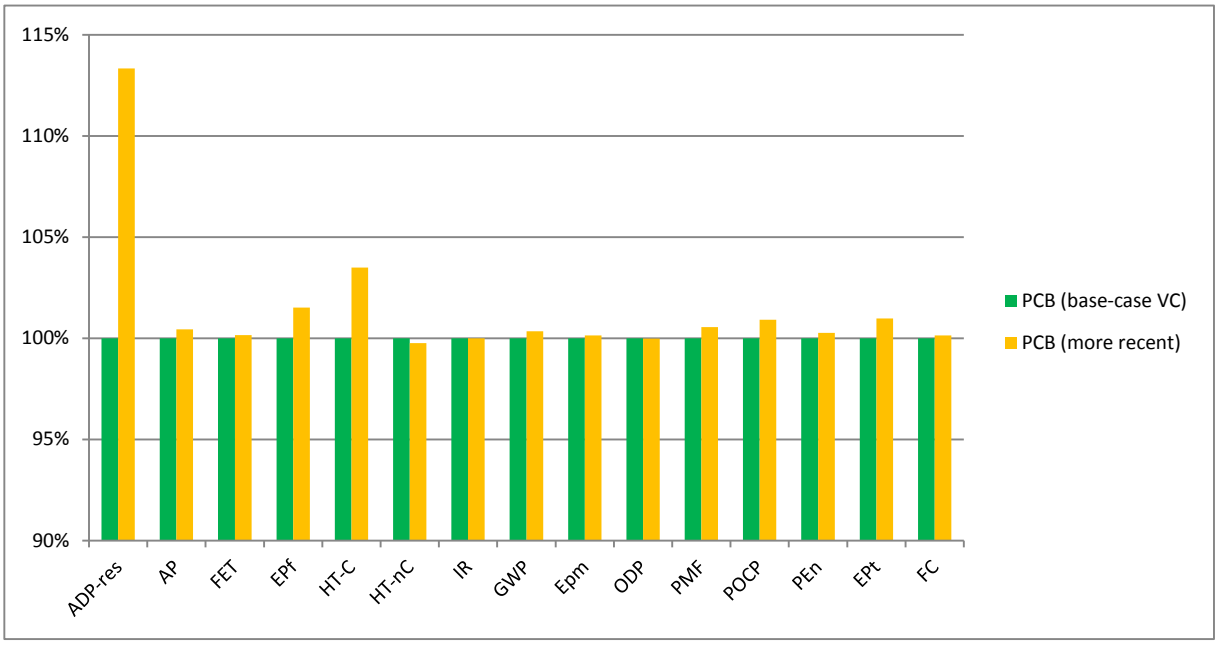


Figure 28: Comparison between the LCIAs of VC with two different PCBs.

Table 29: Percentage difference between the environmental impacts of the VC on varying γ-values and the base-case VC

	γ					
	90 %	**100 %**	**110 %**	**120 %**	**130 %**	**140 %**
ADP-res	-0.97 %	0.00 %	0.97 %	1.95 %	2.92 %	3.90 %
AP	-0.09 %	0.00 %	0.09 %	0.18 %	0.27 %	0.36 %
FET	-0.04 %	0.00 %	0.04 %	0.07 %	0.11 %	0.14 %
EPf	-0.36 %	0.00 %	0.36 %	0.73 %	1.09 %	1.46 %
HT-C	-0.39 %	0.00 %	0.39 %	0.78 %	1.17 %	1.56 %
HT-nC	-0.22 %	0.00 %	0.22 %	0.44 %	0.66 %	0.87 %
IR	-0.01 %	0.00 %	0.01 %	0.02 %	0.02 %	0.03 %
GWP	-0.07 %	0.00 %	0.07 %	0.14 %	0.20 %	027 %
Epm	-0.11 %	0.00 %	0.11 %	0.22 %	0.33 %	0.44 %
ODP	-0.02 %	0.00 %	0.02 %	0.03 %	0.05 %	0.06 %
PMF	-0.17 %	0.00 %	0.17 %	0.35 %	0.52 %	0.70 %
POCP	-0.12 %	0.00 %	0.12 %	0.25 %	0.37 %	0.50 %
PEn	-0.05 %	0.00 %	0.05 %	0.09 %	0.14 %	0.19 %
EPt	-0.13 %	0.00 %	0.13 %	0.27 %	0.40 %	0.54 %
FC	-0.05 %	0.00 %	0.05 %	0.11 %	0.16 %	0.21 %

4.4.2. Use phase

The use phase is affected by both the consumption of electricity and materials (filter and dust-bags). The results of the impact assessment make evident the large impact of the electricity for the GWP and the minor relevance for human toxicity and abiotic depletion.

In order to take into account the energy efficiency standards in force from 1 September 2017, the average values of each energy efficiency class have been considered based on (EU 2013b), so the energy

consumption of the VC ranges between 7 [kWh/y] and 43 [kWh/y]. It's to be noted that the environmental burdens of the electricity usage decrease with the increasing of the energy efficiency of the ErPs (Figure 29).

Figure 30 shows the contribution for the main life-cycle phases to the environmental impact of VC for three different energetic classes: A+++, A and D. These graphs demonstrate the decreasing contribution of the energy consumption in respect to the overall impact, and this is particularly evident for life-cycle GWP and human toxicity (even if lower). Indeed, concerning abiotic depletion, the contributions of the different phases to the VC life-cycle impact don't change, whichever energetic class is considered.

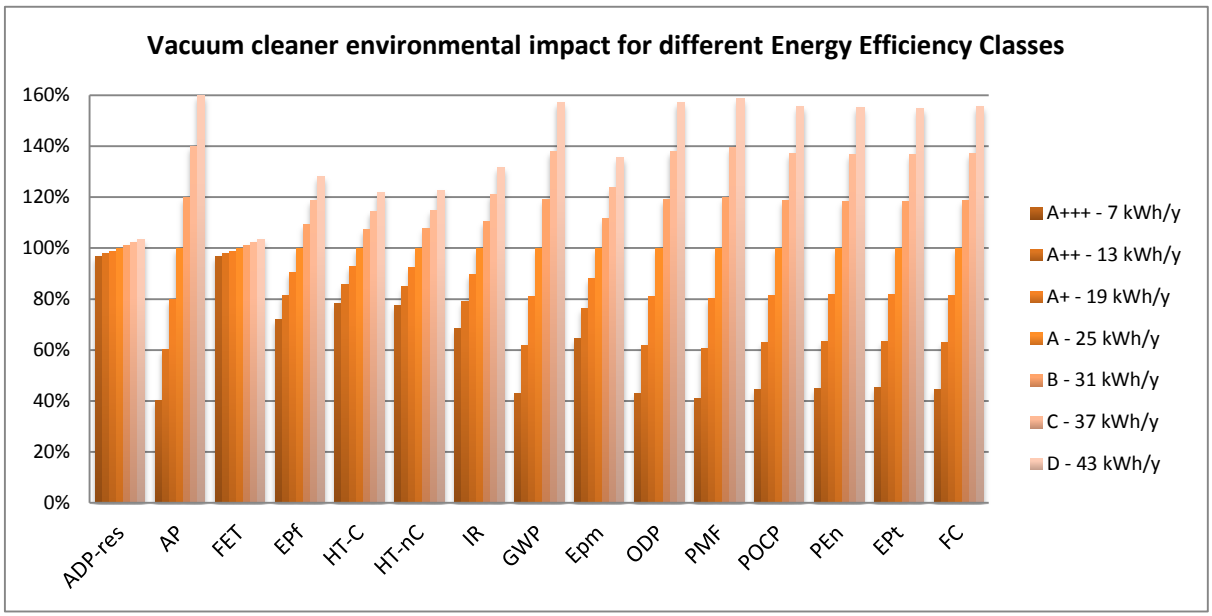


Figure 29: Sensitivity analysis of the energy consumption (related to VC of different energy Efficiency Classes)

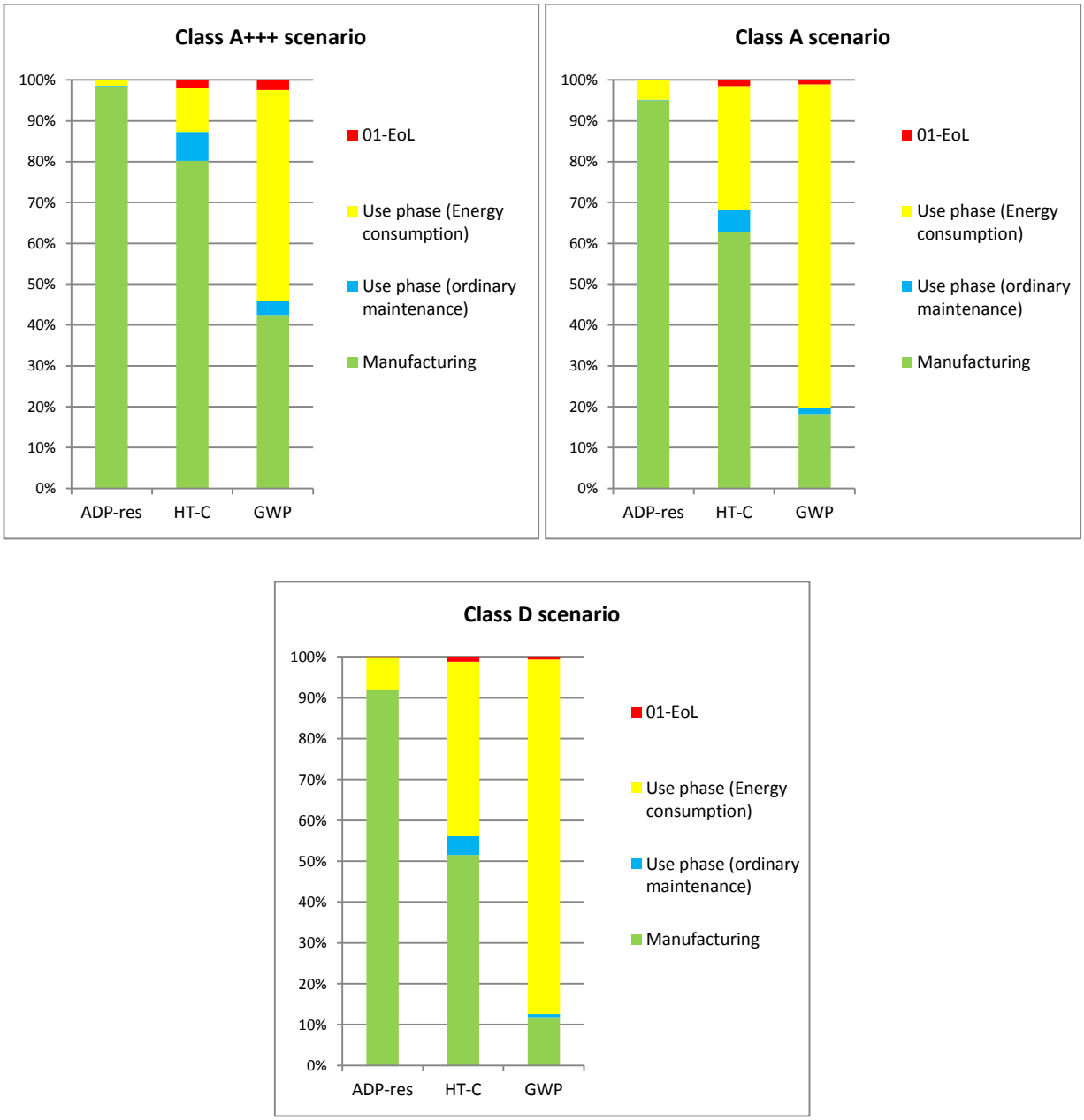


Figure 30: Contribution of the main LC phases to the environmental impact of vacuum cleaner for different Energy Efficiency Classes to the impact categories: Abiotic Depletion Potential, mineral resources (ADP-res), Human Toxicity non-cancer effects (HT-nc) and Global Warming Potential (GWP)

CHAPTER 5
Environmental assessment of durability issues

5.1. Method for the environmental assessment of durability of energy-using products

The environmental assessment of the durability of energy-using products is based on the method developed by Ardente et al. (2012). The environmental assessment of durability refer to two different scenarios: the first is a base-case scenario, meaning a standard product (A) at the end of its operating life is substituted by a new product (B), while the second one is the Durable scenario, meaning an extension (X) of the lifetime of product (A) is considered.

As defined by Ardente et al. (2012), the durability index (D_n) for a general impact category 'n' is illustrated in Formula 1.

Formula 1:

$$D_n = \frac{\frac{P_{B,n}}{T_B} \cdot X + \frac{E_{B,n}}{T_B} \cdot X + \left(U_{B,n} - U_{A,n}\right) \cdot X - R_{A,n}}{P_{A,n} + U_{A,n} \cdot T_A + E_{A,n}} \cdot 100 \ [\ \%]$$

Where:

- D_n = Durability index for the impact category 'n' [%];
- $P_{B,n}$ = Environmental impact for category 'n' for the production of product (B) (including the production of raw materials and manufacturing) [unit];
- T_B = Average operating time of product (B) [hour];
- X = Extension of operating time of product (A) [hour];
- $E_{B,n}$ = Environmental impact for category 'n' for the EoL treatments of product (B) [unit];
- $U_{B,n}$ = Environmental impact per unit of time for category 'n' for the use of product (B) [unit/hour];
- $U_{A,n}$ = Environmental impact per unit of time for category 'n' for the use of product A [unit/hour];
- $R_{A,n}$ = Environmental impact per unit of time for category 'n' for additional treatments (e.g. repairing, refurbishment) necessary for the extension of operating time T_A [unit];
- $P_{A,n}$ = Environmental impact for category 'n' for the production of product (A) (including the production of raw materials and manufacturing) [unit];
- $E_{A,n}$ = Environmental impact for category 'n' for the EoL treatments of product (A) [unit].

This durability index has been successively revised to include additional parameters, as hereinafter illustrated.

5.1.1. Revision of the method: impacts of auxiliary materials and of replacing product

Concerning the use phase, its environmental impact is to be mainly associated to the energy consumption of the ErP under evaluation. But it's to be noted that some ErPs need auxiliaries' materials for accomplishing their duties. Hence, the environmental impact U_n can be expressed as:

Formula 2: $$U_n = A_n + u_n$$

Where:

- A_n = Environmental impact for category 'n' for the auxiliaries' materials consumption [unit/hour];
- u_n = Environmental impact for category 'n' for the energy consumption during the use phase [unit/hour].

The environmental impact per unit of time for the use of product (B) can be expressed as a certain percentage (δ) of the environmental impact per unit of time for the use of product (A).

Formula 3: $$u_B = \delta \cdot u_A$$

As discussed in Ardente & Mathieux (2014), it is always environmentally convenient to prolong the lifetime of a product if $U_B > U_A$ ([75]). Therefore the analysis focuses on the case that the product (B) is more energy efficient than product (A), i.e. when:

$$0 < \delta < 1$$

For the calculation of the durability index, it is also necessary to estimate the impacts on production ($P_{B,n}$) when replacing product (B). These should also take into account the technological progress of the product and changes of manufacturing processes. Ardente and Mathieux (2012a) didn't consider the technology evolution, so it was assumed that the two products had the same impacts (i.e. $P_A = P_B$). Indeed, P_B can be expressed as a function of the impact for the manufacturing of product (A) taking into account a parameter (γ) ([76]):

Formula 4: $$P_{B,n} = \gamma \cdot P_{A,n}, 0 < \gamma$$

Moreover, the factor 'E' takes into account the EoL of the product. Unless big changes in the product and its EoL treatments are expected, it's plausible to affirm that environmental impacts at the EoL are the same for both products ($E_A = E_B$). Note that for the sake of completeness, the recycling/incineration environmental benefits ([77]) of products (A) and (B) should also be considered in the factor 'E'. However, the introduction of these benefits would have the effect of enlarging the complexity of the analysis (due to an expansion of the system boundaries), and in addition the mixing of environmental benefits due to durability with other environmental benefits due to the EoL. Therefore in order to keep the focus on the assessment of the impacts/benefits of durability, potential benefits derived by the EoL are not included.

([75]) Considering the technological progress, it is plausible to assume that the environmental impact for the use of product (B) would be lower than the environmental impact for the use of product (A). However, sometimes modern products can consume more energy due, for example, to additional functions implemented.

([76]) Values of $0 < \gamma < 1$ imply that impact to manufacture product (B) are lower than those of product (A) (e.g. due to dematerialisation of the product); values $\gamma > 1$ imply that impact to manufacture product (B) are higher than those of product (A) (e.g. due to increased complexity of the product and its electronic components).

([77]) Environmental benefits could be assumed due to the production of secondary materials substituting primary materials and/or energy recovered from waste that is substituting conventional energy sources (Ardente & Mathieux 2014).

Based on Ardente and Mathieux (2014), the two products are not characterised by rapid technological changes, and their lifetime can be assumed as the same ($T_A = T_B$).

Under these considerations, the durability index could be expressed as illustrated in Formula 5.

Formula 5:

$$D'_n = \frac{\frac{\gamma \cdot P_{A,n}}{T} \cdot X + \frac{E_n}{T} \cdot X - (1-\delta) \cdot U_{A,n} \cdot X - R_{A,n}}{P_{A,n} + U_{A,n} \cdot \mathrm{T} + E_n} \cdot 100 \ [\ \%]$$

Where:

- γ = Percentage representing variation of the impacts due to the manufacturing of the new product (B) substituting the product (A) [%];
- δ = Percentage representing the higher energy efficiency of the new product substituting the product (A) [%]

(other symbols as in Formula 1).

5.1.2. Revision of the method: additional impacts of durable product

The method developed so far assumed that impacts of product (A) are the same in both the scenarios and that the lifetime extension is reached thanks to repair and maintenance activities.

However, as discussed in various studies, the design of more durable products could imply additional burdens for example due to the use of additional/higher quality materials (Kostecki, 1998; Mora, 2007; AEA Energy & Environment 2009). Although less relevant, some additional impacts of durable products could be related to other aspects as: longer design processes, development of innovative machineries, more tight testing, etc.

For example the Preparatory study on VCs identified as a possible option to increase the product lifetime by 50 %, which is 'likely to impinge on the need to improve the durability of the vacuum cleaner itself' (i.e. increased weights of materials to strengthen items) (AEA Energy & Environment 2009). The study suggests that more materials and thus more environmental impacts are involved in the manufacturing of the more durable product. However, the report did not detail how this was modelled in the Ecoreport tool and how many additional materials have been accounted for.

In order to take into account these factors (i.e. additional burdens for the durable products), previous formulas can be revised by including an additional factor. Similarly to the accounting of the impacts due to the repair or due to manufacturing of the replacing product, impacts of durable products manufacturing ($P'_{A,n}$) can be expressed as a function of the impact for the manufacturing of product (A) ($P_{A,n}$), as:

Formula 6: $$P'_{A,n} = (1+\alpha) \cdot P_{A,n}$$

or analogously:

Formula 7: $$\left(P'_{A,n} - P_{A,n}\right) = \alpha \cdot P_{A,n}$$

where:

- $P'_{a,n}$ = Environmental impact for category 'n' to make product (A) more durable (including all the impacts for the production of raw materials and manufacturing) [unit];

- α = Percentage representing the higher impact to make product (A) more durable [%].

For example, a value of $(\alpha = 10\ \%)$ implies that 10 % additional impacts are necessary to make base-case product more durable.

In order to account for factor α, previous formula in section 5.1.1 is modified as:

Formula 8:

$$D'_n = \frac{\frac{\gamma \cdot P_{A,n}}{T} \cdot X - \frac{\alpha \cdot P_{A,n}}{T} \cdot X + \frac{E_n}{T} \cdot X - (1-\delta) \cdot U_{A,n} \cdot X - R_{A,n}}{P_{A,n} + U_{A,n} \cdot \mathrm{T} + E_n} \cdot 100\ [\ \%]$$

Or analogously:

Formula 9:

$$D'_n = \frac{\frac{(\gamma - \alpha) \cdot P_{A,n}}{T} \cdot X + \frac{E_n}{T} \cdot X - (1-\delta) \cdot U_{A,n} \cdot X - R_{A,n}}{P_{A,n} + U_{A,n} \cdot \mathrm{T} + E_n} \cdot 100\ [\ \%]$$

5.2. Environmental assessment of durability of EuPs: the case-study of vacuum cleaners

The following sections illustrate the environmental assessment of the durability of the case-study vacuum cleaner. The durability index is calculated for all the impact categories included in ILCD/PEF recommendations as discussed in section 4.1. All the results are illustrated in ANNEX 3. However, the analysis illustrated in this chapter will be restricted to only three exemplary impact categories:

- Global Warming Potential (GWP), as dominated by the energy consumption;
- Abiotic Depletion Potential, mineral resource, as dominated by the manufacturing phase;
- Human toxicity non-canc. Effects, equally influenced by both manufacturing and use phase.

The following assumptions have been introduced in the analysis.

In order to consider the variation of the durability index and to assess the environmental performance of products with different lifetimes, the average operating time considered for the canister vacuum cleaner is 500 h. The extension of the operative time (X) is assumed ranging from 0 to 300 hours ([78]), in line with values discussed in the literature (section 2 and table 15). This wide range of values allows to assess the durability index (D_n) according to different product lifetimes, including lifetime requirements introduced by the Ecodesign implementing measures on VC (EU 2013a), and also in relation to additional lifetime extension.

The case-study product is assumed to belong to the energy class 'A' ([79]), with a yearly consumption of 25 [kWh/year] ([80]).

([78]) Consistent with the literature, motors without carbon brushes could have longer lifetime, and some VCs have been tested for more than 1 000 operating hours (section 3.3.1).

([79]) As discussed in section 3.3, the majority of VCs currently put into the market belongs to energy class 'A' and 'B'. The present study is centred on the assessment of the durability of VCs, with a particular focus on the on lifetime extension as introduced by implementing measures and in force from September 2017. It is therefore expected that, at that time, the large majority of VCs will be of class 'A' or higher. Therefore, the present analysis considered as base-case a VC of energy class 'A'.

([80]) This value corresponds to the average consumption for the energy efficiency class 'A'.

Moreover, it is assumed that the two products (A) and (B) use the same amount of dust-bags during the operation. This implies that, in the durability index, only impacts due to the energy consumption are considered:

Formula 10: $$u_n = U_n$$

Concerning the manufacturing and the ordinary maintenance, the same assumptions in chapter 3.5 are adopted here. In order to account the additional impacts of a more complex manufacturing of product (B), it is supposed that the γ parameter (as in Formula 4), varies in four different scenarios as: $\gamma = 100$ % (meaning $P_A = P_B$), $\gamma = 110$ %, $\gamma = 120$ % and $\gamma = 130$ %.

In order to account for the impacts of possible repair intervention (to grant additional extensions of the lifetime), the parameter ($R_{A,n}$) is considered, including the impacts due to the repair or substitution of some vacuum cleaner components. As there are no data available on this in the literature, the analysis has been subdivided into two scenarios: a 'low-repair scenario' (LRS) and a 'high-repair scenario' (HRS). The HRS scenario assumes that some parts of the VC would be substituted. It is noticed that the key parts for the durability of the vacuum cleaner are the hose and the operational motor (EC 2013; AEA Energy & Environment 2009). As discussed in chapter 3.3.3, the motor is usually not substituted because of its high price. Indeed, the hose breakdown represents one of the most common repair treatments for the vacuum cleaner (section 1.3). Other possible problems relate to the loss of suction and breakdown of the casing and power cables. The LCIA (section 4.3) of the canister vacuum cleaner demonstrates that substitution of some of these components would imply additional impacts, depending on the considered impact category. In particular, the most important variations in terms of environmental impact are related to the substitution of the cables (due to the presence of copper) or the PCB, while the substitution of the hose or the nozzle plate have a lower relevance for all the analysed impact categories. Moreover, some breakdowns are related to components that don't affect the functioning of the vacuum cleaner, for instance the hose reel of the casing. Therefore, for this analysis, the LRS takes into account minor repair operations that don't affect the overall environmental impact of the product. Indeed, concerning the HRS, it is supposed that at least one of the components mentioned above is substituted, increasing the final impact. The most important component in terms of impact variation are the PCB and the hose, thus they are used as reference to establish the R_A value for the HRS. In this perspective, depending of the impact categories, R_A can be represented by a variable percentage of the manufacturing impact:

- From 0 % to 1 % for the impact categories: ecotoxicity for aquatic fresh water, ionising radiation, particulate matter, ozone depletion and total freshwater consumption ([81]);
- From 1 % to 3 % for the impact categories: acidification, freshwater, marine and terrestrial eutrophication, human toxicity (non-cancer effects), IPCC Global Warming, photochemical ozone formation and primary energy from non-renewable resources ([82]);
- Higher than 3 % for the impact categories: abiotic depletion and human toxicity (cancer effects) ([83]).

([81]) HRS is assumed to be 1 % of the manufacturing impact.
([82]) HRS is assumed to be 3 % of the manufacturing impact.
([83]) HRS is assumed to be 5 % of the manufacturing impact.

5.3. Analysis of the durability index

The main assumptions for the analysis are summarised in Table 30. Table 31 summarises the results of the LCA applied to the case-study VC. Note that, consistent with the hypotheses of technological development and the results of the LCIA and the sensitivity analysis (sections 4.3 and 4.4), the adopted γ for calculating the durability index is 105 % for all the impact categories except for abiotic depletion, for which γ = 110 %. The values of the durability index are depicted in Table 32, Figure 31 and Figure 32.

Table 30: Summary of the assumptions for the calculation of the durability index

Product 'A'			
Average operating time	T_A	[hours]	500
Yearly energy consumption until 500 hours		[kWh/y]	25
Extension of the lifetime	X	[hours]	0 → 300
Product 'B'			
Variation of the manufacturing impact of product 'B' compared to 'A'	γ	[%]	γ = 105 % (γ = 110 % for ADP)
Variation of the energy consumption impact of product 'B' compared to 'A'	δ	[%]	70 %< δ < 100 %

Table 31: Summary of the life-cycle impacts of canister vacuum cleaners (section 4.3)

	IPCC global warming, excl biogenic carbon		**Human toxicity canc. effects, USEtox (recommended)**		**Abiotic Depletion, mineral resources**	
$P_{A,n}$	2.72E+01 [kg CO2-Equiv.]		2.11E-07 [CTUh]		1.21E-03 [kg Sb-Equiv.]	
E_n	1.59E+00 [kg CO2-Equiv.]		4.99E-09 [CTUh]		9.16E-07 [kg Sb-Equiv.]	
$U_{A,n}$	2.37E-01 [kg CO2-Equiv./hour]		20.3E-10 [CTUh/hour]		1.22E-07 [kg Sb-Equiv./hour]	
$R_{A,n}$	LRS	0.0E+00	LRS	0.0E+00	LRS	0.00E+00
	HRS	8.17E-01	HRS	1.06E-08	HRS	6.06E-05

The obtained results show that the extension of the lifetime ensures environmental benefits for all the assessed impact categories, and that the introduction of more ambitious durability requirements into the Ecodesign implementing measures for VC (EU 2013a) would generate environmental benefits in the EU-27, whichever impact category is taken into account. For instance, for a lifetime extension of 100 hours, the life-cycle GWP compared to the replacement of the VC with a new one 15 % more efficient ([84]) is reduced by 1.69 %. It is worthy that, for some of the assessed impact categories, the Durability Index is negative for low values of δ-parameter, i.e. benefits related to the lifetime extension of the VC strictly depend on the energy efficiency of the new product (B). This is particularly evident for those impact categories dominated by energy consumption (Table 32).

The environmental assessment of durability depicts that the extension of the lifetime of vacuum cleaner generally produces relevant environmental benefits from a life-cycle point of view. This is true even if the replacing product is more energy efficient. Based on this analysis, it is observed that

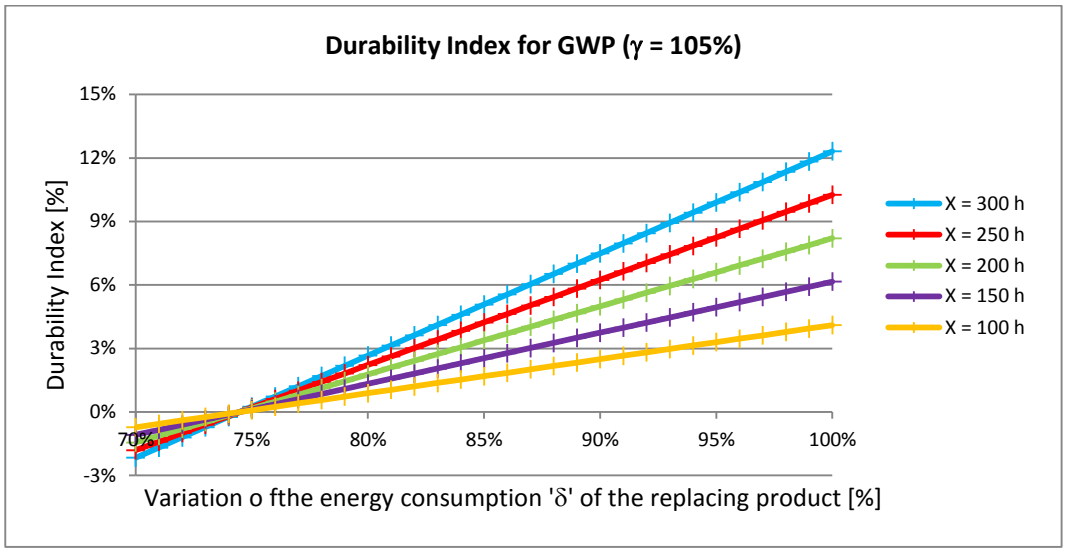
([84]) The value of 15 % energetically more efficient is corresponding to about one energy efficient class higher.

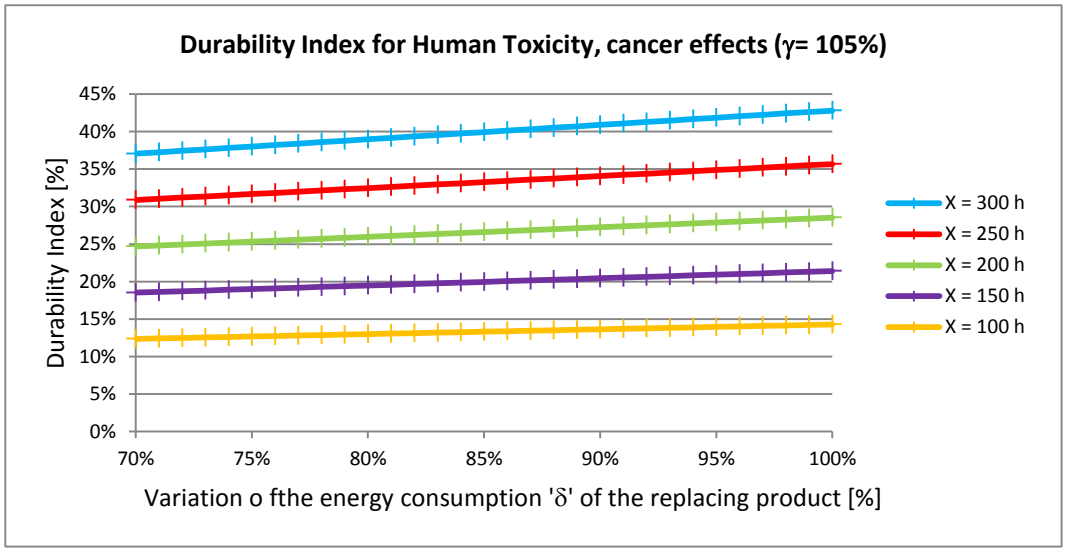
- The higher the lifetime extension the higher the environmental benefit in terms of life-cycle GWP: in fact, a lifetime extension of 250 h can reduce the life-cycle GWP of 4.23 % compared to the replacement of the old product with a new one 15 % more efficient, while a lifetime extension of 100 h, under same hypothesis, can reduce the life-cycle GWP of 1.69 %;
- Concerning the impact categories dominated by energy consumption, the base-case Scenario (i.e. the substitution of the VC with a new more energy efficient product) discloses some environmental benefits for low values of the δ parameter. This is the case of acidification, GWP, ozone depletion, particular matter, photochemical ozone formation and total freshwater consumption. For instance, in terms of life-cycle GWP, the Durability Index (D_n) is negative when the new product is 26 % more efficient than the replaced one (that means the replacing VC is almost two energy efficiency classes higher than the replaced one);
- The environmental benefits are more relevant for the human toxicity and abiotic depletion impact categories. The extension of the lifetime of the vacuum cleaner of 100 h can reduce the life-cycle human toxicity of more than 12.35 % whatever the energy efficiency increase of the replacing product. Similarly, the 100 h lifetime extension can reduce the life-cycle abiotic depletion of more than 20.66. The accounting of additional environmental impacts due to repairing (HRS scenarios) implies lower environmental benefits, especially for low values of the lifetime extension. This difference is negligible for the life-cycle GWP and human toxicity, while is more relevant for the abiotic depletion impact category. This is consistent with the HRS hypotheses illustrated in chapter 3: the replacement of the components doesn't cause great variations for the life-cycle GWP, as this impact category is dominated by the energy consumption, differently for the human toxicity and abiotic depletion.

It is highlighted that the LCA is affected by uncertainties due to the assumptions illustrated in chapter 4 that also affect the durability assessment.

Table 32: Example of Durability Index (D_n) results (lifetime extension of 100 hours)

		ADP-res	AP	FET	EPf	HT-C	HT-nC	IR	GWP	Epm	ODP	PMF	POCP	PEn	EPt	FC
δ [%]	*100 %*	20.95 %	3.37 %	40.09 %	22.10 %	14.27 %	28.83 %	11.74 %	4.10 %	19.57 %	8.66 %	7.44 %	8.98 %	4.73 %	9.39 %	7.58 %
	99 %	20.94 %	3.20 %	40.07 %	21.91 %	14.20 %	28.71 %	11.65 %	3.94 %	19.35 %	8.34 %	7.11 %	8.66 %	4.57 %	9.08 %	7.25 %
	98 %	20.93 %	3.03 %	40.05 %	21.72 %	14.14 %	28.58 %	11.56 %	3.78 %	19.14 %	8.03 %	6.78 %	8.35 %	4.42 %	8.77 %	6.93 %
	97 %	20.92 %	2.87 %	40.03 %	21.53 %	14.08 %	28.46 %	11.48 %	3.62 %	18.93 %	7.71 %	6.45 %	8.03 %	4.26 %	8.46 %	6.60 %
	96 %	20.91 %	2.70 %	40.02 %	21.34 %	14.01 %	28.33 %	11.39 %	3.46 %	18.71 %	7.39 %	6.13 %	7.72 %	4.11 %	8.15 %	6.27 %
	95 %	20.90 %	2.53 %	40.00 %	21.15 %	13.95 %	28.21 %	11.30 %	3.30 %	18.50 %	7.07 %	5.80 %	7.41 %	3.96 %	7.84 %	5.94 %
	94 %	20.89 %	2.36 %	39.98 %	20.97 %	13.89 %	28.08 %	11.21 %	3.14 %	18.29 %	6.76 %	5.47 %	7.09 %	3.80 %	7.53 %	5.62 %
	93 %	20.88 %	2.19 %	39.96 %	20.78 %	13.82 %	27.95 %	11.13 %	2.98 %	18.08 %	6.44 %	5.14 %	6.78 %	3.65 %	7.22 %	5.29 %
	92 %	20.87 %	2.03 %	39.94 %	20.59 %	13.76 %	27.83 %	11.04 %	2.82 %	17.86 %	6.12 %	4.81 %	6.46 %	3.49 %	6.90 %	4.96 %
	91 %	20.86 %	1.86 %	39.93 %	20.40 %	13.69 %	27.70 %	10.95 %	2.66 %	17.65 %	5.81 %	4.48 %	6.15 %	3.34 %	6.59 %	4.63 %
	90 %	20.85 %	1.69 %	39.91 %	20.21 %	13.63 %	27.58 %	10.86 %	2.50 %	17.44 %	5.49 %	4.15 %	5.83 %	3.18 %	6.28 %	4.31 %
	89 %	20.84 %	1.52 %	39.89 %	20.02 %	13.57 %	27.45 %	10.78 %	2.33 %	17.22 %	5.17 %	3.82 %	5.52 %	3.03 %	5.97 %	3.98 %
	88 %	20.83 %	1.36 %	39.87 %	19.83 %	13.50 %	27.33 %	10.69 %	2.17 %	17.01 %	4.85 %	3.49 %	5.21 %	2.87 %	5.66 %	3.65 %
	87 %	20.82 %	1.19 %	39.85 %	19.64 %	13.44 %	27.20 %	10.60 %	2.01 %	16.80 %	4.54 %	3.17 %	4.89 %	2.72 %	5.35 %	3.32 %
	86 %	20.81 %	1.02 %	39.83 %	19.45 %	13.37 %	27.08 %	10.51 %	1.85 %	16.58 %	4.22 %	2.84 %	4.58 %	2.56 %	5.04 %	3.00 %
	85 %	20.80 %	0.85 %	39.82 %	19.26 %	13.31 %	26.95 %	10.43 %	1.69 %	16.37 %	3.90 %	2.51 %	4.26 %	2.41 %	4.73 %	2.67 %
	84 %	20.79 %	0.68 %	39.80 %	19.07 %	13.25 %	26.83 %	10.34 %	1.53 %	16.16 %	3.58 %	2.18 %	3.95 %	2.25 %	4.42 %	2.34 %
	83 %	20.78 %	0.52 %	39.78 %	18.88 %	13.18 %	26.70 %	10.25 %	1.37 %	15.94 %	3.27 %	1.85 %	3.63 %	2.10 %	4.11 %	2.01 %
	82 %	20.77 %	0.35 %	39.76 %	18.69 %	13.12 %	26.58 %	10.16 %	1.21 %	15.73 %	2.95 %	1.52 %	3.32 %	1.94 %	3.80 %	1.69 %
	81 %	20.77 %	0.18 %	39.74 %	18.50 %	13.05 %	26.45 %	10.08 %	1.05 %	15.52 %	2.63 %	1.19 %	3.01 %	1.79 %	3.49 %	1.36 %
	80 %	20.76 %	0.01 %	39.73 %	18.32 %	12.99 %	26.33 %	9.99 %	0.89 %	15.30 %	2.32 %	0.86 %	2.69 %	1.63 %	3.18 %	1.03 %
	79 %	20.75 %	-0.15 %	39.71 %	18.13 %	12.93 %	26.20 %	9.90 %	0.73 %	15.09 %	2.00 %	0.53 %	2.38 %	1.48 %	2.87 %	0.70 %
	78 %	20.74 %	-0.32 %	39.69 %	17.94 %	12.86 %	26.07 %	9.81 %	0.57 %	14.88 %	1.68 %	0.21 %	2.06 %	1.32 %	2.56 %	0.38 %
	77 %	20.73 %	-0.49 %	39.67 %	17.75 %	12.80 %	25.95 %	9.73 %	0.41 %	14.66 %	1.36 %	-0.12 %	1.75 %	1.17 %	2.25 %	0.05 %
	76 %	20.72 %	-0.66 %	39.65 %	17.56 %	12.73 %	25.82 %	9.64 %	0.24 %	14.45 %	1.05 %	-0.45 %	1.43 %	1.01 %	1.94 %	-0.28 %
	75 %	20.71 %	-0.83 %	39.63 %	17.37 %	12.67 %	25.70 %	9.55 %	0.08 %	14.24 %	0.73 %	-0.78 %	1.12 %	0.86 %	1.63 %	-0.61 %
	74 %	20.70 %	-0.99 %	39.62 %	17.18 %	12.61 %	25.57 %	9.46 %	-0.08 %	14.03 %	0.41 %	-1.11 %	0.81 %	0.70 %	1.32 %	-0.93 %
	73 %	20.69 %	-1.16 %	39.60 %	16.99 %	12.54 %	25.45 %	9.38 %	-0.24 %	13.81 %	0.10 %	-1.44 %	0.49 %	0.55 %	1.01 %	-1.26 %
	72 %	20.68 %	-1.33 %	39.58 %	16.80 %	12.48 %	25.32 %	9.29 %	-0.40 %	13.60 %	-0.22 %	-1.77 %	0.18 %	0.39 %	0.70 %	-1.59 %
	71 %	20.67 %	-1.50 %	39.56 %	16.61 %	12.41 %	25.20 %	9.20 %	-0.56 %	13.39 %	-0.54 %	-2.10 %	-0.14 %	0.24 %	0.39 %	-1.92 %
	70 %	20.66 %	-1.66 %	39.54 %	16.42 %	12.35 %	25.07 %	9.11 %	-0.72 %	13.17 %	-0.86 %	-2.43 %	-0.45 %	0.08 %	0.08 %	-2.24 %





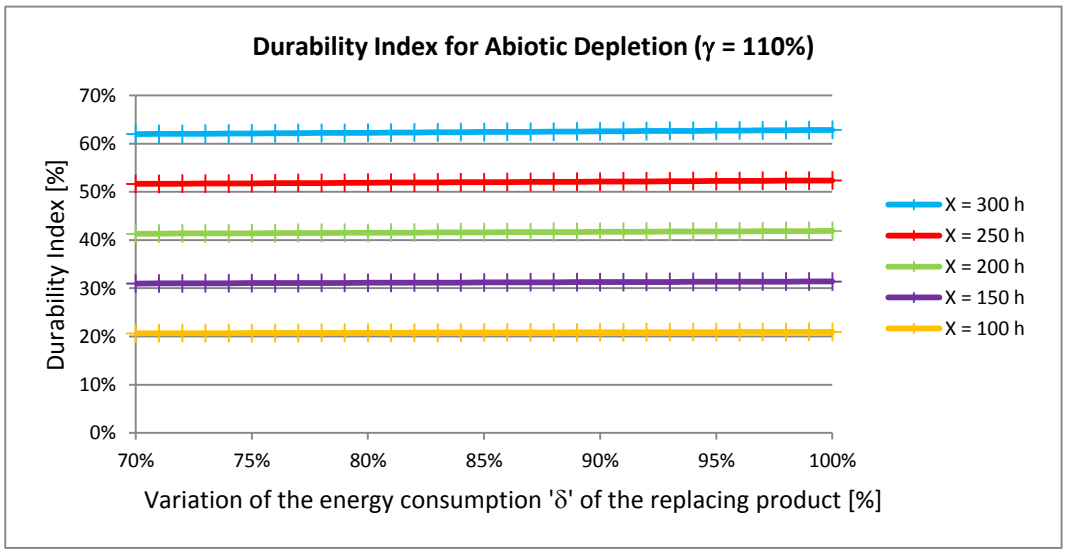
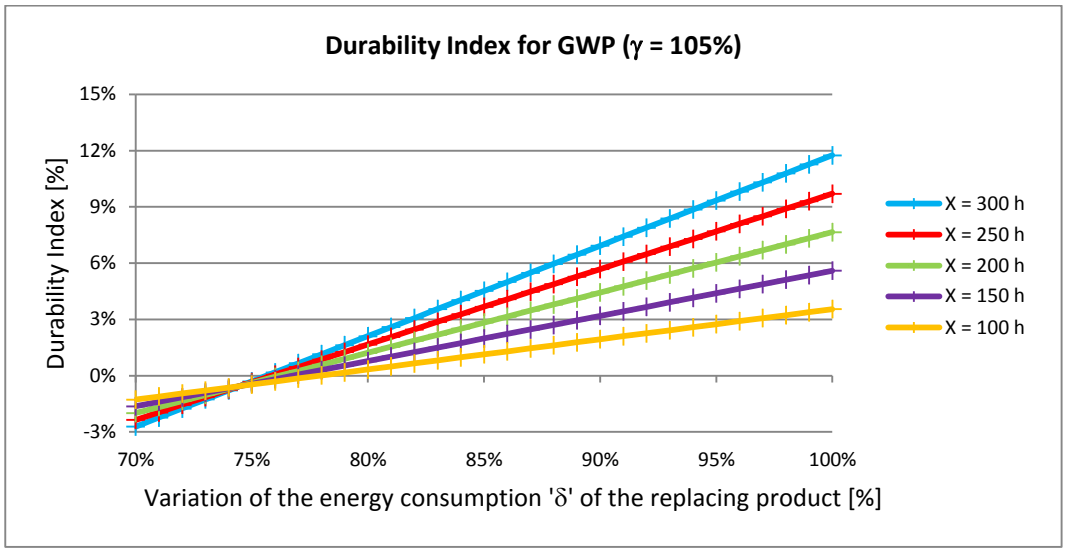
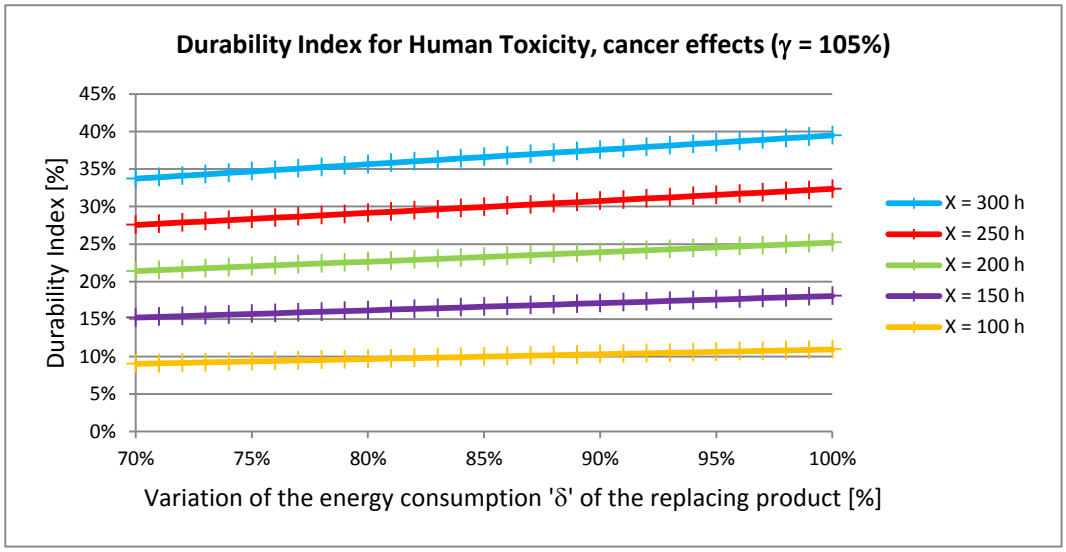


Figure 31: Durability index for the canister vacuum cleaner (LRS scenario)





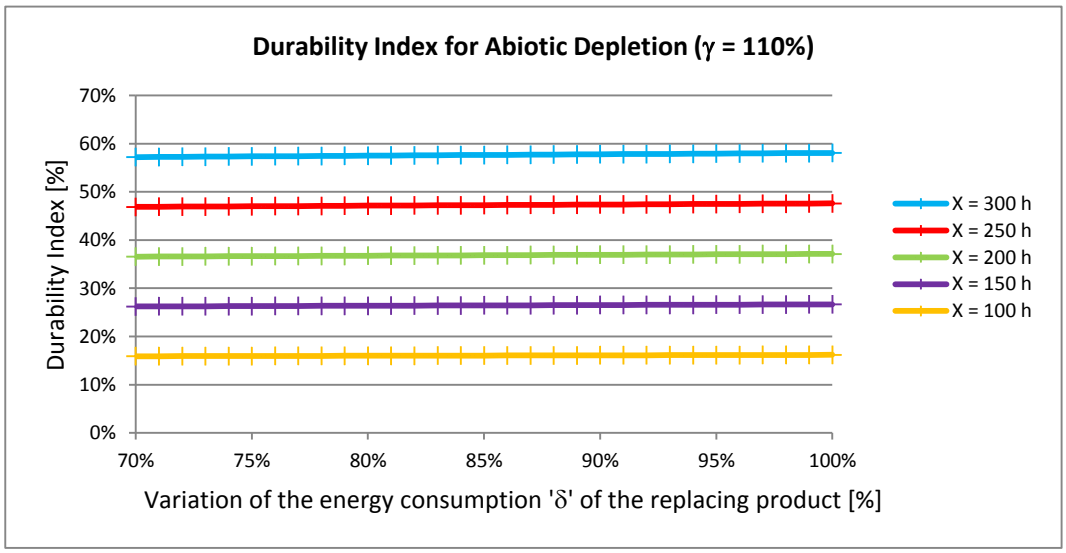
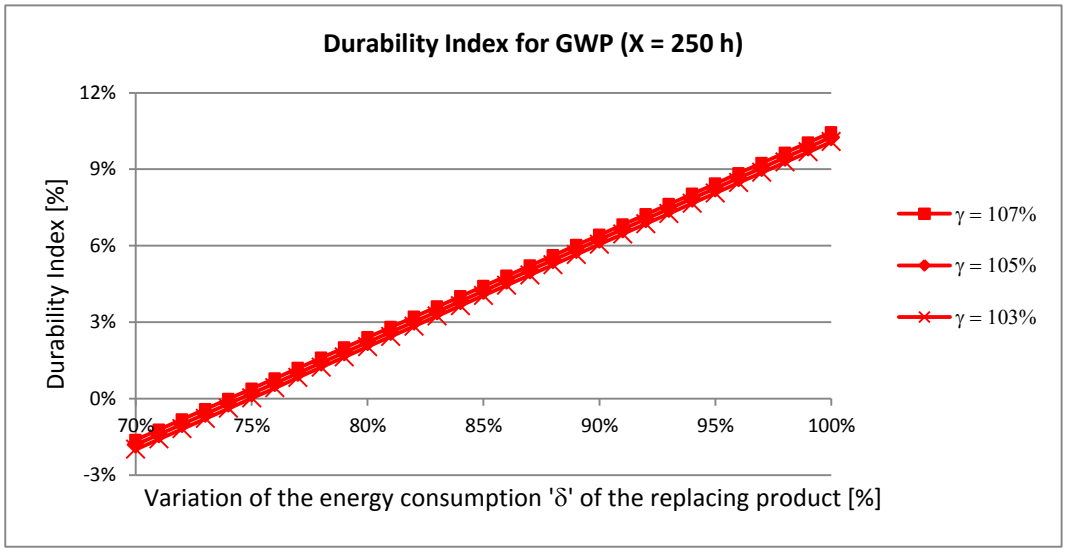


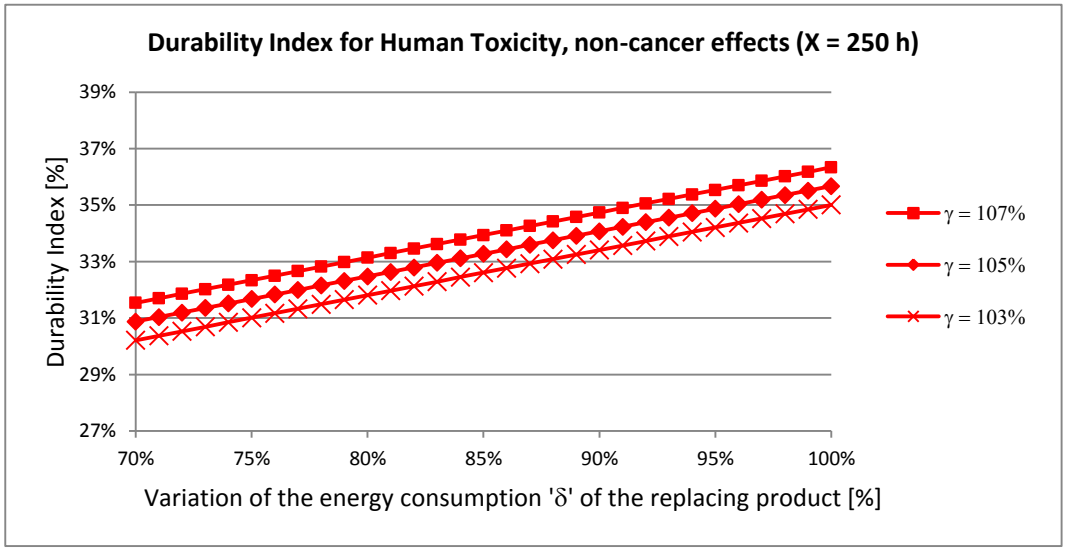
Figure 32: Durability index for the canister vacuum cleaner (HRS scenario)

5.3.1. Sensitivity analysis

With the aim of assessing the influence due to the variation of the manufacturing impacts associated to the replacing product (B) compared to the manufacturing impact of the product (A), the parameter γ in Formula 4 was varied between 103 % and 107 % for all the impact categories except for Abiotic Depletion, for which the γ–range is between 105 % and 115 %. The results in Figure 33 are illustrated for a lifetime extension of 250 h. It is observed that, considering the higher impacts of the replacing product, the benefits are increasing, particularly for those categories dominated by the manufacturing phase. The greatest variation is noticed for the Abiotic Depletion: a value of $\gamma = 115$ % implies about 5 % additional benefits respect to $\gamma = 105$ %.

Note that the Durability Index has been calculated for all the selected 15 impact categories. All the results are reported in ANNEX 3.





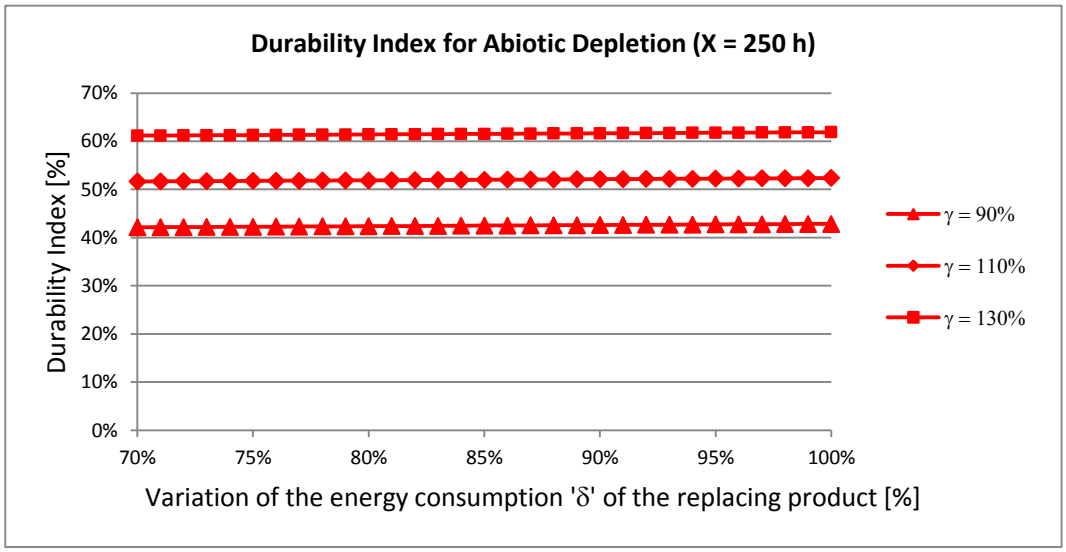


Figure 33: Durability Index for the canister vacuum cleaner on varying γ-values (LRS scenario)

5.3.2. Revision of the method: additional impacts of durable product

The design of more durable products may imply additional burdens, as illustrated in section 5.1.2. According to this more comprehensive scenario, the Durability Index have been calculated considering an additional percentage of impacts necessary to make product (A) more durable. This additional impacts could be related to e.g. higher amounts of materials (or the use of higher quality materials). This aspect is accounted through the parameter 'α' (see Formula 7). Considering the hypothesis illustrated within the Preparatory study ([85]), a higher mass of materials have been considered ([86]). It is observed that this increase in terms of input mass does not considerably affect the LCIA of the VC. The greatest variations correspond to the Human toxicity cancer effects (+ 7.49 % compared to the base-case VC), while an increase lower than 1.5 % compared to the base-case VC has been observed for the following impact categories: ADP_{res}, Acidification, Ecotoxicity for aquatic fresh water, Ionising radiation, Ozone depletion, Particulate matter and Total freshwater consumption.

For the calculation of the Durability Index in this new scenario (Formula 9), it was assumed that the parameter α varies within the following ranges:

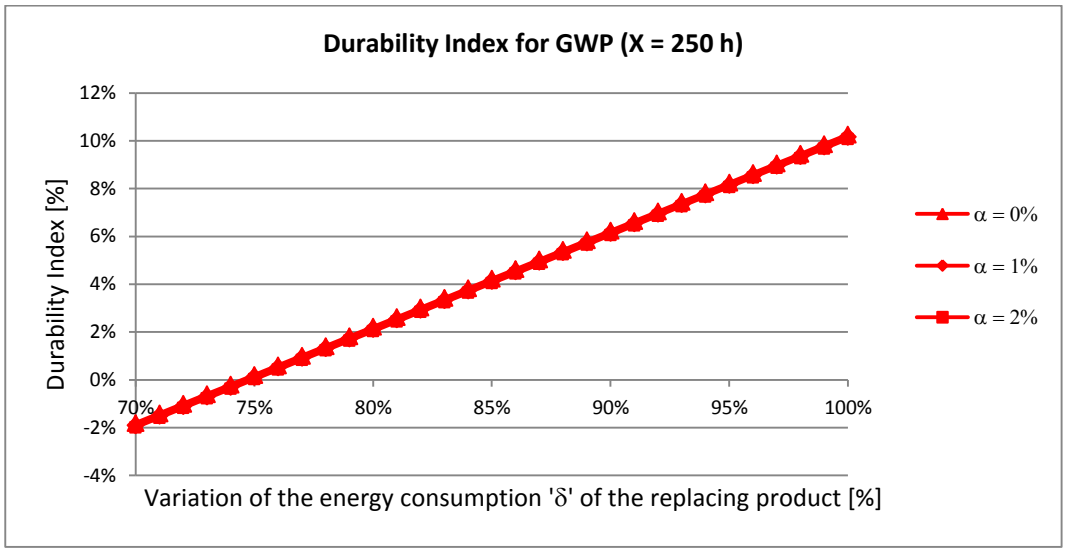
- 3 % < α < 5 % for Abiotic Depletion;
- 5 % < α < 7 % for Human Toxicity (cancer effects);
- α < 3 % for GWP.

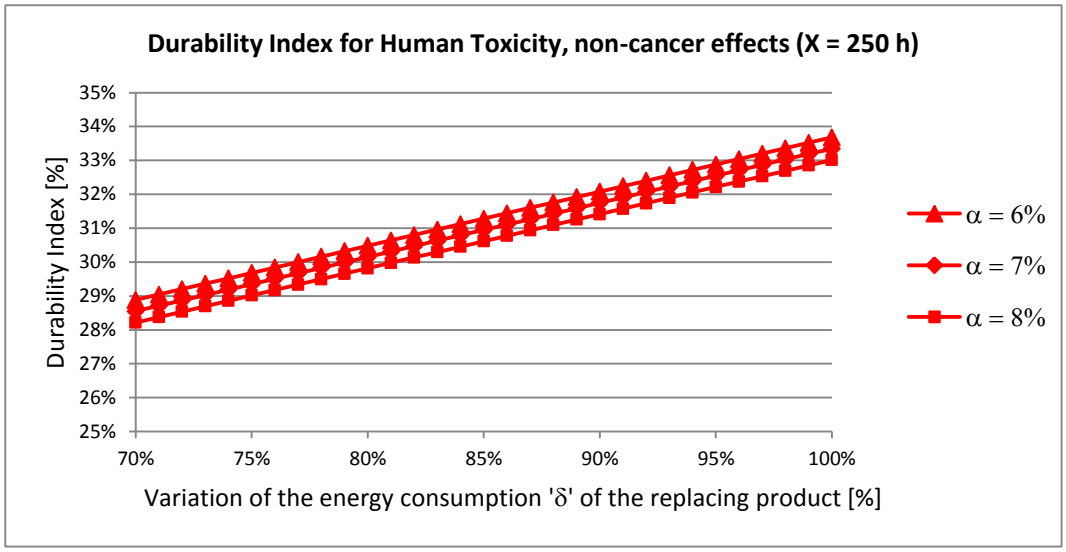
Considering the higher impacts for more durable products, the environmental benefits are decreasing for all the assessed impact categories. However, these differences do not significantly affect the values of the durability index. For instance Figure 34 illustrates the values of the Durability index for the three impact categories for a lifetime extension of 250 h. The greater variation corresponds to the ADP_{res} impact category: for α = 5 %, benefits are around 1 % lower than the benefits corresponding to α = 0 % (independently from the considered value of δ).

Under these assumptions, it can be concluded that additional impacts due to the manufacturing of more durable products do not significantly affect the benefits of extending the lifetime of the VC.

([85]) The 'increased product lifetime' option (i.e. option 8) considered by the Preparatory Study assumed that 'increased weights of materials to strengthen items' could be plausible for those product having a longer lifetime.

([86]) The Preparatory study does not provide details on the assumption for extra materials needed for durable products. In the present study it has been assumed that more durable hose, canister casing, nozzle and wheels would require up to 20 % more mass than the base-case scenario and motor and cables would require up to 5 % more mass than the base-case scenario (see section 4.2.1).





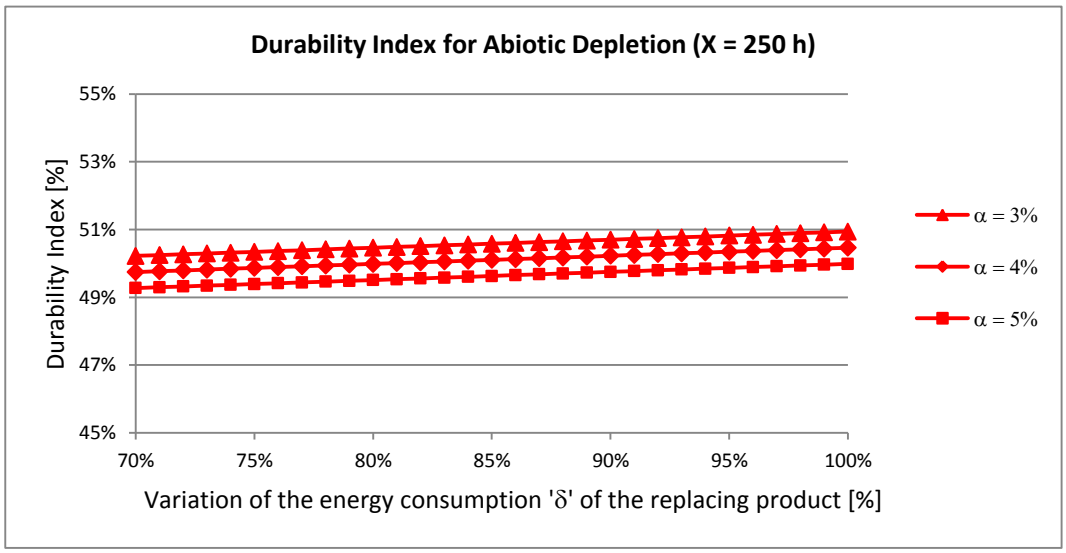


Figure 34: Durability Index for the canister vacuum cleaner by varying α-values (LRS scenario)

CHAPTER 6
Durability assessment through Ecoreport Tool

The previous sections illustrated the environmental assessment of durability of VCs, based on the results of the LCA performed via a common software in use by the scientific community. This chapter presents the assessment of durability based on the results of the Ecoreport tool ([87]) as developed within the 'Methodology for Ecodesign of Energy-related Products'. In particular, the version 3.06 as modified in 2013 has been used to take into account the lifetime parameter [BIO Intelligence Service (2013a)].

The Ecoreport tool gives the possibility to calculate the environmental impacts of products by using a database including 43 materials and 12 components (split into 7 categories). It also allows the adding of extra materials not available in the database (BIO Intelligence Service 2013d).

As a first step input data used for the LCA of the case-study VC (as illustrated in section 4.2) have been implemented in the Ecoreport tool, and results have been compared with the LCIA results (section 3.5). Note that, since not all the input materials were available in the tool, some extra materials have been inserted ad hoc; this is the case of (BMC-GF) and POM (used in the manufacturing of canister case and motor parts). Concerning the maintenance, the Ecoreport tool models the use of dust-bags as auxiliary materials, but not the filters; thus, these have been inserted among the input materials list as part of the manufacturing.

The EoL scenario has been modelled similarly to what illustrated in section 3.3.4 and ANNEX 1. The Ecoreport tool model the EoL of materials according to macro-groups ([88]) and not by product component. Therefore it was not possible to differentiate the EoL scenario for each material. For the present analysis it was considered an average 'recycling rate' for the materials belonging to a specific group ([89]).

The results obtained with the Ecoreport tool are illustrated in Table 33. These results refer to the life-cycle of a vacuum cleaner with a lifetime of 500 hours. The Ecoreport tool also allowed to calculate the 'Life-cycle Impact per product per year of use' obtained as illustrated in Table 34 (calculated as the 'Life-cycle Impact per product' divided by the number of years of lifetime).

([87]) The Ecoreport tool is available at http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/methodology/index_en.htm (accessed March 2015).

([88]) For example, plastics are grouped into Bulk plastics and Tec Plastic.

([89]) For example, for bulk plastics, it was calculated a recycling rate as average of the amount of recycled LD-PE, HD-PE, LLD-PE, PP, PS, EPS, HI-PS, PVC, SAN, PET, ABS.

Table 33: LC Impact assessment of the canister vacuum cleaner (results refer to the overall product lifetime) — Ecoreport tool

	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**4.244,17**		**42,44**	0,00	0,00	0,00	**4.286,61**
2	TecPlastics	g			**0,00**		**0,00**	0,00	0,00	0,00	**0,00**
3	Ferro	g			**981,50**		**9,82**	49,57	941,75	0,00	**0,00**
4	Non-ferro	g			**383,34**		**3,83**	19,36	367,81	0,00	**0,00**
5	Coating	g			**0,00**		**0,00**	0,00	0,00	0,00	**0,00**
6	Electronics	g			**12,00**		**0,12**	0,00	0,00	0,00	**12,12**
7	Misc.	g			**1.200,00**		**12,00**	0,00	0,00	0,00	**1.212,00**
8	Extra	g			**309,00**		**0,00**	0,00	0,00	0,00	**309,00**
9	Auxiliaries	g			**0,00**		**2.800,00**	0,00	0,00	0,00	**2.800,00**
10	Refrigerant	g			**0,00**		**0,00**	0,00	0,00	0,00	**0,00**
	Total weight	g			**7.130,00**		**2.868,21**	68,92	1.309,56	0,00	**8.619,73**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	487,60	179,05	**666,66**	**168,06**	**2.301,35**	0,22	-24,29		**3.111,99**
12	of which, electricity (in primary MJ)	MJ	36,78	106,84	**143,62**	**0,14**	**2.253,16**	0,00	-0,06		**2.396,86**
13	Water (process)	ltr	1.206,30	1,75	**1.208,05**	**0,00**	**12,06**	0,00	-0,59		**1.219,53**
14	Water (cooling)	ltr	27.828,06	50,75	**27.878,81**	**0,00**	**378,28**	0,00	-1,36		**28.255,74**
15	Waste, non-haz./ landfill	g	768,19	561,33	**1.329,52**	**134,92**	**1.275,43**	4,18	-140,64		**2.603,41**
16	Waste, hazardous/ incinerated	g	55,45	0,05	**55,50**	**2,68**	**36,12**	0,00	-0,06		**94,23**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	17,71	9,96	**27,67**	**12,20**	**98,95**	0,00	-1,48		**137,35**
18	Acidification, emissions	g SO2 eq.	153,09	43,07	**196,17**	**36,12**	**436,15**	0,04	-33,00		**635,47**
19	Volatile Organic Compounds (VOC)	g	202,47	0,04	**202,51**	**1,09**	**52,28**	0,00	-0,05		**255,83**
20	Persistent Organic Pollutants (POP)	ng i-Teq	8,42	0,29	**8,71**	**0,76**	**5,35**	0,00	-3,18		**11,65**
21	Heavy Metals	mg Ni eq.	18,92	0,68	**19,60**	**6,87**	**22,99**	0,02	-7,01		**42,47**
22	PAHs	mg Ni eq.	16,50	0,09	**16,59**	**4,83**	**5,42**	0,00	-4,24		**22,60**
23	Particulate Matter (PM, dust)	g	26,88	6,73	**33,61**	**164,63**	**9,28**	0,07	-6,14		**201,46**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	21,57	0,02	**21,59**	**0,21**	**9,92**	0,00	-5,63		**26,10**
25	Eutrophication	g PO4	2,88	0,11	**2,99**	**0,00**	**1,36**	0,00	-0,03		**4,33**

Table 34: LC Impact assessment of the canister vacuum cleaner (impacts refer to 1-year of use) — Ecoreport tool

	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE*			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**424**		**4**	0	0	0	**429**
2	TecPlastics	g			**0**		**0**	0	0	0	**0**
3	Ferro	g			**98**		**1**	5	94	0	**0**
4	Non-ferro	g			**38**		**0**	2	37	0	**0**
5	Coating	g			**0**		**0**	0	0	0	**0**
6	Electronics	g			**1**		**0**	0	0	0	**1**
7	Misc.	g			**120**		**1**	0	0	0	**121**
8	Extra	g			**31**		**0**	0	0	0	**31**
9	Auxiliaries	g			**0**		**280**	0	0	0	**280**
10	Refrigerant	g			**0**		**0**	0	0	0	**0**
	Total weight	g			**713**		**287**	7	131	0	**862**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	49	18	**67**	**17**	**230**	0	-2		**311**
12	of which, electricity (in primary MJ)	MJ	4	11	**14**	**0**	**225**	0	0		**240**
13	Water (process)	ltr	121	0	**121**	**0**	**1**	0	0		**122**
14	Water (cooling)	ltr	2.783	5	2.788	0	38	0	0		**2.826**
15	Waste, non-haz./ landfill	g	77	56	**133**	**13**	**128**	0	-14		**260**
16	Waste, hazardous/ incinerated	g	6	0	**6**	**0**	**4**	0	0		**9**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	2	1	**3**	**1**	**10**	0	0		**14**
18	Acidification, emissions	g SO2 eq.	15	4	**20**	**4**	**44**	0	-3		**64**
19	Volatile Organic Compounds (VOC)	g	20	0	**20**	**0**	**5**	0	0		**26**
20	Persistent Organic Pollutants (POP)	ng i-Teq	1	0	**1**	**0**	**1**	0	0		**1**
21	Heavy Metals	mg Ni eq.	2	0	**2**	**1**	**2**	0	-1		**4**
22	PAHs	mg Ni eq.	2	0	**2**	**0**	**1**	0	0		**2**
23	Particulate Matter (PM, dust)	g	3	1	**3**	**16**	**1**	0	-1		**20**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	2	0	**2**	**0**	**1**	0	-1		**3**
25	Eutrophication	g PO4	0	0	**0**	**0**	**0**	0	0		**0**

The results show that the manufacturing and use phase have a high contribution to almost all the impact categories considered. The EoL and the distribution (i.e. packaging) can be considered as negligible, except for the Particulate Matter's impact category (Figure 35).

It was also noticed that the impacts due to the distribution seems not being affected by the values in the cell '*No. of km over Product-Life*'. On the other hand, impacts due to distribution seem to be solely dependent on the volume of the packaging. Therefore it was not possible to model the impacts due to transport as previously done in the LCE software (e.g. by defining the transport distance and type of vehicle).

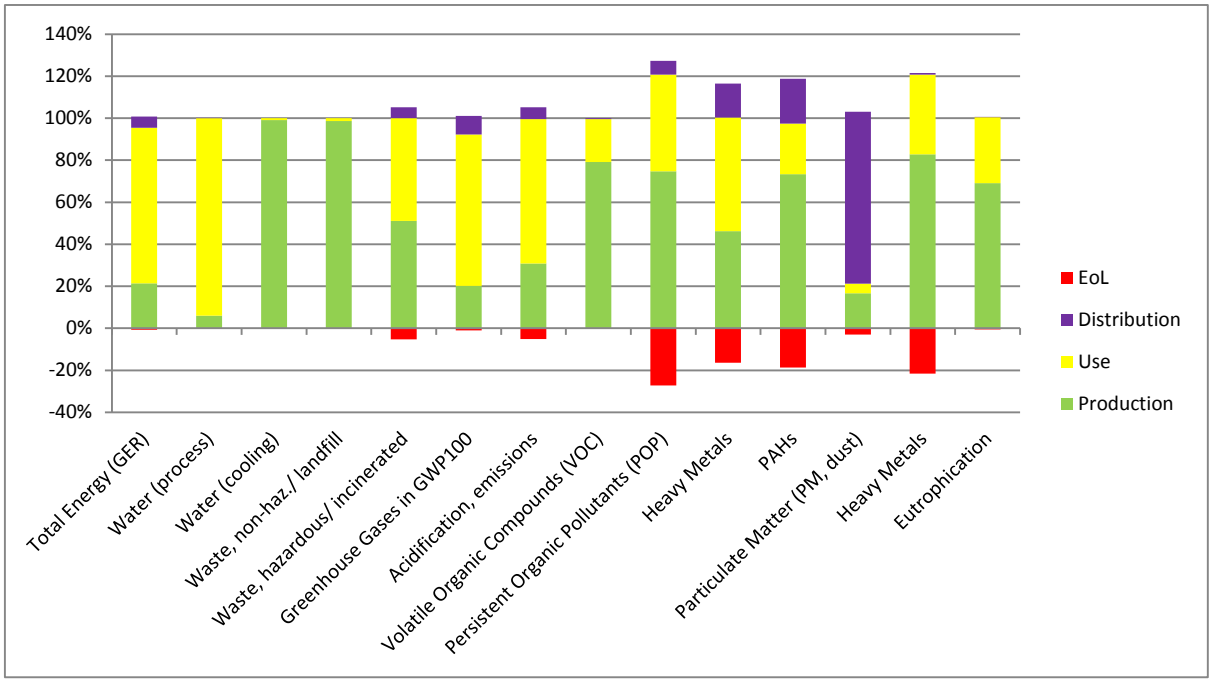


Figure 35: Percentage contribution to the overall impact of the canister vacuum cleaner LC phases (Ecoreport tool)

In order to compare results from the different tools (impact categories have to be consistent). Therefore it has been carried out an analysis of which impact categories, among those commonly implemented into software for the LCA, can be consistent with the categories used by the Ecoreport tool ([90]). The results of this consistency check are showed in Table 35. However, for some of the impact categories available in the Ecoreport tool it was not possible to identify an analogous category in the LCA software. In this case, the impact category has been not considered for the next step of the analysis.

([90]) A detail of the impact categories used in the Ecoreport tool is available in (Kemna 2011b; Kenma et al. 2005; Kemna 2011a).

Table 35: LC Impact assessment of the canister vacuum cleaner

Impact category (Ecoreport Tool)	Unit of Measure	Impact category (LCA software)	Unit of Measure	Comments
Total Energy (GER)	[MJ]	Primary energy demand from non ren. resources (gross cal. value)	[MJ]	Methods are consistent
Water (process)	[l]	Inventory water flow	[l]	The Ecoreport category refers to water from public grid, 'used in a process and then usually disposed off through the sewage system or as vapor air'. Hence, the total amount of life-cycle water flows used within the system boundaries has been considered for the comparison.
Water (cooling)	[l]	-	-	The Ecoreport category refers to 'water from a nearby river that is used to cool an oven or another process and then returned to the same river'. As the disaggregation of the cooling water from the results by the LCA software is difficult, this comparison has been not performed.
Waste, non-haz / landfill	[g]	-	-	Since there are no impact categories available in the LCA software related to waste, this comparison has been not performed.
Waste, hazardous / incinerated	[g]	-	-	
Greenhouse Gases in GWP100	[kg CO_2 eq.]	ILCD/PEF Recommendation — IPCC global warming, excl biogenic carbon	[kg $CO_{2\ Equiv.}$]	Methods are consistent
Acidification, emissions	[g SO_2 eq.]	CML2001 — Apr. 2013, Acidification Potential (AP)	[kg $SO_{2\ eq}$]	For the comparison it has been selected the *CML2001 Acidification Potential (AP)* because both are based on the same units of measure.
Volatile Organic Compounds	[g $_{VOC}$]	ReCiPe 1.08 Midpoint (H) — Photochemical oxidant formation	[kg NMVOC]	The Ecoreport tool accounts for the amount of Non-Methane VOC emitted, without characterization factors (Kemna 2011a; Kemna 2011b). For the comparison it was decided to use both the ReCiPe method and also the quantity of 'NMVOC to air' as contained in the life-cycle inventory.
		Inventory NMVOC to air	[kg NMVOC]	
Persistent Organic Pollutants (POP)	[ng i-T_{eq}]	-	-	The environmental assessment of persistent organic pollutants (POPs) in the Ecoreport tool is expressed as the total concentration equivalent of tetrachlorodibenzodioxin (ng i-Teq). No impact has been identified in the LCA software that accounts the impacts POPs with the same unit of measure.
Heavy Metals	[mg Ni $_{eq.}$]	-	-	The MEEUP method made a subdivision of organic toxins (as carcinogenic PAHs, CO and benzene) and the real metals (Cd, Hg, As, Cu, Cr, Pb and Zn) measured with the same unit of measure is (Ni equivalent). No impact has been identified in the LCA software that accounts PAHs and HMs with the same unit of measure.
PAHs	[mg Ni $_{eq.}$]	-	-	
Particulate Matter	[g $_{PM,\ dust}$]	ReCiPe 1.07 Midpoint (H) — Particulate matter formation	[kg PM10 $_{eq}$]	The MEErP indicator is PM 10 equivalent, and the characterisation factors used are 2 for PM2, and 1 for PM10 and for PM in general. For the comparison it has been selected the *ReCiPe 1.08 Midpoint (H) — Particulate matter formation* impact category (in this method, the characterization factor of PM2.5 is the same as for PM10, equal to 1).
Eutrophication	[g $_{PO4}$]	CML2001 — Apr. 2013, Eutrophication Potential (EP)	[kg Phosphate $_{Equiv.}$]	The *CML Eutrophication Potential (EP)* impact category was used as a reference by MEEUP report for creating the characterization factors for emissions to water.

Comparison of results from the LCA software and those from the Ecoreport tool for the selected impact category is showed in Table 36. It is noticed that impacts from the Ecoreport tool are generally lower, except for the Total Energy and the Volatile Organic Compounds.

Note that for the GER and GWP the difference doesn't exceed 10 %, while the most relevant differences correspond to 'water (process)' and 'eutrophication'. For other impact categories, the divergence of results is much higher.

Concerning VOC and water consumption the environmental impact calculated by the Ecoreport tool are much lower than the chosen impact category for the comparison.

It is worth to note that the extra materials added into the Ecoreport tool, such as the glass fibre (BMC-GF) and the polyoxymethylene (POM) ([91]), have a high contribution to 'water (process)' and to VOC emissions.

6.1. Analysis of durability with results from Ecoreport tool

Based on these considerations, the durability index has been calculated only concerning the GWP impact category. Note that the impacts associated to the LRS have been calculated as the difference between the LCIA results illustrated in

Table 37 and the LCIA results calculated without filters as input. The Ecoreport tool also includes the potential environmental credits for the recycling of VC at the EoL. These credits have been not considered for the calculation of the Durability Index, consistently with formulas illustrated in Chapter 5. Input data for the calculation of the Durability Index are illustrated in

Table 38.

The values of the Durability Index 'D_n' (Figure 36 and Figure 37) resulted very similar to those obtained in chapter 5.3. In particular, the estimated environmental benefits due to the lifetime extension of VC as calculated with values of the Ecoreport tool are slightly higher than those illustrated in the previous chapters, whatever lifetime extension is assumed. For instance, in the analysis in section 5.3 it was estimated that the extension of the lifetime of the vacuum cleaner by 100 h in the LRS scenario would reduce the GWP of 1.69 % ([92]). Calculating the Durability Index with the Ecoreport tool under the same assumptions it results that the benefit in terms of GWP reduction is 3.7 %.

Similarly to the results in section 5.3, the variation between the LRS and the HRS is not relevant, as the GWP impact category is not largely influenced by impacts of repair.

([91]) Impacts of (BMC-GF) have been modelled as illustrated in section 4.2 and ANNEX 1.
([92]) Value calculated compared to the replacement of the old product with a new one 15 % more efficient.

Table 36: Difference between the life-cycle impacts obtained by the Ecoreport Tool 2013 and those calculated by an LCA software with the impact categories selected in Table 35

Impact category	Impacts from Ecoreport tool	LCIA obtained via LCA software	Variation ([93])
Total Energy (GER)	3 112[MJ]	2,923 [MJ]	6.07 %
Water (process)	1 219.5 [l]	451,336 [l]	-36.909 %
Greenhouse Gases in GWP100	137.3 [kg CO_2 eq.]	149.3 [kg CO_2 eq.]	-8.7 %
Acidification, emissions	0.64 [kg SO_2 eq.]	0.71 [kg SO_2 eq.]	-11.3 %
Volatile Organic Compounds (VOC)	0.26 [kg $_{VOC}$]	0.32 [kg NMVOC]	-24.46 %
		0.03 [kg NMVOC]	87.18 %
Particulate Matter (PM, dust)	0.20 [kg $_{PM, dust}$]	0.17 [kg PM10 $_{eq}$]	-13.48 %
Eutrophication	4.33E-03 [kg $_{PO4}$]	4.35E-02 [kg Phosphate $_{Equiv.}$]	-904.34 %

Table 37: Summary of the assumptions for the calculation of the Durability Index — Ecoreport tool 2013

Product 'A'			
Average operating time	T_A	[hours]	500
Yearly energy consumption until 500 hours		[kWh/y]	25
Extension of the lifetime	X	[hours]	0 → 300
Product 'B'			
Variation of the manufacturing impact of product 'B' compared to 'A'	γ	[%]	γ = 105 %
Variation of the energy consumption impact of product 'B' compared to 'A'	δ	[%]	70 %< δ < 100 %

Table 38: Life-cycle impacts of canister vacuum cleaner for the calculation of the Durability Index 'D_n' (as derived from the Ecoreport tool 2013)

	GWP 100	
$P_{A,n}$	3.92E+01 [kg CO2-Equiv.]	
E_n	-1.48E+00 [kg CO2-Equiv.]	
$U_{A,n}$	1.92E-01 [kg CO2-Equiv./hour]	
$R_{A,n}$	LRS	0.00E+00
	HRS	1.18E+00

([93]) Calculated as: (Ecoreport — LCIA)/ Ecoreport [%].

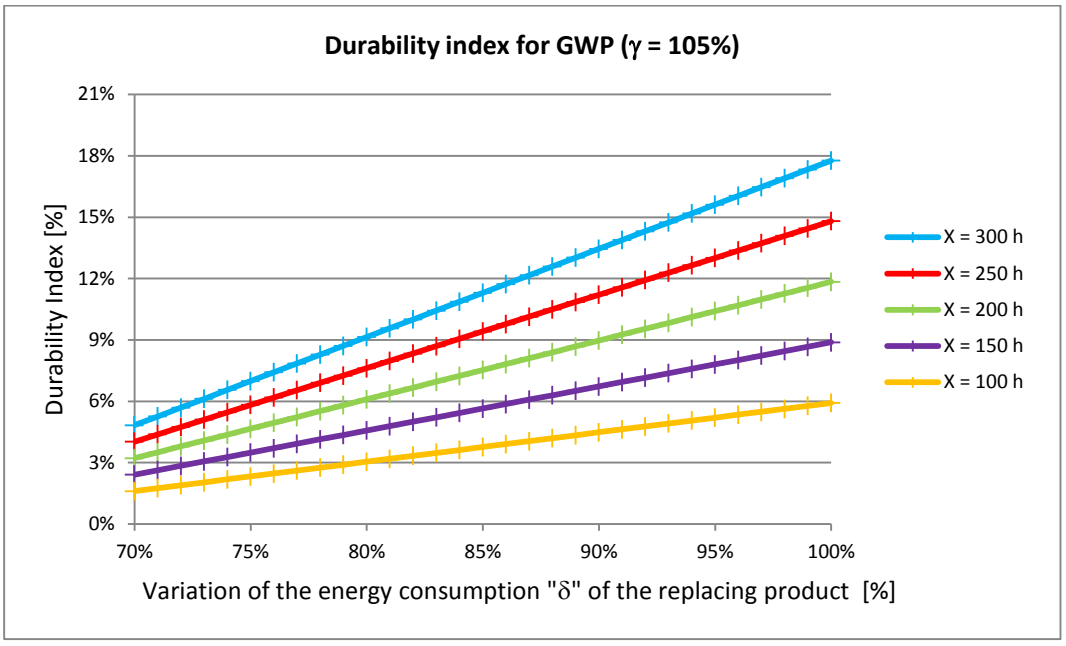


Figure 36: Durability index for the canister vacuum cleaner (LRS scenario), Ecoreport tool

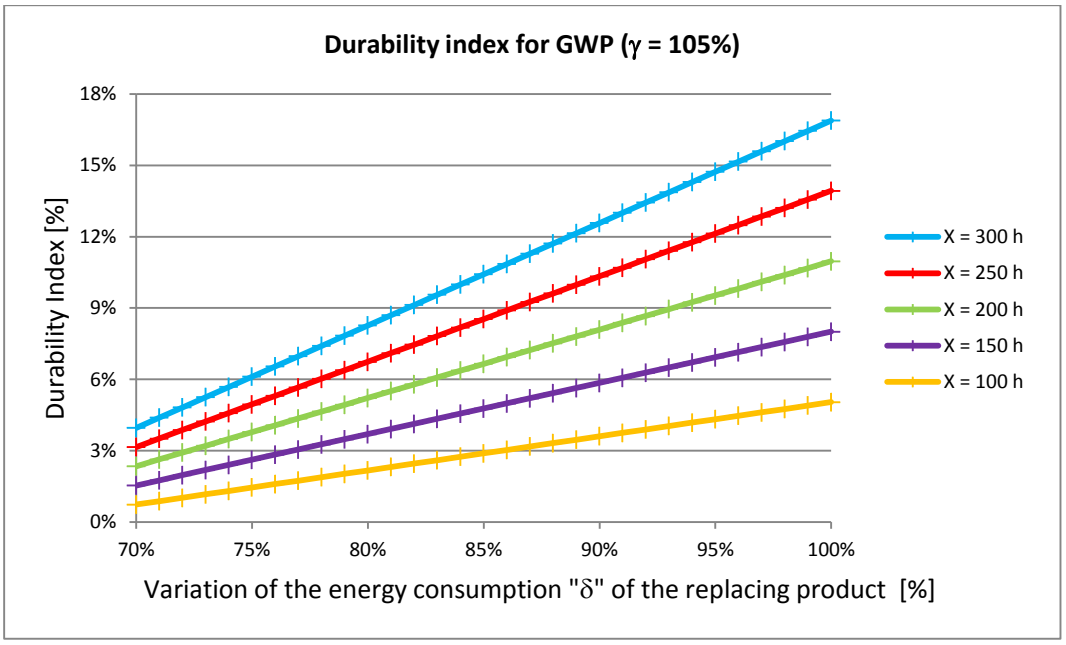


Figure 37: Durability Index for the canister vacuum cleaner (HRS scenario), Ecoreport tool

6.2. Concluding remarks

In conclusion, the analysis performed in the present chapter illustrate that the durability index as developed in (Ardente & Mathieux 2012) and revised in the current report can be implemented/calculated with the values derived from the Ecoreport tool, although some difficulties and limitations occurred (mainly related to the modelling of maintenance and repair, which are relevant for the durability assessment).

The results values of the Durability Index as calculated via the Ecoreport tool and LCA software were very similar for the GWP impact category. The comparison was not performed for other impact categories. In particular, the analysis highlighted that the Ecoreport tool uses impact categories that are generally not consistent with those used by common LCA software. This aspect causes some problems when introducing 'extra materials' into the Ecoreport tool database. This aspect has been previously evidenced in the literature also by BIO Intelligence Service (2013a).

It is finally highlighted that the Ecoreport tool 2013 calculate, compared to the previous tool's versions, the additional table about the environmental 'impact per year of use'. These correspond to the impacts of the life-cycle divided by the lifetime (years) of the product. However, it is not immediately possible to model via the Ecoreport tool particular events occurring in a specific year (e.g. a precise repair operation) as the corresponding impact will be spread out over all the years of use. These results per year, although relevant for other purposes, cannot be used for the assessment of the Durability Index.

CHAPTER 7
Economic assessment of durability issues

The acquisition, operating and maintenance costs of household appliances strongly influence the user decision regarding the substitutions or, instead, their maintenance/repair to prolong their durability. This chapter presents a method to assess the life-cycle costs and/or benefits of using more durable energy using products compared to their substitution with more energy efficient ones. The proposed method follows an approach similar to that one employed for the environmental assessment of durability of products (Ardente & Mathieux 2012).

In order to compare the life-cycle costs of these options, two scenarios are considered (Figure 38).

The first scenario assumes that the product (A) is used for a certain lifetime (T_A), and afterward it is supposed to be replaced by a new product (B) with the same functions. The new product is supposed to be more energy efficient, i.e. with lower energy consumption. Lower energy consumption results in lower energy cost during the use phase, depending on the costs of the electricity.

The second scenario (Durability Scenario) considers the extension of the lifetime of the product (A) from the base-case scenario ($T'_A = T_A + X$, where X represents the extension of the lifetime). This scenario can include some additional expenditure (R) for extraordinary maintenance and repairing to prolong the lifetime.

The aim of the analysis is to compare the overall costs of the two scenarios and to assess if one scenario is preferable than the other under different assumptions. Therefore the difference between the costs in the two scenarios has been calculated. Successively the sensitivity analysis of the key parameters is assessed.

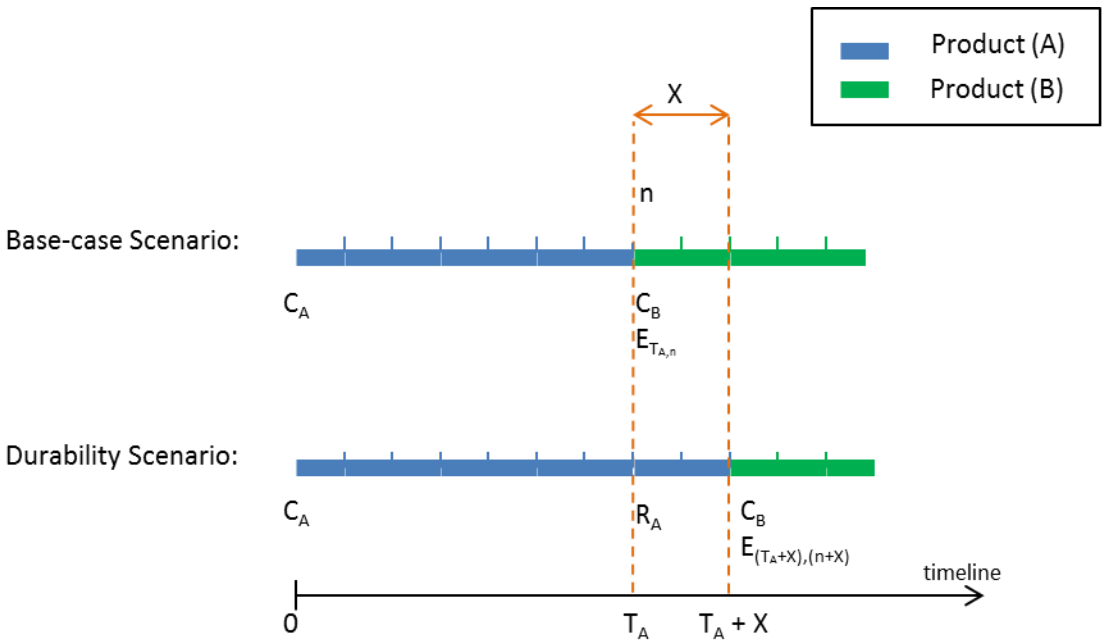


Figure 38: Setting of scenarios to be compared in the assessment of durability

The time frame for the economic assessment of durability is set from the time 0 (starting of the use of product A) up the time 'T_A + X'. Thus, the expenditure occurring every year, as well as the purchase price of product (B), the maintenance of both products (M_A and M_B), and the repair costs should be discounted (using discount rate (i) ([94])) in order to evaluate their present value (PV) ([95]).

In the base-case Scenario, the purchase price of the new product have to be distributed proportionally to the average operating time of product (B) (T_B); this is related to the fact that products are used for more than one year and it facilitates the comparison of the two scenarios. This way, it is possible to consider the product acquisition and maintenance costs also during the extension of the lifetime.

The economic analysis is performed at the design stage of products. Therefore there are various uncertainties (due to lack of data, prices variability, long lifetime of products, etc.) for some of the above-mentioned cost items.

The equations settled for the two scenarios are illustrated in Formula 11 and

Formula 12:

Formula 11: Base-case scenario:

$$C_{TOT,base\ case} = C_A + \sum_{t=1}^{T_A} [\mathrm{PVF}_{t_B,i}(E_{A_t} + M_{A_t} + A_{A_t})] + (\mathrm{PVF}_{t,i} C_B) \cdot \frac{\mathrm{X}}{T_B} + \sum_{t=1}^{X} [\mathrm{PVF}_{t_B,i}(E_{B_t} + M_{B_t} + A_{B_t})]$$

Where:

- PVF = Present Value Factor of the cash flow stream considered [-];
- i = Discount rate [%];
- t = Generic period of time for which the cost is calculated [y]
- C_A = Acquisition costs of the product A [€];
- T_A = Operating lifetime of product A [h];
- E_A = Operating costs associated to the product (A) [€/y];
- M_A =Maintenance costs associated to the product (A) [€/y];
- A_A = Auxiliaries components costs associated to the product (A) [€/y];
- C_B = Acquisition costs of the product (B) [€];
- X = Extended lifetime [hours];
- T_B = Operating lifetime of product (B) [h];
- E_B = Operating costs associated to the product (B) [€];
- M_B =Maintenance costs associated to the product (B) [€/y];
- A_B = Auxiliaries components costs associated to the product (B) [€/y];

([94]) The discount rate is the rate of return used in a discounted cash flow analysis to determine the present value of future cash flows.
([95]) The Present Value is the value of an expected cash flow stream determined as of the date of valuation, meaning discounted at the discount rate. The higher the discount rate, the lower the present value of the future cash flows.

Formula 12: Durable scenario:

$$C_{TOT,\text{durable}} = C_A + \sum_{t=1}^{T_A+X} [\text{PVF}_{t_A,i}(E_{A_t} + M_{A_t} + A_{A_t})] + \text{PVF}_{t,i}(R_A)$$

Where:

- C_A = Acquisition costs of the product A' [€];
- $T_A + X$ = Operating lifetime of the durable product A' [h];
- E_{A_t} = Operating costs associated to the product (A) [€/y];
- M_{A_t} =Maintenance costs associated to the product (A) [€/y];
- A_{A_t} = Auxiliaries components costs associated to the product (A) [€/y];
- R_A = Repair cost associated to the durable product A' [€].

The comparison of the durable scenario with the base-case is calculated as the difference between the life-cycle costs in the two scenarios (Formula 13) (96).

Formula 13:

$$\Delta_{C_{TOT}} = C_{TOT,base\ case} - C_{TOT,\text{durable}}$$

$$\Delta_{C_{TOT}} = \sum_{t=1}^{T_A} [\text{PVF}_{t_B,i}(E_{A_t} + M_{A_t} + A_{A_t})] + (\text{PVF}_{t,i}C_B) \cdot \frac{X}{T_B} + \sum_{t=1}^{X} [\text{PVF}_{t_B,i}(E_{B_t} + M_{B_t} + A_{B_t})] - \sum_{t=1}^{T_A+X} [\text{PVF}_{t_A,i}(E_{A_t} + M_{A_t} + A_{A_t})] - \text{PVF}_{t,i}(R_A)$$

$$\Delta_{C_{TOT}} = (\text{PVF}_{t,i}C_B) \cdot \frac{X}{T_B} + \sum_{t_B=1}^{X} [\text{PVF}_{t_B,i}(E_{t_B} + M_{t_B} + A_{t_B})] - \sum_{t_1=T_A+1}^{T_A+X} [\text{PVF}_{t_A,i}(E_{t_A} + M_{t_A} + A_{t_A})] - \text{PVF}_{t,i}(R_A)$$

Where:

ΔC_{TOT} = difference between the life-cycle costs between the durable scenario and the base-case scenario.

There are economic benefits when the difference between the life-cycle costs between the two scenarios is positive ($\Delta C_{TOT} > 0$), i.e. when the life-cycle costs of the base-case Scenario are higher than the total costs of the durable Scenario ($C_{TOT,base\text{-}case} > C_{TOT,durable}$). Note that the ΔC_{TOT} is independent from the purchase price of the product (A) (as it is the same in both scenarios). The ΔC_{TOT} depends on: the new product price, the energy price, the maintenance and the auxiliaries components during the lifetime

(96) $\sum_{k=1}^{n+m} a_k = \sum_{k=1}^{n} a_k + \sum_{k=n+1}^{n+m} a_k$

extension, the repair costs and to the discount rate. Note that all of these aspects are variables of the analysis.

Additional assumptions are needed about the energy consumption costs associated with the product (B) (E_{t_B}), the purchase cost of the product (B) (C_B) and the maintenance costs of product (B) (M_{t_B}). In general, the cost related to the energy consumption of the product is the product of the energy consumption (e_n) and the cost per [kWh] (E_n). The energy consumption of the new product (e_B) can be assumed to be lower than of product A (e_A), which follows from the initial assumptions. Therefore the costs of energy consumption of new product could be expressed as a percentage of the costs for the energy consumption of the old products:

Formula 14: $$\frac{e_B}{e_A} = \delta$$

In a specific year, the energy cost of the product (B) can be expressed as:

Formula 15: $$E_{t_B} = e_B \cdot E_t \ = \ \delta \cdot e_A \cdot E_t, \quad 0 \leq \delta$$

Similarly, assumptions are made about the purchase price and the maintenance costs of product (B) because actual data are not available due to many different factors influencing the price evolution (technology development, performances, materials, market trends, availability of products, etc.). The purchase price of the new product (C_B) could be expressed as a function of the purchase prive of the product (A) (C_A) as well as the maintenance of the new product (M_B) as a function of maintenance of product (A) (M_A) and the auxiliaries components of the new product (A_B) as a function of the auxiliaries components of the product (A) (A_A):

Formula 16: $$C_B = (1 + \beta) \cdot C_A$$

Formula 17: $$M_B = \rho \cdot M_A$$

Formula 18: $$A_B = \sigma \cdot A_A$$

Finally, the ΔC_{TOT} can be written as in Formula 19.

Formula 19:

$$\Delta_{C_{TOT}} = (\mathrm{PVF}_{t,i} C_B) \cdot \frac{\mathrm{X}}{T_B} + \sum_{\mathrm{t=1}}^{X} \left\{ \mathrm{PVF}_{t_B,i} [(\delta \cdot e_{A,t} \cdot E_t) + (\rho \cdot M_{A,t}) + (\sigma \cdot A_{A,t})] \right\}$$
$$- \sum_{t_1 = T_A + 1}^{T_A + X} [\mathrm{PVF}_{t_{\mathrm{A}},i} (e_{A,t} \cdot E_t + M_{\mathrm{A,t}} + A_{\mathrm{A,t}})] - \mathrm{PVF}_{t,i} (R_A)$$

7.1. Assumptions for the economic assessment of the durability of vacuum cleaners

The method illustrated in section 4.5.1 is applied to a specific case-study: the canister vacuum cleaner analysed in the previous chapters.

Following the previous environmental analysis, it is assumed that the average usage of the vacuum cleaner is 50 hours per year, while the potential lifetime extension (X) of the vacuum cleaner ranges between 0 and 300 hours; moreover, the base-case product (A) has an initial lifetime of 10 years ([97]).

Consistent with the assumptions for the environmental assessment of durability (chapter 5.2 and with the energy efficiency class A in force from 01/09/2017 (EU 2013b; EU 2013a), the yearly energy consumption of product (A) is assumed to be 25 [kWh]. In order to assess the importance of the energy consumption within the life-cycle costs, its variation (δ) associated to the product (B) has ranged between 0 % and 30 %.

According to the Eurostat statistics, the average electricity price for households in 2014 was 0.205 [€/kWh]; moreover, based on (EC 2014b), the growth rate of household electricity prices is 4 % a year in the period 2008-2012 ([98]). Finally, the Preparatory study on Ecodesign of VCs assumed a discount rate of 5 %, while the draft Report of Ricardo-AEA Ltd (Iraldo & Facheris 2015) 3 %. For this study, the discount rate for the base-case VC has been set at 3 %, but a sensitivity analysis has been performed for the values between 1 % and 5 %. Note that inflation is not taken into account and so, the nominal and the real discount rate are assumed to be equal ([99]).

There are no actual data available for the purchase price of product (B), therefore C_B is a variable in this analysis (Formula 16), where β is assumed to vary between -15 % and 25 %. This means that the product (B) could cost up to 25 % more than product (A) but also that the product (B) could have a lower purchase price of the product (A). However, for the base-case scenario it is assumed that C_B is 20 % higher than C_A.

Similarly, as data about repair cost are not available in literature, based on the price on some components (mainly hose and nozzle plate) available on the market, the R_A value is assumed to be a certain percentage of the purchase price of the product A; in particular, a value equal to 20 % of C_A was considered for the analysis ([100]).

Both the scenarios have additional costs due to use of auxiliary materials and ordinary maintenance. However, it is assumed that these cost items equally affect both the scenarios, independently from the considered lifetime. Since the aim of the analysis is to calculate the difference of the life-cycle costs in the two scenarios, these additional costs are not influencing the results and have been excluded.

([97]) For calculation reasons, 10 years correspond to 500 operating hours.

([98]) http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_natural_gas_price_statistics#Electricity_prices_for_household_consumers (accessed March 2015).

([99]) The real discount rate is the difference between the nominal discount rate and the inflation rate. Consistent with the Preparatory study, the inflation was not considered.

([100]) This value is lower than the 'Repair and maintenance costs' assumed by the Preparatory study, in which this item is about 30 % of the purchase price of the longer lasting VC. However, a sensitivity analysis has been performed make varying the repair cost item between 0 and 40 % of the purchase price of the product (A).

7.2. Analysis of the difference between the life-cycle costs of the two scenarios (ΔC_{TOT})

The main assumptions on vacuum cleaner characteristics and market prices are summarised in Table 39.

Figure 39 shows the difference between the base-case scenario and the durable scenario, with the lifetime extended up to 11 years (550 hours). According to (EU 2013a), it is assumed that the minimum operating life of the vacuum cleaner motor is 500 h, and therefore the repair costs until 500h are zero (R = 0 €). Based on these assumptions, the extension of the lifetime up to 550 hours is reasonable regardless of the energy efficiency of the new vacuum cleaner. This gain is of about EUR 11-13, depending on δ.

When repair costs are included in the analysis for longer than 1-year lifetime extension, results slightly change as illustrated in Figure 40. It is observed that:

- The repair costs to prolong the lifetime beyond 500 hours of operating time make the durable scenario less viable from the economic point of view.
- Despite the repair costs, the durable scenario has economic benefits when the lifetime is increased by more than 1 year: the higher the extension of the lifetime the higher the benefits.

Table 39: Summary of the assumptions for the calculation of the ΔC_{TOT}

Parameter		Unit of measure	Amount
Lifetime	$T_A = T_B$	[hours]	500
Lifetime extension	X	[hours]	0 → 300
Price of product A ([101])	C_A	[€]	150
Price of product (B)	C_B	[€]	$(1+\beta)* C_A$ $-15\ \% \leq \beta \leq 25\ \%$
Yearly consumption until 500 hours	e_A	[kWh]	25
Price of electricity	El_{t_1}	[€/kWh]	0.205
Variation of the energy consumption of product 'B' compared to 'A'	δ	[%]	$70\ \% \leq \delta \leq 100\ \%$
Growth rate of electricity price		[-]	4 %
Discount rate	i	[-]	3 %
Repair costs ([102])	R	[€]	$20\ \% * C_A$

([101]) http://www.cnet.com/topics/vacuum-cleaners/buying-guide/, (accessed March 2015), http://www.altroconsumo.it/confronta-scegli/elettrodomestici/aspirapolvere/guida-all-acquisto-dell-aspirapolvere (accessed March 2015). This is also consistent to the purchase price considered by the Preparatory study, after 10 years and with a discount rate of 3 %.

([102]) The repair expenditures will occur after 11 years lifetime of product (A). 20 % has been assumed as a rough estimation for the analysis, however this assumption has been modelled later in the sensitivity analysis (section 7.2.2.3). Finally, for this analysis has been assumed that no repair operations occur before 500 hours of VC lifetime.

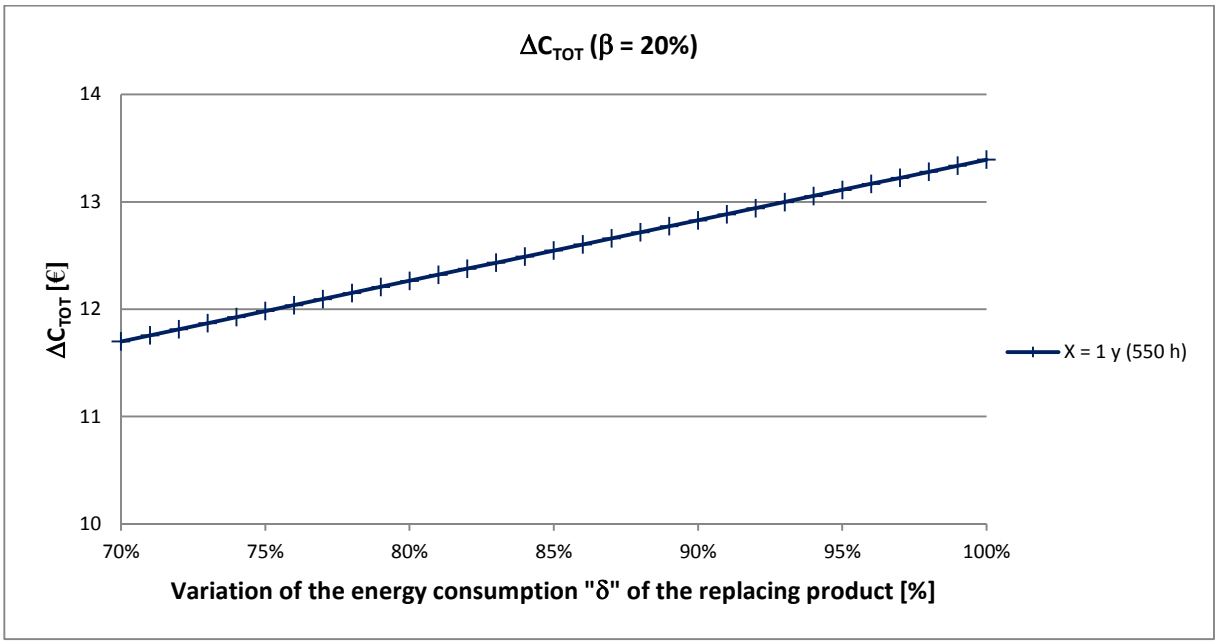


Figure 39: ΔC_{TOT} for the canister vacuum cleaners with a lifetime of 500 h and 550 h

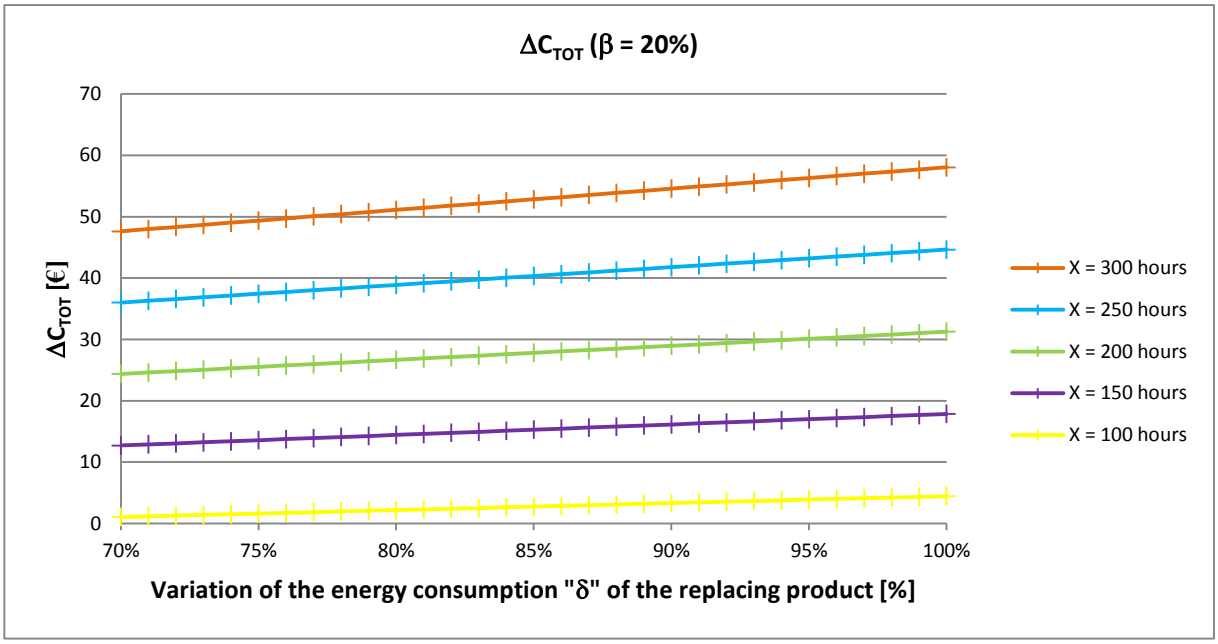


Figure 40: ΔC_{TOT} for the canister vacuum cleaners (on varying X-values)

With the purpose of checking the importance of some of the parameter of the analysis, the total costs of the two scenarios have been calculated and a sensitivity analysis has been performed.

7.2.1. Life Cycle Costs

In order to evaluate the life-cycle costs, the price associated to auxiliaries (i.e. bags) and ordinary maintenance (i.e. filters) has been assumed based on available information on the market and consistent with assumptions adopted for the environmental assessment of durability (section 5.2). In particular, the

replacement of 7 dust-bags and one set of filters per year are assumed ([103]). In terms of expenses, the price of one dust-bag is supposed to be EUR 1.75; concerning filters, the replacement of one set of filter means an average replacement of two filters per year with a price of EUR 2 per set of filters. Note that these costs strictly depend on the quality of the bags and filters as well as on the type of the filter.

The results in (Figure 41) prove that the longer lasting vacuum cleaner represents the most viable option: despite the higher energy efficiency of the new product. After 550 hours (corresponding to 1 year of lifetime extension), the repair cost occurs: in fact the total cost increase of about EUR 22. In any case, the total cost of the durable scenario is always lower than the base-case ones, consistent with the previous discussion (Figure 40).

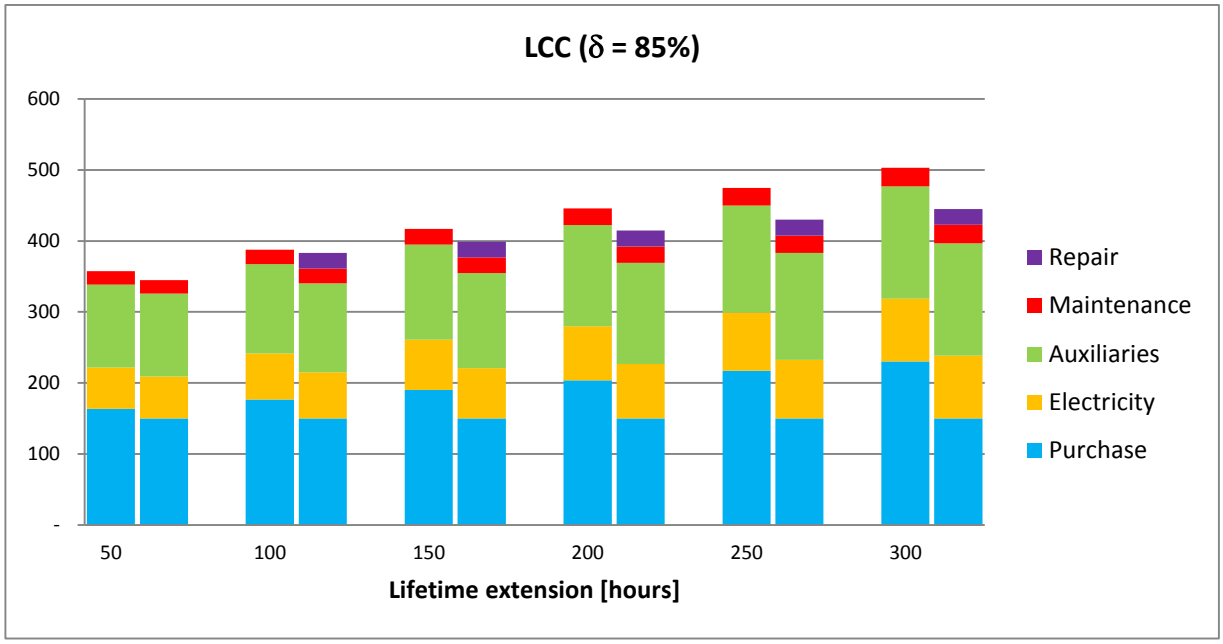


Figure 41: LCC of the base-case (first column) and the durable scenario (second column)

The distribution of the main cost items in the life-cycle costs proves that the purchase price of the VC is most important item for both scenarios. At the same time, even though the new product (B) is more efficient, the electricity price has almost the same contribution (between 16 % and 18 % of the life-cycle costs) irrespective of the lifetime extension options or the price growth of the new product. It is interesting to note that the contribution of the auxiliaries and the filters replacement is always higher than 35 % of the life-cycle costs.

Concerning the durable scenario, the higher lifetime extension the higher is the contribution of the electricity and the dust-bags/filter items, while the contributions of the purchase price of product (A) is lower. Note that the repair costs, not included in the base-case scenario, represent less than 6 % of life-cycle costs (Table 40).

([103]) Assumptions about maintenance are based on information available at: http://hoover.com/parts/category/filters/ (accessed March 2015), http://www.ebay.com/itm/34174012-Hoover-Canister-Replacement-Vacuum-Cleaner-Secondary-Filter-Windtunnel-/181510501303 (accessed March 2015).

Table 40: Cost item distribution within the canister vacuum cleaner LCC

X [hours]	BASE-CASE SCENARIO																				DURABLE SCENARIO					
	δ = 100%					δ = 90%					δ = 80%					δ = 70%										
	TOT	P	E	A	M	TOT	P	E	A	M	TOT	P	E	A	M	TOT	P	E	A	M	TOT	P	E	A	M	R
0		46 %	16 %	33 %	5 %		46 %	16 %	33 %	5 %		46 %	16 %	33 %	5 %		46 %	16 %	33 %	5 %		46 %	16 %	33 %	5 %	0 %
50	+ 9 %	46 %	17 %	33 %	5 %	+ 9 %	46 %	16 %	33 %	5 %	+ 9 %	46 %	16 %	33 %	5 %	+ 9 %	46 %	16 %	33 %	5 %	+5 %	43 %	17 %	34 %	6 %	0 %
100	+ 18 %	46 %	17 %	32 %	5 %	+ 18 %	46 %	16 %	32 %	5 %	+ 17 %	46 %	16 %	33 %	5 %	+ 17 %	46 %	16 %	33 %	5 %	+ 17 %	39 %	17 %	33 %	5 %	6 %
150	+ 27 %	46 %	17 %	32 %	5 %	+ 26 %	46 %	17 %	32 %	5 %	+ 26 %	46 %	16 %	32 %	5 %	+ 25 %	46 %	16 %	33 %	5 %	+ 21 %	38 %	18 %	34 %	5 %	6 %
200	+ 36 %	46 %	17 %	32 %	5 %	+ 35 %	46 %	17 %	32 %	5 %	+ 34 %	46 %	16 %	32 %	5 %	+ 34 %	46 %	16 %	32 %	5 %	+ 26 %	36 %	18 %	34 %	6 %	5 %
250	+ 44 %	46 %	17 %	32 %	5 %	+ 43 %	46 %	17 %	32 %	5 %	+ 43 %	46 %	16 %	32 %	5 %	+ 42 %	47 %	16 %	32 %	5 %	+ 31 %	35 %	19 %	35 %	6 %	5 %
300	+ 53 %	46 %	18 %	32 %	5 %	+ 52 %	46 %	17 %	32 %	5 %	+ 51 %	46 %	16 %	32 %	5 %	+ 50 %	47 %	16 %	32 %	5 %	+ 35 %	34 %	20 %	36 %	6 %	5 %

TOT = increase of the total costs respect to X = 0P = Purchase
E = Electricity costs
M = Costs for Maintenance
M = Costs for Auxiliaries components
R = Repair costs

7.2.2. Sensitivity analysis

The parameters assessed in the sensitivity analysis are

- Purchase price of the base-case product (C_A);
- Purchase price of the replacing product (C_B);
- Repair costs (R);
- Auxiliaries costs (A);
- Maintenance costs (M);
- Discount rate (i);
- Electricity price growth rate.

For the sensitivity analysis, it is assumed a value of $\delta = 85\,\%$, corresponding with a product (B) belonging to one energy efficiency class higher than the base-case product (A) (yearly consumption lower of 6 [kWh/y], section 1.2).

7.2.2.1. Purchase price of the base-case product (C_A)

The purchase price of the base-case product is made ranging between EUR 100 and EUR 200. It is worthy to note that this variation doesn't only affect the purchase price item but also the purchase price of the replacing product (C_B) and the repair costs (R).

Figure 42 proves that the higher the purchase price of the base-case product, the higher the economic benefits associated to the durable scenario. Moreover, these benefits increase at increasing of the lifetime extension.

Hence, the purchase price of the base-case product (C_A) has a relevant effect on the LCC of the VC. This sensitivity analysis has assumed a wide range of variation of C_A-values to reflect the uncertainties on the initial assumption on the purchase prices.

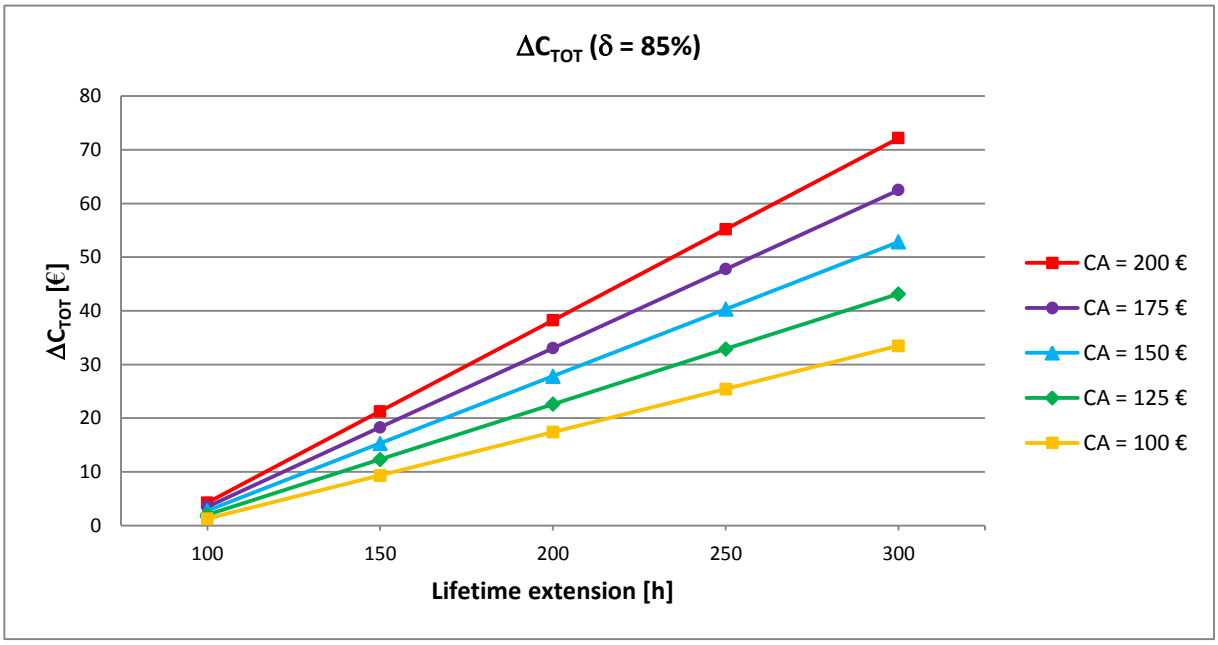


Figure 42: ΔC_{TOT} for the canister vacuum cleaner (on varying C_A-values)

7.2.2.2. Purchase price of the replacing product (C_B)

The considered range of β-values is between -15 % and 25 %. Figure 43 shows that the increase on the new product price doesn't relevantly affect the life-cycle cost of the vacuum cleaner. Higher economic benefits are related to higher lifetime extension. The difference between the scenario with β = -15 % and β = 25 % is lower than EUR 27. Note that for lower value of lifetime extension, the durable VC does not have economic benefits, particularly for low β-values. Indeed, the durable option is always favourable after a lifetime extension of 130 h.

Hence, the purchase price of the replacing product (C_B) has a relevant effect on the LCC of the VC. This sensitivity analysis has assumed a wide range of variation of β-values to reflect the uncertainties on the initial assumption on the purchase prices.

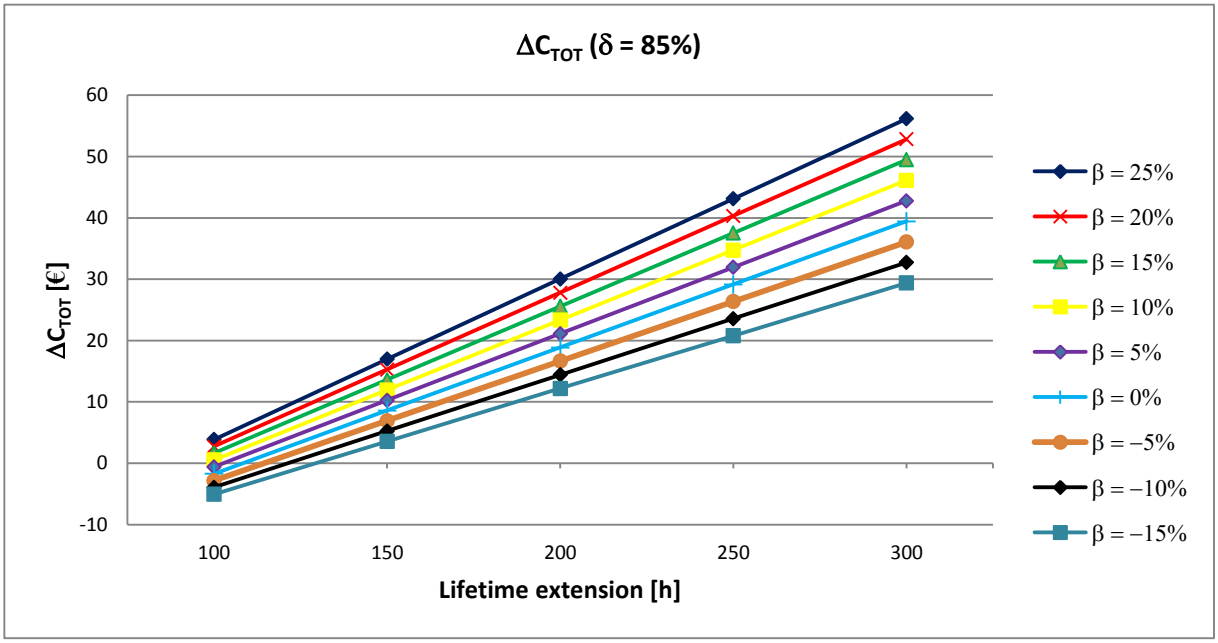


Figure 43: ΔC_{TOT} for the canister vacuum cleaner (on varying β-values)

7.2.2.3. Repair costs (R)

The repair costs (R) of product (A) are assumed to vary between 0 % and 40 % of the purchasing price (C_A). The results show that the repair cost can affect the economic convenience of the durable scenario compared to the base-case, when low lifetime extensions are considered. For instance, for R = 30 %, there is an economic benefits when the lifetime extension is higher than 130 hours, while for R = 40 % this value is higher (175 hours).

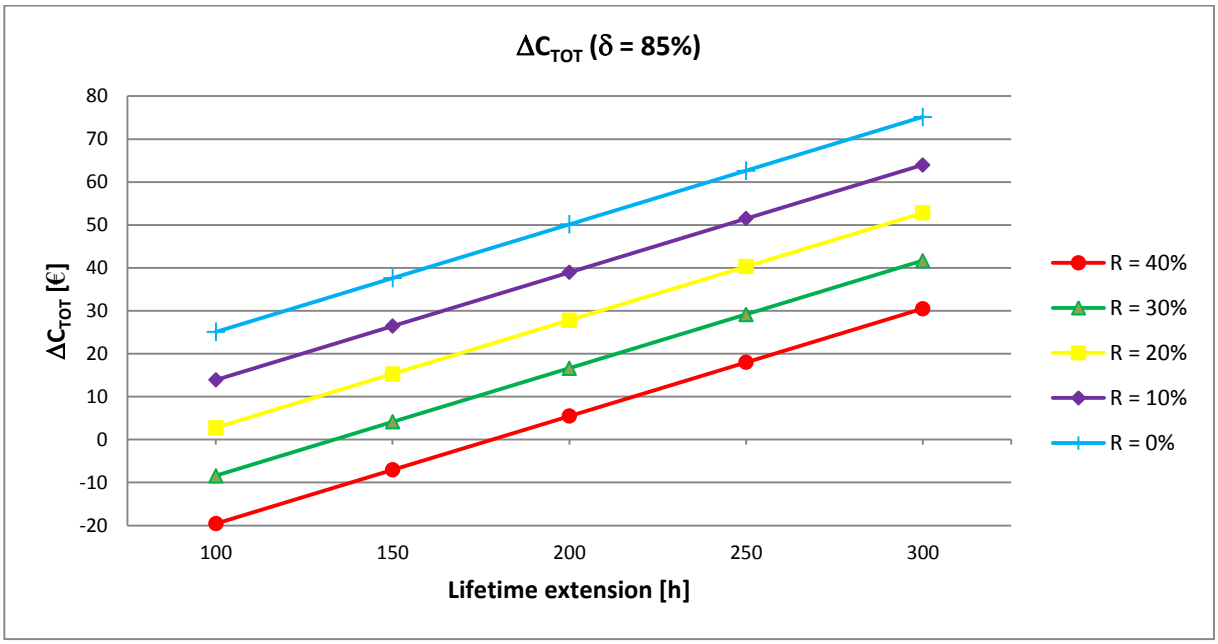


Figure 44: ΔC_{TOT} for the canister vacuum cleaners (on varying R-values)

7.2.2.4. Auxiliaries costs (A)

Costs occurring for the replacement of the dust-bags have varied between EUR 1.5/bag and EUR 2/bag. The amount of replacements during the lifetime of VC is always the same (i.e. 7 bags per year).

Results in Figure 45 depicts that the increase of the auxiliaries cost doesn't significantly affect the life-cycle costs of the VC. The difference between the cheaper option (i.e. EUR 1.5/bag) and the more expensive options (i.e. EUR 2/bag) is lower than EUR 35, about 10 % of the LC costs.

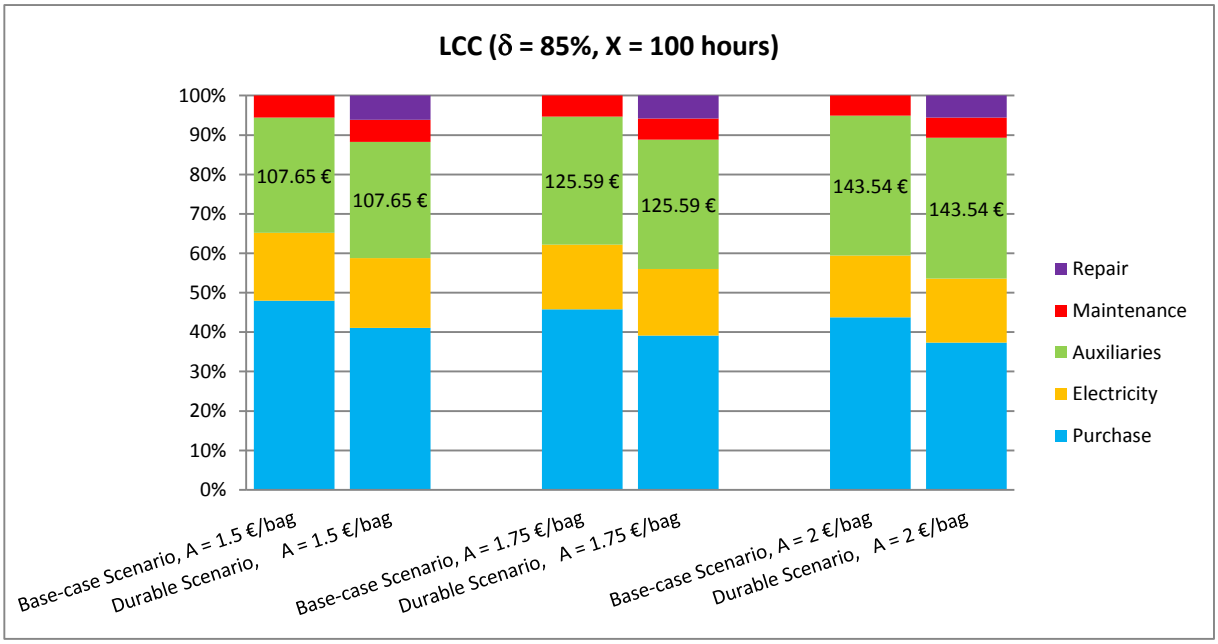


Figure 45: Cost items contribution to the LCC of the Base-case and the Durable Scenario (on varying A-values)

7.2.2.5. Maintenance costs (M)

Due to the uncertainty of the filter price, the sensitivity analysis corresponding to this parameter includes a higher range of variation respect to the previous one. The M-parameter varies between EUR 2 and EUR 10 per set of filters, supposing to change 1 set of filters per year.

Results in Table 41 prove that the higher are the maintenance costs the higher is the variation of the life-cycle costs. For both the Base-case Scenario and the Durable Scenario, the higher variation corresponds to the higher lifetime extension.

Table 41: Maintenance contribution to the LCC (on varying M parameter)

BASE-CASE SCENARIO

X [h]	M = 2 €/filter	M = 5 €/filter	M = 8 €/filter	M = 11 €/filter	M = 14 €/filter
0	5 %	12 %	18 %	24 %	28 %
50	5 %	12 %	18 %	24 %	28 %
100	5 %	12 %	18 %	24 %	28 %
150	5 %	51 %	18 %	23 %	28 %
200	5 %	12 %	18 %	23 %	28 %
250	5 %	12 %	18 %	23 %	28 %
300	5 %	12 %	18 %	23 %	28 %

DURABLE SCENARIO

X [h]	M = 2 €/filter	M = 5 €/filter	M = 8 €/filter	M = 11 €/filter	M = 14 €/filter
0	5 %	12 %	17 %	22 %	27 %
50	5 %	12 %	18 %	23 %	28 %
100	5 %	12 %	18 %	24 %	28 %
150	5 %	52 %	19 %	24 %	29 %
200	6 %	13 %	19 %	25 %	29 %
250	6 %	13 %	20 %	25 %	30 %
300	6 %	13 %	20 %	25 %	30 %

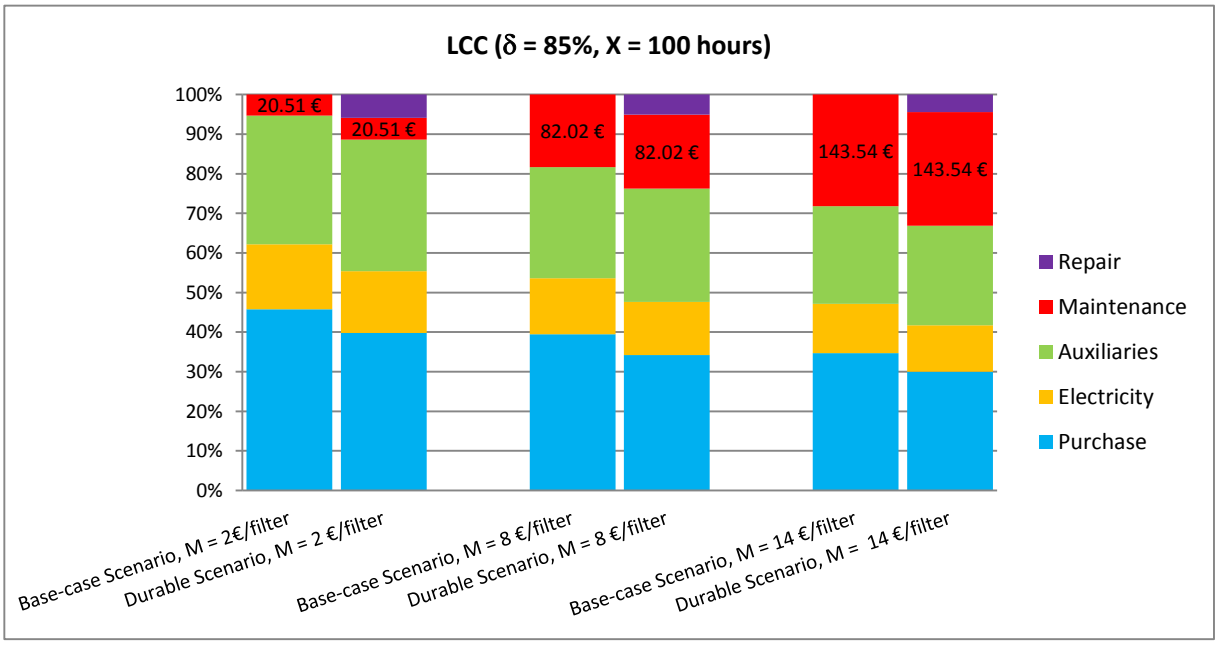


Figure 46: Cost items contribution to the LCC of the Base-case and the Durable Scenario (on varying M-values)

It is noticed that in the case of bagless VCs the contribution of the auxiliaries would be null. However, the costs of filters prices could be higher than the range considered in this analysis.

7.2.2.6. Discount rate (i)

The discount rate is supposed to vary between 1 % and 5 % (EC 2013; Davis 2008; AEA Energy & Environment 2009).

The results confirm that the lower is the discount rate the higher is the difference between the base-case and the durable scenario, meaning higher economic benefits. In any case, the variation of the discount rate doesn't cause great changes on the results. In fact, the difference between the $\Delta C_{TOT,i=3\,\%}$ and $\Delta C_{TOT=1\,\%}$ and $\Delta C_{TOT=5\,\%}$ is always lower than EUR 11 (Figure 47).

Table 42: ΔC_{TOT} on varying i-values

	$\Delta C_{TOT,i}$					
	X = 50 h	**X = 100 h**	**X = 150 h**	**X = 200 h**	**X = 250 h**	**X = 300 h**
i = 1 %	15.27	3.34	18.54	33.71	48.85	63.95
i = 3 %	12.55	2.76	15.29	27.82	40.33	52.83
i =5 %	10.35	2.29	12.66	23.03	33.41	43.79

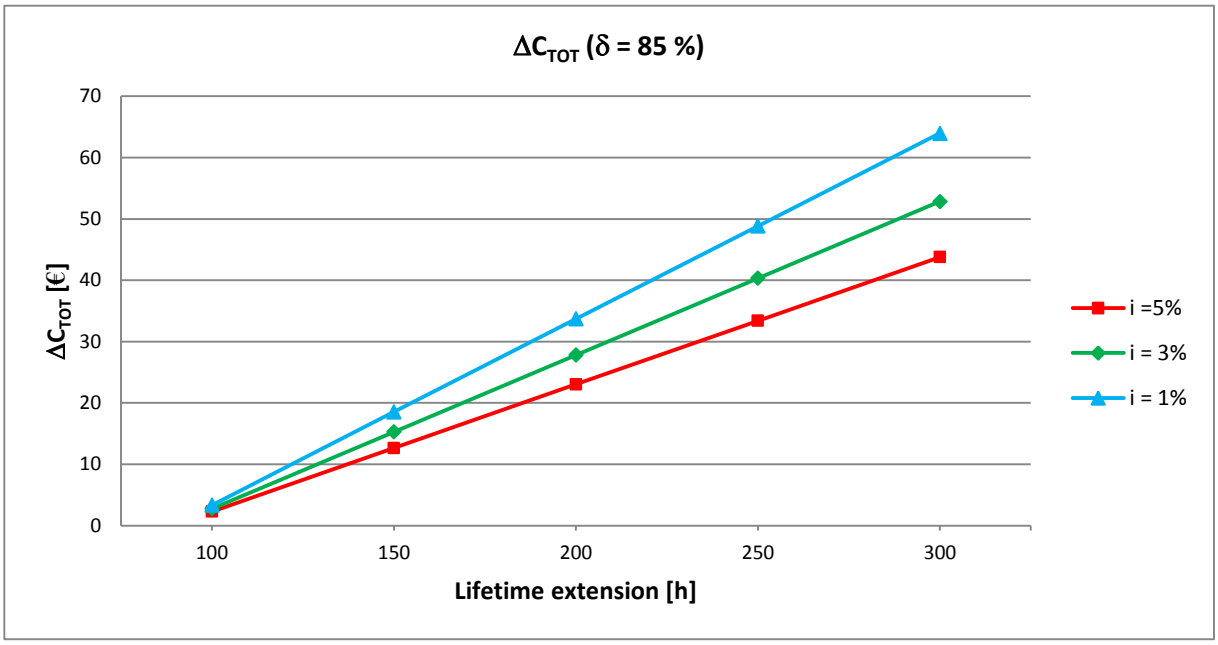


Figure 47: ΔC_{TOT} for the canister vacuum cleaners (on varying i-values)

7.2.2.7. Electricity price

The influence of the electricity price growth rate to the final economic assessment of durability can be considered as negligible for the case study, as previously anticipated by the distribution of cost items. Varying the growth rate of the electricity price between 1 % and 7 %, the difference between the life-cycle costs remain substantially unchanged (Figure 48).

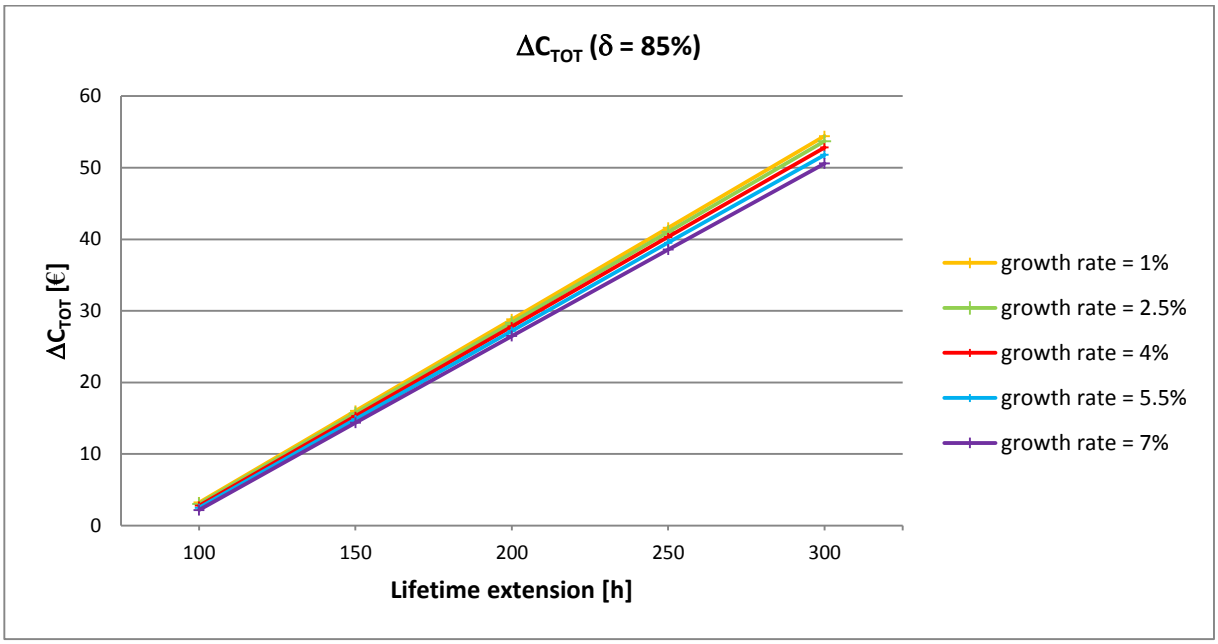


Figure 48: ΔC_{TOT} for the canister vacuum cleaners (on varying the growth rate values)

Conclusions

Context

This report aimed at assessing the durability of the Vacuum Cleaners (VCs) product group from both an environmental and economic point of view.

The starting point of the analysis was the analysis of existing ecodesign requirements on durability of VCs ([104]), complemented with the analysis of the scientific literature. This analysis showed that few studies have been so far developed on LCA of VC and even less specifically on the durability assessment. VCs are generally recognised as a 'use-phase dominant' product, since the majority of the impacts relates to the energy consumption during their operations. Manufacturing is also relevant for some life-cycle impacts. However, studies in the literature differ in several assumptions, as for example the average lifetime ([105]), user behaviour (including number of operating hours per year) and power consumption.

Life Cycle Assessment

A Life Cycle Assessment (LCA) has been performed on a case-study VC ([106]). The functional unit, consistent with the Preparatory Study on VCs, is a bagged canister VC with an operating time of 10 years and an energy consumption of 25 [kWh/y]. The analysis, performed through a LCA software tool confirmed that the VC is a use-dominant product: the energy consumption accounts between 30 % and 80 % of almost all the impact categories; the impact of manufacturing range from 15 % (for the 'Acidification' impact category) up to 95 % (for the 'Abiotic Depletion Potential'); the contribution of auxiliaries (i.e. dust-bags) and maintenance (i.e. filters) never exceeds 20 % of the impacts (higher values concerns the 'Freshwater Eutrophication'); the contribution of End-of-Life ([107]) (EoL) is always lower than 7 % for all the considered impact categories. The analysis also identified the relevant contribution to some impacts due to the manufacturing of the printed circuit board (PCB), the manufacturing of copper and steel parts, and of some plastic parts (in acrylonitrile-butadiene-styrene — ABS).

A sensitivity analysis has been implemented considering potential changes in the manufacturing (e.g. the use of a more complex PCB). This would affect mainly the ADP (with an increase up to 14 %) and 'Human Toxicity' (up to 4 %) impact categories, while not affecting much other categories. Concerning the use-phase, the energy consumption of the VC has been varied between 7 [kWh/y] and 43 [kWh/y]. The Life Cycle Impact Assessment (LCIA) proves that the higher is the energy efficiency class, the lower is the life-cycle environmental impact, with particular significance for the impact categories dominated by energy consumption (as 'Global Warming Potential (GWP)', 'Acidification' and 'Primary Energy Consumption').

Durability Assessment (environmental perspective)

Successively, the environmental benefits/impacts due to the extensions of the lifetime of VC have been analysed by applying the 'Durability Index' as developed within the 'REAPro' method. The method has been revised from original formulas as illustrated in Ardente et al. (2012), in order to capture new aspects of the durability (including the assessment of the impacts of auxiliary materials used during the operation,

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([104]) The requirements, in force starting from the 1 September 2017, request that the hose shall be useable after 40 000 oscillations under strain; and operational motor shall be working for at least 500 hours.

([105]) It has been observed that the average lifetime of VCs ranges between 5 and 9 years, although some reference considered values up to 20 years.

([106]) Bill of Materials refers to a product dismantled with overall mass of 5.7 kg, complemented with information from the literature.

([107]) The modelling of EoL did not include potential impacts and benefits related to the production of secondary materials.

the impacts due to the manufacturing of a more durable product, and the impacts of the potential substituting product). The 'Durability Index' is based on the comparison between a base-case scenario ([108]) and a durable scenario ([109]). The index has been calculated assuming a variation of the lifetime from 500 hours up to 800 hours.

The analysis proved that the environmental benefits are depending on the energy efficiency of the potential replacing product and the considered impact category. Higher benefits are estimated for those impact categories more influenced by the manufacturing. Considering the GWP indicator, extending the lifetime of the VC by 100 h (i.e. 2 years) saves around 1.5 % of GWP compared to its replacement with a 15 % more efficient product. Alternatively, the same lifetime extension generates higher benefits (up to 20 %) for other impact category (as the 'Abiotic Depletion Potential' (ADP)). The analysis proves also that higher benefits can be obtained for higher extension of the lifetime. For instance, in comparison to the replacement of the VC with a new one 15 % more efficient, a lifetime extension of 300 hours can reduce the GWP impact by 5 %.

The analysis has also included the modelling of possible environmental impacts due to repair operations. It has been observed that the introduction of repairing implies lower environmental benefits, nevertheless the durable option resulted environmentally in the large majority of scenarios considered. Finally, a sensitivity analysis has been performed by varying the impact due to the manufacturing of the replacing product and by accounting for extra impacts due to the manufacturing of a more durable product. However, these variations did not affect much the previous results.

In order to perform a comprehensive assessment of durability, the analysis of durability has been also performed by using the *Ecoreport tool 2013* ([110]). The life-cycle impacts of the case-study VC have been calculated based on the same assumptions of the previous chapters and used to calculate the new values of the 'Durability index'. It was noticed that the Ecoreport tool uses impact categories that are not fully consistent with those used in the previous analysis (i.e. the ILCD/PEF impact categories as implemented in the LCA software) and this limited the comparability of the results. The analysis nonetheless concluded that:

- The life-cycle impacts calculated according to the two tools (Ecoreport tool and LCA software) differ by about 10 % for the GER and GWP impact categories, between 10 % and 15 % for Acidification and Particulate Matter, about 25 % for Volatile Organic Compounds (VOC), more than 100 % for water consumption, and Eutrophication. For some impact categories (i.e. cooling water, hazardous and non-hazardous wastes, persistent organic pollutants, heavy metals and Polycyclic aromatic hydrocarbon) a comparison between the results of the two tools was not possible.
- The 2013 version of the Ecoreport tool takes into account durability aspects through the lifetime parameter. The 'product life' input ([years]) permits the calculation of the 'Life-cycle Impact per product per year of use' ([111]). However the result is aggregated and it is not possible to assess the relevance of specific operations occurring, for instance, repair or maintenance operations.
- The study demonstrated the applicability of the 'Durability index' through the Ecoreport tool, even though some limitations have been observed. For example, the Ecoreport tool has a limited set of input materials/components. The tool allows the inclusion of new materials, but it was not possible to introduce some

([108]) The base-case scenario refers to the replacement of base-case product after a certain time (Ardente et al. 2012).
([109]) The durable scenario refers to the extension of the lifetime of the base-case time (Ardente et al. 2012).
([110]) The version considered for this analysis was the v.3.06 as modified in 2013 to take into account the lifetime parameter [BIO Intelligence Service (2013a)].
([111]) This is obtained by dividing the 'Life Cycle Impact per product' by the number of years of lifetime.

impact categories for new inventory data due to the previously mentioned inconsistency among impact categories considered in the two tools.

- Moreover, some life-cycle aspects in the Ecoreport tool are modelled through aggregated sections. Therefore some key aspects of durability (as repairing and maintenance) as included in the REAPro were difficult to be modelled via the Ecoreport tool.
- Finally the 'Durability index' has been calculated with the Ecoreport tool only for the GWP impact. The results obtained via Ecoreport tool revealed to be similar to those previously obtained via the LCA software. For instance, compared to the replacement of a new VC 15 % more efficient, extending the VC by 100 h instead than replacing it with a new product 15 % more energy efficient, would reduce the by 3.7 % (compared to the 1.5 % previously calculated with the LCA software).

Durability Assessment (economic perspective)

Finally, authors enlarged the method to assess also the potential economic benefits/costs related to the extension of the lifetime of VCs. Similarly to the environmental assessment of durability, this assessment is based on the comparison between two different scenarios concerning the lengths of the lifetime (in a life-cycle perspective) of a VC and its potential replacement with a more energy efficient one. Taking into account the overall costs occurring during the VCs lifetime, the outcomes proved for example that the lifetime extension of 100 h brings a life-cycle saving of about EUR 11-13, depending on the energy efficiency class of the replacing VC. Moreover, higher lifetime extensions could entail higher economic benefits. Even assuming some repair costs to prolong the lifetime beyond 500 h, the extension of the lifetime resulted beneficial in the large majority of the scenarios. A sensitivity analysis has been also performed within this economic assessment. This pointed out that the variation of the discount rate and of the growth rate of electricity do not affect the final outcomes, while the variation of the purchase price of both the base-case VC and the new VC, as well as the repair cost, are more relevant.

Conclusions

In conclusion, the report demonstrates the economic and environmental benefits of extending the lifetime of VCs in the large majority of scenarios considered. These results could be used to promote the design of more durable VCs, e.g. via more ambitious ecodesign measures. The report also highlights the relevance of reparability from both environmental and economic points of view. Repairability of products could be promoted for instance through a proper 'design for repairing' of products but also the availability of information and tools for the repair and/or replacement of some VCs components. It is also confirmed the relevance of a proper use and maintenance of the VC during the use-phase and to avoid the loss of energy efficiency throughout the lifetime. The report also highlighted that more detailed information about durability aspects of VCs would improve the awareness of consumers and drive them towards more sustainable behaviour and choices, for instance regarding the proper maintenance of the VC or the preference of repairing the product versus its replacement with a new one.

Acknowledgments

This report had been developed within the project 'Environmental Footprint and Material Efficiency Support for Product Policy' funded by DG Environment (070307/2012/ENV.C1/635340).

We would like to thank the Joint Research Centre - Institute for Prospective Technological Studies - Sustainable Production and Consumption Unit – for the review of this report and for the valuable comments provided to improve it.

Annex 1 — Life Cycle Inventory of the canister vacuum cleaner

As underlined by Chiu & Chu (2012), the major difficulties about the LCI data collection should be associated to the availability of reliable database of both materials and processes.

For modelling the canister vacuum cleaner Gabi6 software and GaBi Professional database have been used. In some cases, some Ecoinvent 2.2 processes have been used (as for cables and paper for the instruction manual).

Consistent with the goal of the study, except for the hose and the operational motor, all the other components of the vacuum cleaner have been grouped.

For clarity, Table 43 illustrates the detail of the processes used in the analysis. Note that for the assessment of the impacts of the manufacturing of components, the following processes have been used:

- injection moulding for all the plastics components;
- die-casting for aluminium;
- stamping and bending for steel.

Table 43: Inventory data used for the LCA of canister vacuum cleaner

MATERIAL	NAME OF THE PROCESS	SOURCE
ABS	Acrylonitrile-butadiene-styrene granulate (ABS) DE: Plastic injection moulding part (unspecific) PE	GaBi GaBi
Aluminum	EU-27: Aluminium ingot mix PE DE: Aluminium die-cast part PE	GaBi GaBi
PE-HD	DE: Polyethylene High Density Granulate (HDPE/PE-HD) Mix PE DE: Plastic injection moulding part (unspecific) PE	GaBi GaBi
PE-LD	EU-27: Polyethylene Linear Low Density Granulate (LLDPE/PE-LLD) PE DE: Plastic injection moulding part (unspecific) PE	GaBi GaBi
PP	Polypropylene granulate (PP) DE: Plastic injection moulding part (unspecific) PE	GaBi GaBi
PVC	DE: Polyvinyl Chloride Granulate (Suspension; S-PVC) Mix PE DE: Plastic injection moulding part (unspecific) PE	GaBi GaBi
Rubber	Styrene-butadiene-rubber (SBR) DE: Plastic injection moulding part (unspecific) PE	GaBi GaBi
Steel	DE: Steel cold rolled coil PE GLO: Steel sheet stamping and bending (5 % loss) PE	GaBi GaBi

For some materials (ABS.PP; BMC-GF; POM) life-cycle inventory data were not available in the two aforesaid databases. For these materials a life-cycle inventory has been created as following.

ABS.PP (Acrylonitrile-butadiene-styrene - Polypropylene)

It is supposed that 90 % of the material is made up of ABS, and the remaining 10 % of PP. Injection moulding process has been considered for the impact of the manufacturing.

BMC-GF (Bulk moulding compound — Glass Fibre)

The average composition of the polyester fiberglass resin has been extrapolated based on literature data.

Polyoxymethylene (POM)

The assessment of the composition of polyoxymethylene has been based on a technical sheet of an engineering group leading with specific polymer chemical intermediates ([112]). Note that the only intermediate modelled with Ecoinvent v2.2 was the 'RER: 2-butanol, at plant'.

The hose

The inventory data used for the hose model are showed in Table 44.

Table 44: Inventory data used for the LCA of canister vacuum cleaner's hose

MATERIAL	MASS [kg]	SOURCE
ABS	0.461	GaBi
PE	0.214	GaBi
PP	0.018	GaBi
Rubber	0.003	GaBi

([112]) www.shafaghsenowbar.com, POM_550JnSHu (accessed January 2015)

Motor

The total weight of the motor is 1.862 kg, which means more than 30 % of the vacuum cleaner weight. Note that in the inventory, 13 g were not defined.

Table 45: Inventory data used for the LCA of canister vacuum cleaner's motor

MATERIAL	NAME OF THE PROCESS	MASS [kg]	SOURCE
Aluminum	See Table 43	0.042	
Brass	EU-27: Brass (CuZn20) PE	0.025	GaBi
Copper	CN: Copper sheet PE	0.124	GaBi
Copper windings	EU-27: Copper Wire Mix DKI/ECI Steel (see Table 43) Aluminum (see Table 43)	0.0326 0.271 0.0579	GaBi
BMC-GF	See Table 43	0.267	
Graphite	RER: graphite, at plant	0.007	Ecoinvent
Polyethylene granulate (PE)	See Table 43	0.016	
Polypropylene granulate (PP)	See Table 43	0.259	
Rubber sealing compound	See Table 43	0.133	
Steel	See Table 43	0.614	

For almost all the materials it was possible to find the corresponding life-cycle inventory data in the GaBi database ([113]). About the winding assembly, an average composition has been estimated based on literature data (De Almeida et al. 2008; De Almeida et al. 2013; Olivetti et al. 2012).

Canister

According to the gal and scope of the study and to chapter 4.1.3, all the other components of the vacuum cleaner have been grouped.

([113]) http://www.gabi-software.com/databases/

Table 46: Inventory data used for the LCA of canister vacuum cleaner's canister

COMPONENT	MATERIAL	NAME OF THE PROCESS	MASS [kg]	SOURCE
Canister case	ABS	See Table 43	2	
	POM	See Table 43	0.042	
	Rubber	See Table 43	0.002	
	Steel	See Table 43	0.004	
Hose Reel	Brass	EU-27: Brass (CuZn20) PE	0.004	GaBi
	ABS	See Table 43	0.142	
	PE	See Table 43	0.021	
	Rubber	See Table 43	0.002	
	Steel	See Table 43	0.052	
Attachment cord	PVC	See Table 43	0.194	
	Copper	EU-27: Copper Wire Mix DKI/ECI	0.089	DKI/ECI
Nozzle plate	ABS.PP	See Table 43	0.052	
	PE-HD	See Table 43	0.020	
	PP	See Table 43	0.219	
	Steel	See Table 43	0.019	
Filter	PE-HD	See Table 43	0.017	
Wheels	PP	See Table 43	0.209	
Cables	Brass	EU-27: Brass (CuZn20) PE	0.002	GaBi
	PE	See Table 43	0.015	
	PVC	See Table 43	0.011	
	Wires	EU-27: Copper Wire Mix DKI/ECI	0.005	DKI/ECI
Cables	Brass	See Table 43	0.001	
	PVC	See Table 43	0.002	
	Wires	EU-27: Copper Wire Mix DKI/ECI	0.002	DKI/ECI
PCB	PCB	GLO: printed wiring board, power supply unit desktop PC, Pb free, at plant	0.012	Ecoinvent
	Steel	See Table 43	0.014	

Packaging

To model the packaging, both the cardboard for the box and the paper for the instruction manual have been considered. Moreover, a small percentage of plastic (PE-LD) has been included. Data are based on a waste material declaration of Philips' canister vacuum cleaner.

Table 47: Inventory data used for the LCA of canister vacuum cleaner's packaging

MATERIAL	NAME OF THE PROCESS	MASS [kg]	SOURCE
PE-LD	See Table 43	0.06	
Paper	RER: paper, woodfree, uncoated, at regional storage	0.10	Ecoinvent
Cardboard	Corrugated board (2012)	1.10	PE/FEFCO

Transports

The manufacturing phase of any product should comprehend the transports for the raw material retrieval but also those one associated to the product delivery. As is not possible to standardise these data, some assumptions have been done in order to take in account also the transport contribution to the final environmental impact of the product.

The factory is supposed to be settled within the European Union, and in particular in the United Kingdom (Cambuslang, South Lanarkshire), where in effect there is a Hoover factory (http://www.hoover.co.uk/about-us/).

The main assumptions for the procurement of raw materials is that plastic parts cover a distance of about 100 km, while all the other materials, 200 km. About packaging, a transport on a lorry for 100 km has been included. Concerning delivery, it was hypothesized that from UK vacuum cleaners are delivered around the European Union. Thus, an average distance of 1 000 km has been considered. Finally, the transports associated to the end-of-life are assumed to be about 100 km for one canister vacuum cleaner.

Table 48: Inventory data used for the LCA of canister vacuum cleaner's transports

TRANSPORTED MATERIAL	DISTANCE [km]	MASS*DISTANCE [kgkm]
plastics	100	432.32
metals	200	279.57
packaging	100	126.00
delivery	1 000	6 981.00
EoL	100	698.10

End of Life

Mainly based on the IEC/TR 62635, the recycling and recovery rate of product parts inclined towards the separation process used in the LCA modelling are illustrated hereinafter (Table 49).

Table 49: Inventory data used for the LCA of canister vacuum cleaner's EoL

MATERIAL	MASS [g]	RECYCLING RATE	AMOUNT RECYCLED [g]
ABS	2 653.80	74 %	1 990.35
Al	99.92	91 %	90.93
BMC-GF	267.00	0 %	267.00
brass	30.00	100 %	30.00
copper	253.42	100 %	253.42
graphite	7.00	0 %	0.00
PCB	12.00	0 %	0.00
PE	303.00	90 %	272.70
POM	42.00	0 %	0.00
PP	710.20	90 %	639.18
PVC (incineration)	207.17	100 %	207.17
Rubber	140.00	90 %	126.00
Steel	974.50	94 %	916.03
Cardboard	1 100.00	90 %	990.00
LDPE	60.00	90 %	54.00
Paper	100.00	90 %	0.90

It was assumed the entire plastic fraction not recycled is incinerated (except PVC that is all incinerated), while all other fractions are sent to a landfill. A transport of about 100 km has been considered for taking the vacuum cleaner until the treatment plant.

Moreover, based on (Huysman et al. n.d.) transport, energy and chemical elements necessary for the treatment processes have been considered:

Table 50: Inventory data used for the LCA of canister vacuum cleaner's EoL

MATERIAL	NAME OF THE PROCESS	QUANTITY		SOURCE
Carbon black	DE: Carbon black (furnace black; general purpose) PE	0.079	kg	GaBi
Limestone	CH: limestone, milled, packed, at plant	0.348	kg	Ecoinvent
Electricity	EU-27: Electricity grid mix PE	10.298	MJ	Ecoinvent
Chemicals organic	GLO: chemicals organic, at plant	0.118	kg	Ecoinvent
Magnetite	GLO: magnetite, at plant	0.054	kg	GaBi
Transports	EU-27: Lorry transport PE	9.029	kgkm	GaBi

Annex 2 — LCIA for the environmental durability assessment

Table 51: Life-cycle impacts for the calculation of the Durability index 'D_n'

	Abiotic Depletion Potential, mineral resources	Acidification, accumulated exceedance	Ecotoxicity for aquatic fresh water, USEtox (recommended)	Freshwater eutrophication, EUTREND model, ReCiPe	Human toxicity cancer effects, USEtox (recommended)	Human toxicity non-canc. effects, USEtox (recommended)	Ionising radiation, human health effect model, ReCiPe	IPCC global warming, excl biogenic carbon	Marine eutrophication, EUTREND model, ReCiPe	Ozone depletion, WMO model, ReCiPe	Particulate matter/Respiratory inorganics, RiskPoll	Photochemical ozone formation, LOTOS-EUROS model, ReCiPe	Primary energy from non renewable resources (net cal. value)	Terrestrial eutrophication, accumulated exceedance	Total freshwater consumption, including rainwater, Swiss Ecoscarcity
	[kg Sb-Equiv.]	[Mole of H+ eq.]	[CTUe]	[kg P eq]	[CTUh]	[CTUh]	[kg U235 eq]	[kg CO2-Equiv.]	[kg N-Equiv.]	[kg CFC-11 eq]	[kg PM2,5-Equiv.]	[kg NMVOC]	[MJ]	Mole of N eq.]	[UBP]
$P_{A,n}$	1.21E-03	1.20E-01	7.39E+01	1.61E-04	2.11E-07	6.22E-06	2.77E+01	2.72E+01	4.29E-03	2.11E-08	8.17E-03	6.39E-02	5.84E+02	2.37E-01	2.57E+01
E_n	9.16E-07	8.64E-03	1.22E-01	4.17E-06	4.99E-09	4.92E-08	3.68E+00	1.59E+00	2.53E-04	1.82E-09	5.71E-04	3.10E-03	3.01E+01	1.25E-02	1.66E+00
$U_{A,n}$*	1.22E-07	1.34E-03	7.05E-03	2.97E-07	2.03E-10	5.72E-09	4.89E-02	2.37E-01	1.04E-05	1.76E-10	8.08E-05	4.92E-04	4.21E+00	1.72E-03	2.48E-01
$R_{A,n}$	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	6.06E-05	3.60E-03	7.39E-01	4.83E-06	1.06E-08	1.87E-07	2.77E-01	8.17E-01	1.29E-04	2.11E-10	8.17E-05	1.92E-03	1.75E+01	7.10E-03	2.57E-01

$U_{A,n}$ *: Impact per unit of hour

Annex 3 — Durability index of canister vacuum cleaner case-study

Durability Index of the canister vacuum cleaner for the 'Low Repairing Scenario (LRS)' and the 'High Repairing Scenario (HRS)'

		D_n [Abiotic Depletion] – LRS scenario						D_n [Abiotic Depletion] – HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	*100 %*	0.00	20.95	31.42	41.89	52.37	62.84	-4.76	16.19	26.66	37.14	47.61	58.08
	99 %	0.00	20.94	31.41	41.87	52.34	62.81	-4.76	16.18	26.65	37.12	47.59	58.05
	98 %	0.00	20.93	31.39	41.86	52.32	62.78	-4.76	16.17	26.63	37.10	47.56	58.03
	97 %	0.00	20.92	31.38	41.84	52.30	62.75	-4.76	16.16	26.62	37.08	47.54	58.00
	96 %	0.00	20.91	31.36	41.82	52.27	62.73	-4.76	16.15	26.61	37.06	47.51	57.97
	95 %	0.00	20.90	31.35	41.80	52.25	62.70	-4.76	16.14	26.59	37.04	47.49	57.94
	94 %	0.00	20.89	31.33	41.78	52.22	62.67	-4.76	16.13	26.58	37.02	47.47	57.91
	93 %	0.00	20.88	31.32	41.76	52.20	62.64	-4.76	16.12	26.56	37.00	47.44	57.88
	92 %	0.00	20.87	31.31	41.74	52.18	62.61	-4.76	16.11	26.55	36.98	47.42	57.85
	91 %	0.00	20.86	31.29	41.72	52.15	62.58	-4.76	16.10	26.53	36.96	47.39	57.83
	90 %	0.00	20.85	31.28	41.70	52.13	62.55	-4.76	16.09	26.52	36.95	47.37	57.80
	89 %	0.00	20.84	31.26	41.68	52.10	62.53	-4.76	16.08	26.51	36.93	47.35	57.77
	88 %	0.00	20.83	31.25	41.66	52.08	62.50	-4.76	16.07	26.49	36.91	47.32	57.74
	87 %	0.00	20.82	31.23	41.65	52.06	62.47	-4.76	16.07	26.48	36.89	47.30	57.71
	86 %	0.00	20.81	31.22	41.63	52.03	62.44	-4.76	16.06	26.46	36.87	47.28	57.68
	85 %	0.00	20.80	31.21	41.61	52.01	62.41	-4.76	16.05	26.45	36.85	47.25	57.65
	84 %	0.00	20.79	31.19	41.59	51.99	62.38	-4.76	16.04	26.43	36.83	47.23	57.62
	83 %	0.00	20.78	31.18	41.57	51.96	62.35	-4.76	16.03	26.42	36.81	47.20	57.60
	82 %	0.00	20.77	31.16	41.55	51.94	62.32	-4.76	16.02	26.40	36.79	47.18	57.57
	81 %	0.00	20.77	31.15	41.53	51.91	62.30	-4.76	16.01	26.39	36.77	47.16	57.54
	80 %	0.00	20.76	31.13	41.51	51.89	62.27	-4.76	16.00	26.38	36.75	47.13	57.51
	79 %	0.00	20.75	31.12	41.49	51.87	62.24	-4.76	15.99	26.36	36.74	47.11	57.48
	78 %	0.00	20.74	31.10	41.47	51.84	62.21	-4.76	15.98	26.35	36.72	47.08	57.45
	77 %	0,00	20,73	31,09	41,45	51,82	62,18	-4,76	15,97	26,33	36,70	47,06	57,42
	76 %	0,00	20,72	31,08	41,44	51,79	62,15	-4,76	15,96	26,32	36,68	47,04	57,40
	75 %	0,00	20,71	31,06	41,42	51,77	62,12	-4,76	15,95	26,30	36,66	47,01	57,37
	74 %	0,00	20,70	31,05	41,40	51,75	62,10	-4,76	15,94	26,29	36,64	46,99	57,34
	73 %	0,00	20,69	31,03	41,38	51,72	62,07	-4,76	15,93	26,28	36,62	46.96	57.31
	72 %	0.00	20.68	31.02	41.36	51.70	62.04	-4.76	15.92	26.26	36.60	46.94	57.28
	71 %	0.00	20.67	31.00	41.34	51.67	62.01	-4.76	15.91	26.25	36.58	46.92	57.25
	70 %	0.00	20.66	30.99	41.32	51.65	61.98	-4.76	15.90	26.23	36.56	46.89	57.22

		D_n [Acidification] – LRS scenario						D_n [Acidification] – HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	*100 %*	0.00	3.37	5.05	6.74	8.42	10.11	-0.45	2.92	4.60	6.29	8.42	9.66
	99 %	0.00	3.20	4.80	6.40	8.00	9.61	-0.45	2.75	4.35	5.95	8.00	9.15
	98 %	0.00	3.03	4.55	6.07	7.58	9.10	-0.45	2.58	4.10	5.62	7.58	8.65
	97 %	0.00	2.87	4.30	5.73	7.17	8.60	-0.45	2.42	3.85	5.28	7.17	8.15
	96 %	0.00	2.70	4.05	5.40	6.75	8.09	-0.45	2.25	3.60	4.95	6.75	7.64
	95 %	0.00	2.53	3.80	5.06	6.33	7.59	-0.45	2.08	3.35	4.61	6.33	7.14
	94 %	0.00	2.36	3.54	4.73	5.91	7.09	-0.45	1.91	3.09	4.27	5.91	6.64
	93 %	0.00	2.19	3.29	4.39	5.49	6.58	-0.45	1.74	2.84	3.94	5.49	6.13
	92 %	0.00	2.03	3.04	4.05	5.07	6.08	-0.45	1.58	2.59	3.60	5.07	5.63
	91 %	0.00	1.86	2.79	3.72	4.65	5.58	-0.45	1.41	2.34	3.27	4.65	5.13
	90 %	0.00	1.69	2.54	3.38	4.23	5.07	-0.45	1.24	2.09	2.93	4.23	4.62
	89 %	0.00	1.52	2.29	3.05	3.81	4.57	-0.45	1.07	1.83	2.60	3.81	4.12
	88 %	0.00	1.36	2.03	2.71	3.39	4.07	-0.45	0.91	1.58	2.26	3.39	3.62
	87 %	0.00	1.19	1.78	2.38	2.97	3.56	-0.45	0.74	1.33	1.93	2.97	3.11
	86 %	0.00	1.02	1.53	2.04	2.55	3.06	-0.45	0.57	1.08	1.59	2.55	2.61
	85 %	0.00	0.85	1.28	1.70	2.13	2.56	-0.45	0.40	0.83	1.25	2.13	2.11
	84 %	0.00	0.68	1.03	1.37	1.71	2.05	-0.45	0.23	0.58	0.92	1.71	1.60
	83 %	0.00	0.52	0.78	1.03	1.29	1.55	-0.45	0.07	0.32	0.58	1.29	1.10
	82 %	0.00	0.35	0.52	0.70	0.87	1.05	-0.45	-0.10	0.07	0.25	0.87	0.60
	81 %	0.00	0.18	0.27	0.36	0.45	0.54	-0.45	-0.27	-0.18	-0.09	0.45	0.09
	80 %	0.00	0.01	0.02	0.03	0.03	0.04	-0.45	-0.44	-0.43	-0.42	0.03	-0.41
	79 %	0.00	-0.15	-0.23	-0.31	-0.39	-0.46	-0.45	-0.60	-0.68	-0.76	-0.39	-0.91
	78 %	0.00	-0.32	-0.48	-0.64	-0.81	-0.97	-0.45	-0.77	-0.93	-1.09	-0.81	-1.42
	77 %	0.00	-0.49	-0.74	-0.98	-1.23	-1.47	-0.45	-0.94	-1.19	-1.43	-1.23	-1.92
	76 %	0.00	-0.66	-0.99	-1.32	-1.64	-1.97	-0.45	-1.11	-1.44	-1.77	-1.64	-2.42
	75 %	0.00	-0.83	-1.24	-1.65	-2.06	-2.48	-0.45	-1.28	-1.69	-2.10	-2.06	-2.93
	74 %	0.00	-0.99	-1.49	-1.99	-2.48	-2.98	-0.45	-1.44	-1.94	-2.44	-2.48	-3.43
	73 %	0.00	-1.16	-1.74	-2.32	-2.90	-3.48	-0.45	-1.61	-2.19	-2.77	-2.90	-3.93
	72 %	0.00	-1.33	-1.99	-2.66	-3.32	-3.99	-0.45	-1.,78	-2.44	-3.11	-3.32	-4.44
	71 %	0.00	-1.50	-2.25	-2.99	-3.74	-4.49	-0.45	-1.95	-2.70	-3.44	-3.74	-4.94
	70 %	0.00	-1.66	-2.50	-3.33	-4.16	-4.99	-0.45	-2.12	-2.95	-3.78	-4.16	-5.44

D_n [Ecotoxicity for aquatic fresh water] – LRS scenario								D_n [Ecotoxicity for aquatic fresh water] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	20.04	30.07	40.09	50.11	60.13	-0.95	19.09	29.11	39.14	49.16	59.18
	99 %	0.00	20.04	30.05	40.07	50.09	60.11	-0.95	19.08	29.10	39.12	49.14	59.15
	98 %	0.00	20.03	30.04	40.05	50.07	60.08	-0.95	19.07	29.09	39.10	49.11	59.13
	97 %	0.00	20.02	30.03	40.03	50.04	60.05	-0.95	19.06	29.07	39.08	49.09	59.10
	96 %	0.00	20.01	30.01	40.02	50.02	60.02	-0.95	19.06	29.06	39.06	49.07	59.07
	95 %	0.00	20.00	30.00	40.00	50.00	60.00	-0.95	19.05	29.05	39.04	49.04	59.04
	94 %	0.00	19.99	29.98	39.98	49.97	59.97	-0.95	19.04	29.03	39.03	49.02	59.02
	93 %	0.00	19.98	29.97	39.96	49.95	59.94	-0.95	19.03	29.02	39.01	49.00	58.99
	92 %	0.00	19.97	29.96	39.94	49.93	59.91	-0.95	19.02	29.00	38.99	48.98	58.96
	91 %	0.00	19.96	29.94	39.93	49.91	59.89	-0.95	19.01	28.99	38.97	48.95	58.93
	90 %	0.00	19.95	29.93	39.91	49.88	59.86	-0.95	19.00	28.98	38.95	48.93	58.91
	89 %	0.00	19.94	29.92	39.89	49.86	59.83	-0.95	18.99	28.96	38.94	48.91	58.88
	88 %	0.00	19.94	29.90	39.87	49.84	59.81	-0.95	18.98	28.95	38.92	48.89	58.85
	87 %	0.00	19.93	29.89	39.85	49.82	59.78	-0.95	18.97	28.94	38.90	48.86	58.83
	86 %	0.00	19.92	29.88	39.83	49.79	59.75	-0.95	18.96	28.92	38.88	48.84	58.80
	85 %	0.00	19.91	29.86	39.82	49.77	59.72	-0.95	18.96	28.91	38.86	48.82	58.77
	84 %	0.00	19.90	29.85	39.80	49.75	59.70	-0.95	18.95	28.90	38.84	48.79	58.74
	83 %	0.00	19.89	29.83	39.78	49.72	59.67	-0.95	18.94	28.88	38.83	48.77	58.72
	82 %	0.00	19.88	29.82	39.76	49.70	59.64	-0.95	18.93	28.87	38.81	48.75	58.69
	81 %	0.00	19.87	29.81	39.74	49.68	59.62	-0.95	18.92	28.85	38.79	48.73	58.66
	80 %	0.00	19.86	29.79	39.73	49.66	59.59	-0.95	18.91	28.84	38.77	48.70	58.63
	79 %	0.00	19.85	29.78	39.71	49.63	59.56	-0.95	18.90	28.83	38.75	48.68	58.61
	78 %	0.00	19.84	29.77	39.69	49.61	59.53	-0.95	18.89	28.81	38.74	48.66	58.58
	77 %	0.00	19.84	29.75	39.67	49.59	59.51	-0.95	18.88	28.80	38.72	48.64	58.55
	76 %	0.00	19.83	29.74	39.65	49.57	59.48	-0.95	18.87	28.79	38.70	48.61	58.53
	75 %	0.00	19.82	29.73	39.63	49.54	59.45	-0.95	18,.86	28.77	38.68	48.59	58.50
	74 %	0.00	19.81	29.71	39.62	49.52	59.42	-0.95	18.86	28.76	38.66	48.57	58.47
	73 %	0.00	19.80	29.70	39.60	49.50	59.40	-0.95	18.85	28.75	38.65	48.54	58.44
	72 %	0.00	19.79	29.68	39.58	49.47	59.37	-0.95	18.84	28,.73	38.63	48.52	58.42
	71 %	0.00	19.78	29.67	39.56	49.45	59.34	-0.95	18.83	28.72	38.61	48.50	58.39
	70 %	0.00	19.77	29.66	39.54	49.43	59.32	-0.95	18.82	28.70	38.59	48.48	58.36

		D_n [Freshwater eutrophication] – LRS scenario						D_n [Freshwater eutrophication] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	11.05	16.58	22.10	27.63	33.15	-1.54	9.51	15.03	20.56	26.09	31.61
	99 %	0.00	10.96	16.43	21.91	27.39	32.87	-1.54	9.42	14.89	20.37	25.85	31.33
	98 %	0.00	10.86	16.29	21.72	27.15	32.58	-1.54	9.32	14.75	20.18	25.61	31.04
	97 %	0.00	10.77	16.15	21.53	26.92	32.30	-1.54	9.23	14.61	19.99	25.38	30.76
	96 %	0.00	10.67	16.01	21.34	26.68	32.02	-1.54	9.13	14.47	19.80	25.14	30.47
	95 %	0.00	10.58	15.87	21.15	26.44	31.73	-1.54	9.04	14.33	19.61	24.90	30.19
	94 %	0.00	10.48	15.72	20.97	26.21	31.45	-1.54	8.94	14.18	19.42	24.67	29.91
	93 %	0.00	10.39	15.58	20.78	25.97	31.16	-1.54	8.85	14.04	19.24	24.43	29.62
	92 %	0.00	10.29	15.44	20.59	25.73	30.88	-1.54	8.75	13.90	19.05	24.19	29.34
	91 %	0.00	10.20	15.30	20.40	25.50	30.60	-1.54	8.66	13.76	18.86	23.96	29.06
	90 %	0.00	10.10	15.16	20.21	25.26	30.31	-1.54	8.56	13.62	18.67	23.72	28.77
	89 %	0.00	10.01	15.01	20.02	25.02	30.03	-1.54	8.47	13.47	18.48	23.48	28.49
	88 %	0.00	9.91	14.87	19.83	24.79	29.74	-1.54	8.37	13.33	18.29	23.25	28.20
	87 %	0.00	9.82	14.73	19.64	24.55	29.46	-1.54	8.28	13.19	18.10	23.01	27.92
	86 %	0.00	9.73	14.59	19.45	24.31	29.18	-1.54	8.18	13.05	17.91	22.77	27.64
	85 %	0.00	9.63	14.45	19.26	24.08	28.89	-1.54	8.09	12.91	17.72	22.54	27.35
	84 %	0.00	9.54	14.30	19.07	23.84	28.61	-1.54	8.00	12.76	17.53	22.30	27.07
	83 %	0.00	9.44	14.16	18.88	23.60	28.32	-1.54	7.90	12.62	17.34	22.06	26.78
	82 %	0.00	9.35	14.02	18.69	23.37	28.04	-1.54	7.81	12.48	17.15	21.83	26.50
	81 %	0.00	9.25	13.88	18.50	23.13	27.76	-1.54	7.71	12.34	16.96	21.59	26.22
	80 %	0.00	9.16	13.74	18.32	22.89	27.47	-1.54	7.62	12.20	16.77	21.35	25.93
	79 %	0.00	9.06	13.59	18.13	22.66	27.19	-1.54	7.52	12.05	16.59	21.12	25.65
	78 %	0.00	8.97	13.45	17.94	22.42	26.91	-1.54	7.43	11.91	16.40	20.88	25.36
	77 %	0.00	8.87	13.31	17.75	22.18	26.62	-1.54	7.33	11.77	16.21	20.64	25.08
	76 %	0.00	8.78	13.17	17.56	21.95	26.34	-1.54	7.24	11.63	16.02	20.41	24.80
	75 %	0.00	8.68	13.03	17.37	21.71	26.05	-1.54	7.14	11.49	15.83	20.17	24.51
	74 %	0.00	8.59	12.88	17,.18	21.47	25.77	-1.54	7.05	11.34	15.64	19.93	24.23
	73 %	0.00	8.50	12.74	16.99	21.24	25.49	-1.54	6.95	11.20	15.45	19.70	23.95
	72 %	0.00	8.40	12.60	16.80	21.00	25.20	-1.54	6.86	11.06	15.26	19.46	23.66
	71 %	0.00	8.31	12.46	16.61	20.77	24.92	-1.54	6.77	10.92	15.07	19.22	23.38
	70 %	0.00	8.21	12.32	16.42	20.53	24.63	-1.54	6.67	10.78	14.88	18.99	23.09

D_n [Human toxicity cancer effects] – LRS scenario								D_n [Human toxicity cancer effects] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	14.27	21.40	28.54	35.67	42.81	-3.32	10.95	18.08	25.22	32.35	39.48
	99 %	0.00	14.20	21.31	28.41	35.51	42.61	-3.32	10.88	17.98	25.09	32.19	39.29
	98 %	0.00	14.14	21.21	28.28	35.35	42.42	-3.32	10.82	17.89	24.96	32.03	39.10
	97 %	0.00	14.08	21.12	28.15	35.19	42.23	-3.32	10.75	17.79	24.83	31.87	38.91
	96 %	0.00	14.01	21.02	28.03	35.03	42.04	-3.32	10.69	17.70	24.70	31.71	38.72
	95 %	0.00	13.95	20.92	27.90	34.87	41.85	-3.32	10.63	17.60	24.58	31.55	38.52
	94 %	0.00	13.89	20.83	27.77	34.71	41.66	-3.32	10.56	17.51	24.45	31.39	38.33
	93 %	0.00	13.82	20.73	27.64	34.55	41.46	-3.32	10.50	17.41	24.32	31.23	38.14
	92 %	0.00	13.76	20.64	27.51	34.39	41.27	-3.32	10.43	17.31	24.19	31.07	37.95
	91 %	0.00	13.69	20.54	27.39	34.23	41.08	-3.32	10.37	17.22	24.06	30.91	37.76
	90 %	0.00	13.63	20.44	27.26	34.07	40.89	-3.32	10.31	17.12	23.94	30.75	37.57
	89 %	0.00	13.57	20.35	27.13	33.91	40.70	-3.32	10.24	17.03	23.81	30.59	37.37
	88 %	0.00	13.50	20.25	27.00	33.75	40.50	-3.32	10.18	16.93	23.68	30.43	37.18
	87 %	0.00	13.44	20.16	26.88	33.59	40.31	-3.32	10.11	16.83	23.55	30.27	36.99
	86 %	0.00	13.37	20.06	26.75	33.43	40.12	-3.32	10.05	16.74	23.42	30.11	36.80
	85 %	0.00	13.31	19.96	26.62	33.27	39.93	-3.32	9.99	16.64	23.30	29.95	36.61
	84 %	0.00	13.25	19.87	26.49	33.11	39.74	-3.32	9.92	16.55	23.17	29.79	36.41
	83 %	0.00	13.18	19.77	26.36	32.95	39.55	-3.32	9.86	16.45	23.04	29.63	36.22
	82 %	0.00	13.12	19.68	26.24	32.79	39.35	-3.32	9.80	16.35	22.91	29.47	36.03
	81 %	0.00	13.05	19.58	26.11	32.63	39.16	-3.32	9.73	16.26	22.78	29.31	35.84
	80 %	0.00	12.99	19.48	25.98	32.47	38.97	-3.32	9.67	16.16	22.66	29.15	35.65
	79 %	0.00	12.93	19.39	25.85	32.31	38.78	-3.32	9.60	16.07	22.53	28.99	35.46
	78 %	0.00	12.86	19.29	25.72	32.15	38.59	-3.32	9.54	15.97	22.40	28.83	35.26
	77 %	0.00	12.80	19.20	25.60	31.99	38.39	-3.32	9.48	15.87	22.27	28.67	35.07
	76 %	0.00	12.73	19.10	25.47	31.83	38.20	-3.32	9.41	15.78	22.15	28.51	34.88
	75 %	0.00	12.67	19.01	25.34	31.68	38.01	-3.32	9.35	15.68	22.02	28.35	34.69
	74 %	0.00	12.61	18.91	25.21	31.52	37.82	-3.32	9.28	15.59	21.89	28.19	34.50
	73 %	0.00	12.54	18.81	25.08	31.36	37.63	-3.32	9.22	15.49	21.76	28.03	34.30
	72 %	0.00	12.48	18.72	24.96	31.20	37.43	-3.32	9.16	15.39	21.63	27.87	34.11
	71 %	0.00	12.41	18.62	24.83	31.04	37.24	-3.32	9.09	15.30	21.51	27.71	33.92
	70 %	0.00	12.35	18.53	24.70	30.88	37.05	-3.32	9.03	15.20	21.38	27.55	33.73

		D_n [Human toxicity non-canc. effect] – LRS scenario						D_n [Human toxicity non-canc. effect] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	14.42	21.62	28.83	36.04	43.25	-2.04	12.37	19.58	26.79	34.00	41.20
	99 %	0.00	14.35	21.53	28.71	35.88	43.06	-2.04	12.31	19.49	26.66	33.84	41.02
	98 %	0.00	14.29	21.44	28.58	35.73	42.87	-2.04	12.25	19.39	26.54	33.68	40.83
	97 %	0.00	14.23	21.34	28.46	35.57	42.68	-2.04	12.18	19.30	26.41	33.53	40.64
	96 %	0.00	14.17	21.25	28.33	35.41	42.50	-2.04	12.12	19.20	26.29	33.37	40.45
	95 %	0.00	14.10	21.15	28.21	35.26	42.31	-2.04	12.06	19.11	26.16	33.21	40.26
	94 %	0.00	14.04	21.06	28.08	35.10	42.12	-2.04	12.00	19.02	26.04	33.06	40.08
	93 %	0.00	13.98	20.97	27.95	34.94	41.93	-2.04	11.93	18.92	25.91	32.90	39.89
	92 %	0.00	13.91	20.87	27.83	34.79	41.74	-2.04	11.87	18.83	25.79	32.74	39.70
	91 %	0.00	13.85	20.78	27.70	34.63	41.56	-2.04	11.81	18.73	25.66	32.59	39.51
	90 %	0.00	13.79	20.68	27.58	34.47	41.37	-2.04	11.75	18.64	25.53	32.43	39.32
	89 %	0.00	13.73	20.59	27.45	34.32	41.18	-2.04	11.68	18.55	25.41	32.27	39.14
	88 %	0.00	13.66	20.50	27.33	34.16	40.99	-2.04	11.62	18.45	25.28	32.12	38.95
	87 %	0.00	13.60	20.40	27.20	34.00	40.80	-2.04	11.56	18.36	25.16	31.96	38.76
	86 %	0.00	13.54	20.31	27.08	33.85	40.62	-2.04	11.49	18.26	25.03	31.80	38.57
	85 %	0.00	13.48	20.21	26.95	33.69	40.43	-2.04	11.43	18.17	24.91	31.65	38.38
	84 %	0.00	13.41	20.12	26.83	33.53	40.24	-2.04	11.37	18.08	24.78	31.49	38.20
	83 %	0.00	13.35	20.03	26.70	33.38	40.05	-2.04	11.31	17.98	24.66	31.33	38.01
	82 %	0.00	13.29	19.93	26.58	33.22	39.86	-2.04	11.24	17.89	24.53	31.18	37.82
	81 %	0.00	13.23	19.84	26.45	33.06	39.68	-2.04	11.18	17.79	24.41	31.02	37.63
	80 %	0.00	13.16	19.74	26.33	32.91	39.49	-2.04	11.12	17.70	24.28	30.86	37.44
	79 %	0.00	13.10	19.65	26.20	32.75	39.30	-2.04	11.06	17.61	24.16	30.71	37.26
	78 %	0.00	13.04	19.56	26.07	32.59	39.11	-2.04	10.99	17.51	24.03	30.55	37.07
	77 %	0.00	12.97	19.46	25.95	32.44	38.92	-2.04	10.93	17.42	23.91	30.39	36.88
	76 %	0.00	12.91	19.37	25.82	32.28	38.74	-2.04	10.87	17.32	23.78	30.24	36.69
	75 %	0.00	12.85	19.27	25.70	32.12	38.55	-2.04	10.81	17.23	23.65	30.08	36.50
	74 %	0.00	12.79	19.18	25.57	31.97	38.36	-2.04	10.74	17.14	23.53	29.92	36.32
	73 %	0.00	12.72	19.09	25.45	31.81	38.17	-2.04	10.68	17.04	23.40	29.77	36.13
	72 %	0.00	12.66	18.99	25.32	31.65	37.98	-2.04	10.62	16.95	23.28	29.61	35.94
	71 %	0.00	12.60	18.90	25.20	31.50	37.80	-2.04	10.55	16.85	23.15	29.45	35.75
	70 %	0.00	12.54	18.80	25.07	31.34	37.61	-2.04	10.49	16.76	23.03	29.30	35.56

D_n [Ionising radiation, human health effect] – LRS scenario								D_n [Ionising radiation, human health effect] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	11.74	17.61	23.48	29.35	35.22	-0.50	11.24	17.11	22.98	28.85	34.72
	99 %	0.00	11.65	17.48	23.30	29.13	34.96	-0.50	11.16	16.98	22.81	28.63	34.46
	98 %	0.00	11.56	17.35	23.13	28.91	34.69	-0.50	11.07	16.85	22.63	28.42	34.20
	97 %	0.00	11.48	17.22	22.95	28.69	34.43	-0.50	10.98	16.72	22.46	28.20	33.94
	96 %	0.00	11.39	17.08	22.78	28.47	34.17	-0.50	10.89	16.59	22.28	27.98	33.67
	95 %	0.00	11.30	16.95	22.60	28.25	33.91	-0.50	10.81	16.46	22.11	27.76	33.41
	94 %	0.00	11.21	16.82	22.43	28.04	33.64	-0.50	10.72	16.33	21.93	27.54	33.15
	93 %	0.00	11.13	16.69	22.25	27.82	33.38	-0.50	10.63	16.19	21.76	27.32	32.88
	92 %	0.00	11.04	16.56	22.08	27.60	33.12	-0.50	10.54	16.06	21.58	27.10	32.62
	91 %	0.00	10.95	16.43	21.90	27.38	32.86	-0.50	10.46	15.93	21.41	26.88	32.36
	90 %	0.00	10.86	16.30	21.73	27.16	32.59	-0.50	10.37	15.80	21.23	26.66	32.10
	89 %	0.00	10.78	16.16	21.55	26.94	32.33	-0.50	10.28	15.67	21.06	26.45	31.83
	88 %	0.00	10.69	16.03	21.38	26.72	32.07	-0.50	10.19	15.54	20.88	26.23	31.57
	87 %	0.00	10.60	15.90	21.20	26.50	31.80	-0.50	10.11	15.41	20.71	26.01	31.31
	86 %	0.00	10.51	15.77	21.03	26.28	31.54	-0.50	10.02	15.27	20.53	25.79	31.05
	85 %	0.00	10.43	15.64	20.85	26.07	31.28	-0.50	9.93	15.14	20.36	25.57	30.78
	84 %	0.00	10.34	15.51	20.68	25.85	31.02	-0.50	9.84	15.01	20.18	25.35	30.52
	83 %	0.00	10.25	15.38	20.50	25.63	30.75	-0.50	9.75	14.88	20.01	25.13	30.26
	82 %	0.00	10.16	15.25	20.33	25.41	30.49	-0.50	9.67	14.75	19.83	24.91	29.99
	81 %	0.00	10.08	15.11	20.15	25.19	30.23	-0.50	9.58	14.62	19.66	24.69	29.73
	80 %	0.00	9.99	14.98	19.98	24.97	29.97	-0.50	9.49	14.49	19.48	24.48	29.47
	79 %	0.00	9.90	14.85	19.80	24.75	29.70	-0.50	9.40	14.36	19.31	24.26	29.21
	78 %	0.00	9.81	14.72	19.63	24.53	29.44	-0.50	9.32	14.22	19.13	24.04	28.94
	77 %	0.00	9.73	14.59	19.45	24.31	29.18	-0.50	9.23	14.09	18.96	23.82	28.68
	76 %	0.00	9.64	14.46	19.28	24.10	28.91	-0.50	9.14	13.96	18.78	23.60	28.42
	75 %	0.00	9.55	14.33	19.10	23.88	28.65	-0.50	9.05	13.83	18.61	23.38	28.16
	74 %	0.00	9.46	14.19	18.93	23.66	28.39	-0.50	8.97	13.70	18.43	23.16	27.89
	73 %	0.00	9.38	14.06	18.75	23.44	28.13	-0.50	8.88	13.57	18.25	22.94	27.63
	72 %	0.00	9.29	13.93	18.58	23.22	27.86	-0.50	8.79	13.44	18.08	22.72	27.37
	71 %	0.00	9.20	13.80	18.40	23.00	27.60	-0.50	8.70	13.30	17.90	22.50	27.11
	70 %	0.00	9.11	13.67	18.23	22.78	27.34	-0.50	8.62	13.17	17.73	22.29	26.84

		D_n [GWP, excl. biogenic carbon] – LRS scenario						D_n [GWP, excl. biogenic carbon] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	4.10	6.16	8.21	10.26	12.31	-0.56	3.55	5.60	7.65	9.70	11.76
	99 %	0.00	3.94	5.91	7.89	9.86	11.83	-0.56	3.39	5.36	7.33	9.30	11.27
	98 %	0.00	3.78	5.67	7.56	9.46	11.35	-0.56	3.23	5.12	7.01	8.90	10.79
	97 %	0.00	3.62	5.43	7.24	9.05	10.86	-0.56	3.07	4.88	6.69	8.50	10.31
	96 %	0.00	3.46	5.19	6.92	8.65	10.38	-0.56	2.91	4.64	6.37	8.10	9.83
	95 %	0.00	3.30	4.95	6.60	8.25	9.90	-0.56	2.74	4.39	6.04	7.69	9.34
	94 %	0.00	3.14	4.71	6.28	7.85	9.42	-0.56	2.58	4.15	5.72	7.29	8.86
	93 %	0.00	2.98	4.47	5.96	7.45	8.93	-0.56	2.42	3.91	5.40	6.89	8.38
	92 %	0.00	2.82	4.23	5.63	7.04	8.45	-0.56	2.26	3.67	5.08	6.49	7.90
	91 %	0.00	2.66	3.98	5.31	6.64	7.97	-0.56	2.10	3.43	4.76	6.09	7.41
	90 %	0.00	2.50	3.74	4.99	6.24	7.49	-0.56	1.94	3.19	4.44	5.68	6.93
	89 %	0.00	2.33	3.50	4.67	5.84	7.00	-0.56	1.78	2.95	4.11	5.28	6.45
	88 %	0.00	2.17	3.26	4.35	5.44	6.52	-0.56	1.62	2.71	3.79	4.88	5.97
	87 %	0.00	2.01	3.02	4.03	5.03	6.04	-0.56	1.46	2.46	3.47	4.48	5.48
	86 %	0.00	1.85	2.78	3.71	4.63	5.56	-0.56	1.30	2.22	3.15	4.08	5.00
	85 %	0.00	1.69	2.54	3.38	4.23	5.08	-0.56	1.14	1.98	2.83	3.67	4.52
	84 %	0.00	1.53	2.30	3.06	3.83	4.59	-0.56	0.98	1.74	2.51	3.27	4.04
	83 %	0.00	1.37	2.06	2.74	3.43	4.11	-0.56	0.81	1.50	2.18	2.87	3.55
	82 %	0.00	1.21	1.81	2.42	3.02	3.63	-0.56	0.65	1.26	1.86	2.47	3.07
	81 %	0.00	1.05	1.57	2.10	2.62	3.15	-0.56	0.49	1.02	1.54	2.07	2.59
	80 %	0.00	0.89	1.33	1.78	2.22	2.66	-0.56	0.33	0.78	1.22	1.66	2.11
	79 %	0.00	0.73	1.09	1.45	1.82	2.18	-0.56	0.17	0.53	0.90	1.26	1.63
	78 %	0.00	0.57	0.85	1.13	1.42	1.70	-0.56	0.01	0.29	0.58	0.86	1.14
	77 %	0.00	0.41	0.61	0.81	1.01	1.22	-0.56	-0.15	0.05	0.26	0.46	0.66
	76 %	0.00	0.24	0.37	0.49	0.61	0.73	-0.56	-0.31	-0.19	-0.07	0.06	0.18
	75 %	0.00	0.08	0.13	0.17	0.21	0.25	-0.56	-0.47	-0.43	-0.39	-0.35	-0.30
	74 %	0.00	-0.08	-0.12	-0.15	-0.19	-0.23	-0.56	-0.63	-0.67	-0.71	-0.75	-0.79
	73 %	0.00	-0.24	-0.36	-0.48	-0.60	-0.71	-0.56	-0.79	-0.91	-1.03	-1.15	-1.27
	72 %	0.00	-0.40	-0.60	-0.80	-1.00	-1.20	-0.56	-0.95	-1.15	-1.35	-1.55	-1.75
	71 %	0.00	-0.56	-0.84	-1.12	-1.40	-1.68	-0.56	-1.11	-1.39	-1.67	-1.95	-2.23
	70 %	0.00	-0.72	-1.08	-1.44	-1.80	-2.16	-0.56	-1.28	-1.64	-2.00	-2.36	-2.72

D_n [Marine eutrophication] – LRS scenario								D_n [Marine eutrophication] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	9.78	14.68	19.57	24.46	29.35	-1.32	8.46	13.35	18.24	23.14	28.03
	99 %	0.00	9.68	14.52	19.35	24.19	29.03	-1.32	8.35	13.19	18.03	22.87	27.71
	98 %	0.00	9.57	14.36	19.14	23.93	28.71	-1.32	8.25	13.03	17.82	22.60	27.39
	97 %	0.00	9.46	14.20	18.93	23.66	28.39	-1.32	8.14	12.87	17.60	22.34	27.07
	96 %	0.00	9.36	14.04	18.71	23.39	28.07	-1.32	8.03	12.71	17.39	22.07	26.75
	95 %	0.00	9.25	13.88	18.50	23.13	27.75	-1.32	7.93	12.55	17.18	21.80	26.43
	94 %	0.00	9.14	13.72	18.29	22.86	27.43	-1.32	7.82	12.39	16.96	21.54	26.11
	93 %	0.00	9.04	13.56	18.08	22.59	27.11	-1.32	7.71	12.23	16.75	21.27	25.79
	92 %	0.00	8.93	13.40	17.86	22.33	26.79	-1.32	7.61	12.07	16.54	21.00	25.47
	91 %	0.00	8.82	13.24	17.65	22.06	26.47	-1.32	7.50	11.91	16.33	20.74	25.15
	90 %	0.00	8.72	13.08	17.44	21.79	26.15	-1.32	7.39	11.75	16.11	20.47	24.83
	89 %	0.00	8.61	12.92	17.22	21.53	25.83	-1.32	7.29	11.59	15.90	20.20	24.51
	88 %	0.00	8.50	12.76	17.01	21.26	25.51	-1.32	7.18	11.43	15.69	19.94	24.19
	87 %	0.00	8.40	12.60	16.80	21.00	25.19	-1.32	7.07	11.27	15.47	19.67	23.87
	86 %	0.00	8.29	12.44	16.58	20.73	24.87	-1.32	6.97	11.11	15.26	19.41	23.55
	85 %	0.00	8.18	12.28	16.37	20.46	24.55	-1.32	6.86	10.95	15.05	19.14	23.23
	84 %	0.00	8.08	12.12	16.16	20.20	24.24	-1.32	6.75	10.79	14.83	18.87	22.91
	83 %	0.00	7.97	11.96	15.94	19.93	23.92	-1.32	6.65	10.63	14.62	18.61	22.59
	82 %	0.00	7.87	11.80	15.73	19.66	23.60	-1.32	6.54	10.47	14.41	18.34	22.27
	81 %	0.00	7.76	11.64	15.52	19.40	23.28	-1.32	6.44	10.31	14.19	18.07	21.95
	80 %	0.00	7.65	11.48	15.30	19.13	22.96	-1.32	6.33	10.15	13.98	17.81	21.63
	79 %	0.00	7.55	11.32	15.09	18.86	22.64	-1.32	6.22	9.99	13.77	17.54	21.31
	78 %	0.00	7.44	11.16	14.88	18.60	22.32	-1.32	6.12	9.83	13.55	17.27	20.99
	77 %	0.00	7.33	11.00	14.66	18.33	22.00	-1.32	6.01	9.68	13.34	17.01	20.67
	76 %	0.00	7.23	10.84	14.45	18.06	21.68	-1.32	5.90	9.52	13.13	16.74	20.35
	75 %	0.00	7.12	10.68	14.24	17.80	21.36	-1.32	5.80	9.36	12.91	16.47	20.03
	74 %	0.00	7.01	10.52	14.03	17.53	21.04	-1.32	5.69	9.20	12.70	16.21	19.71
	73 %	0.00	6.91	10.36	13.81	17.27	20.72	-1.32	5.58	9.04	12.49	15.94	19.39
	72 %	0.00	6.80	10.20	13.60	17.00	20.40	-1.32	5.48	8.88	12.28	15.68	19.08
	71 %	0.00	6.69	10.04	13.39	16.73	20.08	-1.32	5.37	8.72	12.06	15.41	18.76
	70 %	0.00	6.59	9.88	13.17	16.47	19.76	-1.32	5.26	8.56	11.85	15.14	18.44

		D_n [Ozone depletion] – LRS scenario						D_n [Ozone depletion] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	4.33	6.50	8.66	10.83	12.99	-0.19	4.14	6.30	8.47	10.63	12.80
	99 %	0.00	4.17	6.26	8.34	10.43	12.51	-0.19	3.98	6.07	8.15	10.24	12.32
	98 %	0.00	4.01	6.02	8.03	10.03	12.04	-0.19	3.82	5.83	7.84	9.84	11.85
	97 %	0.00	3.85	5.78	7.71	9.64	11.56	-0.19	3.66	5.59	7.52	9.45	11.37
	96 %	0.00	3.70	5.54	7.39	9.24	11.09	-0.19	3.51	5.35	7.20	9.05	10.90
	95 %	0.00	3.54	5.31	7.07	8.84	10.61	-0.19	3.35	5.11	6.88	8.65	10.42
	94 %	0.00	3.38	5.07	6.76	8.45	10.14	-0.19	3.19	4.88	6.57	8.26	9.94
	93 %	0.00	3.22	4.83	6.44	8.05	9.66	-0.19	3.03	4.64	6.25	7.86	9.47
	92 %	0.00	3.06	4.59	6.12	7.65	9.18	-0.19	2.87	4.40	5.93	7.46	8.99
	91 %	0.00	2.90	4.35	5.81	7.26	8.71	-0.19	2.71	4.16	5.61	7.07	8.52
	90 %	0.00	2.74	4.12	5.49	6.86	8.23	-0.19	2.55	3.93	5.30	6.67	8.04
	89 %	0.00	2.59	3.88	5.17	6.46	7.76	-0.19	2.39	3.69	4.98	6.27	7.57
	88 %	0.00	2.43	3.64	4.85	6.07	7.28	-0.19	2.24	3.45	4.66	5.88	7.09
	87 %	0.00	2.27	3.40	4.54	5.67	6.80	-0.19	2.08	3.21	4.35	5.48	6.61
	86 %	0.00	2.11	3.16	4.22	5.27	6.33	-0.19	1.92	2.97	4.03	5.08	6.14
	85 %	0.00	1.95	2.93	3.90	4.88	5.85	-0.19	1.76	2.74	3.71	4.69	5.66
	84 %	0.00	1.79	2.69	3.58	4.48	5.38	-0.19	1.60	2.50	3.39	4.29	5.19
	83 %	0.00	1.63	2.45	3.27	4.08	4.90	-0.19	1.44	2.26	3.08	3.89	4.71
	82 %	0.00	1.48	2.21	2.95	3.69	4.43	-0.19	1.28	2.02	2.76	3.50	4.23
	81 %	0.00	1.32	1.97	2.63	3.29	3.95	-0.19	1.13	1.78	2.44	3.10	3.76
	80 %	0.00	1.16	1.74	2.32	2.89	3.47	-0.19	0.97	1.55	2.13	2.70	3.28
	79 %	0.00	1.00	1.50	2.00	2.50	3.00	-0.19	0.81	1.31	1.81	2.31	2.81
	78 %	0.00	0.84	1.26	1.68	2.10	2.52	-0,19	0.65	1.07	1.49	1.91	2.33
	77 %	0.00	0.68	1.02	1.36	1.71	2.05	-0.19	0.49	0.83	1.17	1.51	1.86
	76 %	0.00	0.52	0.79	1.05	1.31	1.57	-0.19	0.33	0.59	0.86	1.12	1.38
	75 %	0.00	0.36	0.55	0.73	0.91	1.09	-0.19	0.17	0.36	0.54	0.72	0.90
	74 %	0.00	0.21	0.31	0.41	0.52	0.62	-0.19	0.02	0.12	0.22	0.33	0.43
	73 %	0.00	0.05	0.07	0.10	0.12	0.14	-0.19	-0.14	-0.12	-0.10	-0.07	-0.05
	72 %	0.00	-0.11	-0.17	-0.22	-0.28	-0.33	-0.19	-0.30	-0.36	-0.41	-0.47	-0.52
	71 %	0.00	-0.27	-0.40	-0.54	-0.67	-0.81	-0.19	-0.46	-0.59	-0.73	-0.86	-1.00
	70 %	0.00	-0.43	-0.64	-0.86	-1.07	-1.28	-0.19	-0.62	-0.83	-1.05	-1.26	-1.47

D_n [Particulate matter/Respiratory inorganics] – LRS scenario								D_n [Particulate matter/Respiratory inorganics] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	3.72	5.58	7.44	9.30	11.16	-0.17	3.55	5.42	7.28	9.14	11.00
	99 %	0.00	3.56	5.33	7.11	8.89	10.67	-0.17	3.39	5.17	6.95	8.72	10.50
	98 %	0.00	3.39	5.09	6.78	8.48	10.18	-0.17	3.23	4.92	6.62	8.31	10.01
	97 %	0.00	3.23	4.84	6.45	8.07	9.68	-0.17	3.06	4.68	6.29	7.90	9.52
	96 %	0.00	3.06	4.59	6.13	7.66	9.19	-0.17	2.90	4.43	5.96	7.49	9.02
	95 %	0.00	2.90	4.35	5.80	7.25	8.70	-0.17	2.73	4.18	5.63	7.08	8.53
	94 %	0.00	2.73	4.10	5.47	6.84	8.20	-0.17	2.57	3.94	5.30	6.67	8.04
	93 %	0.00	2.57	3.85	5.14	6.42	7.71	-0.17	2.40	3.69	4.97	6.26	7.54
	92 %	0.00	2.41	3.61	4.81	6.01	7.22	-0.17	2.24	3.44	4.64	5.85	7.05
	91 %	0.00	2.24	3.36	4.48	5.60	6.72	-0.17	2.07	3.19	4.32	5.44	6.56
	90 %	0.00	2.08	3.11	4.15	5.19	6.23	-0.17	1.91	2.95	3.99	5.02	6.06
	89 %	0.00	1.91	2.87	3.82	4.78	5.74	-0.17	1.75	2.70	3.66	4.61	5.57
	88 %	0.00	1.75	2.62	3.49	4.37	5.24	-0.17	1.58	2.45	3.33	4.20	5.08
	87 %	0.00	1.58	2.37	3.17	3.96	4.75	-0.17	1.42	2.21	3.00	3.79	4.58
	86 %	0.00	1.42	2.13	2.84	3.55	4.26	-0.17	1.25	1.96	2.67	3.38	4.09
	85 %	0.00	1.25	1.88	2.51	3.14	3.76	-0.17	1.09	1.71	2.34	2.97	3.60
	84 %	0.00	1.09	1.63	2.18	2.72	3.27	-0.17	0.92	1.47	2.01	2.56	3.10
	83 %	0.00	0.93	1.39	1.85	2.31	2.78	-0.17	0.76	1.22	1.68	2.15	2.61
	82 %	0.00	0.76	1.14	1.52	1.90	2.28	-0.17	0.59	0.97	1.36	1.74	2.12
	81 %	0.00	0.60	0.89	1.19	1.49	1.79	-0.17	0.43	0.73	1.03	1.32	1.62
	80 %	0.00	0.43	0.65	0.86	1.08	1.30	-0.17	0.27	0.48	0.70	0.91	1.13
	79 %	0.00	0.27	0.40	0.53	0.67	0.80	-0.17	0.10	0.23	0.37	0.50	0.64
	78 %	0.00	0.10	0.15	0.21	0.26	0.31	-0.17	-0.06	-0.01	0.04	0.09	0.14
	77 %	0.00	-0.06	-0.09	-0.12	-0.15	-0.18	-0.17	-0.23	-0.26	-0.29	-0.32	-0.35
	76 %	0.00	-0.23	-0.34	-0.45	-0.57	-0.68	-0.17	-0.39	-0.51	-0.62	-0.73	-0.84
	75 %	0.00	-0.39	-0.59	-0.78	-0.98	-1.17	-0.17	-0.56	-0.75	-0.95	-1.14	-1.34
	74 %	0.00	-0.55	-0.83	-1.11	-1.39	-1.66	-0.17	-0.72	-1.00	-1.28	-1.55	-1.83
	73 %	0.00	-0.72	-1.08	-1.44	-1.80	-2.16	-0.17	-0.89	-1.25	-1.60	-1.96	-2.32
	72 %	0.00	-0.88	-1.33	-1.77	-2.21	-2.65	-0.17	-1.05	-1.49	-1.93	-2.38	-2.82
	71 %	0.00	-1.05	-1.57	-2.10	-2.62	-3.14	-0.17	-1.21	-1.74	-2.26	-2.79	-3.31
	70 %	0.00	-1.21	-1.82	-2.43	-3.03	-3.64	-0.17	-1.38	-1.99	-2.59	-3.20	-3.80

D_n [Photochemical ozone formation] – LRS scenario								D_n [Photochemical ozone formation] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	4.49	6.73	8.98	11.22	13.47	-0.61	3.88	6.12	8.36	10.61	12.85
	99 %	0.00	4.33	6.50	8.66	10.83	12.99	-0.61	3.72	5.88	8.05	10.22	12.38
	98 %	0.00	4.17	6.26	8.35	10.44	12.52	-0.61	3.56	5.65	7.74	9.82	11.91
	97 %	0.00	4.02	6.03	8.03	10.04	12.05	-0.61	3.40	5.41	7.42	9.43	11.44
	96 %	0.00	3.86	5.79	7.72	9.65	11.58	-0.61	3.25	5.18	7.11	9.04	10.97
	95 %	0.00	3.70	5.55	7.41	9.26	11.11	-0.61	3.09	4.94	6.79	8.64	10.50
	94 %	0.00	3.55	5.32	7.09	8.86	10.64	-0.61	2.93	4.71	6.48	8.25	10.02
	93 %	0.00	3.39	5.08	6.78	8.47	10.17	-0.61	2.78	4.47	6.16	7.86	9.55
	92 %	0.00	3.23	4.85	6.46	8.08	9.69	-0.61	2.62	4.23	5.85	7.47	9.08
	91 %	0.00	3.07	4.61	6.15	7.69	9.22	-0.61	2.46	4.00	5.54	7.07	8.61
	90 %	0.00	2.92	4.38	5.83	7.29	8.75	-0.61	2.30	3.76	5.22	6.68	8.14
	89 %	0.00	2.76	4.14	5.52	6.90	8.28	-0.61	2.15	3.53	4.91	6.29	7.67
	88 %	0.00	2.60	3.90	5.21	6.51	7.81	-0.61	1.99	3.29	4.59	5.89	7.20
	87 %	0.00	2.45	3.67	4.89	6.11	7.34	-0.61	1.83	3.06	4.28	5.50	6.72
	86 %	0.00	2.29	3.43	4.58	5.72	6.87	-0.61	1.68	2.82	3.96	5.11	6.25
	85 %	0.00	2.13	3.20	4.26	5.33	6.39	-0.61	1.52	2.58	3.65	4.72	5.78
	84 %	0.00	1.97	2.96	3.95	4.94	5.92	-0.61	1.36	2.35	3.34	4.32	5.31
	83 %	0.00	1.82	2.73	3.63	4.54	5.45	-0.61	1.20	2.11	3.02	3.93	4.84
	82 %	0.00	1.66	2.49	3.32	4.15	4.98	-0.61	1.05	1.88	2.71	3.54	4.37
	81 %	0.00	1.50	2.25	3.01	3.76	4.51	-0.61	0.89	1.64	2.39	3.14	3.89
	80 %	0.00	1.35	2.02	2.69	3.36	4.04	-0.61	0.73	1.41	2.08	2.75	3.42
	79 %	0.00	1.19	1.78	2.38	2.97	3.56	-0.61	0.58	1.17	1.76	2.36	2.95
	78 %	0.00	1.03	1.55	2.06	2.58	3.09	-0.61	0.42	0.93	1.45	1.96	2.48
	77 %	0.00	0.87	1.31	1.75	2.18	2.62	-0.61	0.26	0.70	1.14	1.57	2.01
	76 %	0.00	0.72	1.08	1.43	1.79	2.15	-0.61	0.10	0.46	0.82	1.18	1.54
	75 %	0.00	0.56	0.84	1.12	1.40	1.68	-0.61	-0.05	0.23	0.51	0.79	1.07
	74 %	0.00	0.40	0.60	0.81	1.01	1.21	-0.61	-0.21	-0.01	0.19	0.39	0.59
	73 %	0.00	0.25	0.37	0.49	0.61	0.74	-0.61	-0.37	-0.24	-0.12	0.00	0.12
	72 %	0.00	0.09	0.13	0.18	0.22	0.26	-0.61	-0.52	-0.48	-0.44	-0.39	-0.35
	71 %	0.00	-0.07	-0.10	-0.14	-0.17	-0.21	-0.61	-0.68	-0.72	-0.75	-0.79	-0.82
	70 %	0.00	-0.23	-0.34	-0.45	-0.57	-0.68	-0.61	-0.84	-0.95	-1.07	-1.18	-1.29

D_n [Primary energy from non renewable resources (gross cal. value)] – LRS scenario								D_n [Primary energy from non renewable resources (gross cal. value)] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	4.73	7.09	9.46	11.82	14.19	-0.64	4.09	6.45	8.81	11.18	13.54
	99 %	0.00	4.57	6.86	9.15	11.44	13.72	-0.64	3.93	6.22	8.50	10.79	13.08
	98 %	0.00	4.42	6.63	8.84	11.05	13.26	-0.64	3.78	5.99	8.20	10.40	12.61
	97 %	0.00	4.26	6.40	8.53	10.66	12.79	-0.64	3.62	5.75	7.89	10.02	12.15
	96 %	0.00	4.11	6.16	8.22	10.27	12.33	-0.64	3.47	5.52	7.58	9.63	11.69
	95 %	0.00	3.96	5.93	7.91	9.89	11.87	-0.64	3.31	5.29	7.27	9.24	11.22
	94 %	0.00	3.80	5.70	7.60	9.50	11.40	-0.64	3.16	5.06	6.96	8.86	10.76
	93 %	0.00	3.65	5.47	7.29	9.11	10.94	-0.64	3.00	4.82	6.65	8.47	10.29
	92 %	0.00	3.49	5.24	6.98	8.73	10.47	-0.64	2.85	4.59	6.34	8.08	9.83
	91 %	0.00	3.34	5.00	6.67	8.34	10.01	-0.64	2.69	4.36	6.03	7.69	9.36
	90 %	0.00	3.18	4.77	6.36	7.95	9.54	-0.64	2.54	4.13	5.72	7.31	8.90
	89 %	0.00	3.03	4.54	6.05	7.56	9.08	-0.64	2.38	3.89	5.41	6.92	8.43
	88 %	0.00	2.87	4.31	5.74	7.18	8.61	-0.64	2.23	3.66	5.10	6.53	7.97
	87 %	0.00	2.72	4.07	5.43	6.79	8.15	-0.64	2.07	3.43	4.79	6.15	7.50
	86 %	0.00	2.56	3.84	5.12	6.40	7.68	-0.64	1.92	3.20	4.48	5.76	7.04
	85 %	0.00	2.41	3.61	4.81	6.02	7.22	-0.64	1.76	2.97	4.17	5.37	6.58
	84 %	0.00	2.25	3.38	4.50	5.63	6.75	-0.64	1.61	2.73	3.86	4.99	6.11
	83 %	0.00	2.10	3.15	4.19	5.24	6.29	-0.64	1.45	2.50	3.55	4.60	5.65
	82 %	0.00	1.94	2.91	3.88	4.85	5.83	-0.64	1.30	2.27	3.24	4.21	5.18
	81 %	0.00	1.79	2.68	3.57	4.47	5.36	-0.64	1.14	2.04	2.93	3.82	4.72
	80 %	0.00	1.63	2.45	3.26	4.08	4.90	-0.64	0.99	1.80	2.62	3.44	4.25
	79 %	0.00	1.48	2.22	2.95	3.69	4.43	-0.64	0.83	1.57	2.31	3.05	3.79
	78 %	0.00	1.32	1.98	2.64	3.31	3.97	-0.64	0.68	1.34	2.00	2.66	3.32
	77 %	0.00	1.17	1.75	2.34	2.92	3.50	-0.64	0.52	1.11	1.69	2.28	2.86
	76 %	0.00	1.01	1.52	2.03	2.53	3.04	-0.64	0.37	0.88	1.38	1.89	2.39
	75 %	0.00	0.86	1.29	1.72	2.14	2.57	-0.64	0.21	0.64	1.07	1.50	1.93
	74 %	0.00	0.70	1.05	1.41	1.76	2.11	-0.64	0.06	0.41	0.76	1.11	1.47
	73 %	0.00	0.55	0.82	1.10	1.37	1.64	-0.64	-0.10	0.18	0.45	0.73	1.00
	72 %	0.00	0.39	0.59	0.79	0.98	1.18	-0.64	-0.25	-0.05	0.14	0.34	0.54
	71 %	0.00	0.24	0.36	0.48	0.60	0.72	-0.64	-0.41	-0.29	-0.17	-0.05	0.07
	70 %	0.00	0.08	0.13	0.17	0.21	0.25	-0.64	-0.56	-0.52	-0.48	-0.43	-0.39

		D_n [Terrestrial eutrophication] – LRS scenario						D_n [Terrestrial eutrophication] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	4.69	7.04	9.39	11.73	14.08	-0.64	4.06	6.40	8.75	11.10	13.44
	99 %	0.00	4.54	6.81	9.08	11.35	13.62	-0.64	3.90	6.17	8.44	10.71	12.98
	98 %	0.00	4.38	6.58	8.77	10.96	13.15	-0.64	3.75	5.94	8.13	10.32	12.51
	97 %	0.00	4.23	6.34	8.46	10.57	12.68	-0.64	3.59	5.70	7.82	9.93	12.05
	96 %	0.00	4.07	6.11	8.15	10.18	12.22	-0.64	3.43	5.47	7.51	9.54	11.58
	95 %	0.00	3.92	5.88	7.84	9.79	11.75	-0.64	3.28	5.24	7.20	9.16	11.12
	94 %	0.00	3.76	5.64	7.53	9.41	11.29	-0.64	3.12	5.01	6.89	8.77	10.65
	93 %	0.00	3.61	5.41	7.22	9.02	10.82	-0.64	2.97	4.77	6.58	8.38	10.18
	92 %	0.00	3.45	5.18	6.90	8.63	10.36	-0.64	2.81	4.54	6.27	7.99	9.72
	91 %	0.00	3.30	4.95	6.59	8.24	9.89	-0.64	2.66	4.31	5.96	7.60	9.25
	90 %	0.00	3.14	4.71	6.28	7.85	9.43	-0.64	2.50	4.07	5.65	7.22	8.79
	89 %	0.00	2.99	4.48	5.97	7.47	8.96	-0.64	2.35	3.84	5.34	6.83	8.32
	88 %	0.00	2.83	4.25	5.66	7.08	8.49	-0.64	2.19	3.61	5.02	6.44	7.86
	87 %	0.00	2.68	4.01	5.35	6.69	8.03	-0.64	2.04	3.38	4.71	6.05	7.39
	86 %	0.00	2.52	3.78	5.04	6.30	7.56	-0.64	1.88	3.14	4.40	5.66	6.93
	85 %	0.00	2.37	3.55	4.73	5.92	7.10	-0.64	1.73	2.91	4.09	5.28	6.46
	84 %	0.00	2.21	3.32	4.42	5.53	6.63	-0.64	1.57	2.68	3.78	4.89	5.99
	83 %	0.00	2.06	3.08	4.11	5.14	6.17	-0.64	1.42	2.45	3.47	4.50	5.53
	82 %	0.00	1.90	2.85	3.80	4.75	5.70	-0.64	1.26	2.21	3.16	4.11	5.06
	81 %	0.00	1.75	2.62	3.49	4.36	5.24	-0.64	1.11	1.98	2.85	3.72	4.60
	80 %	0.00	1.59	2.39	3.18	3.98	4.77	-0.64	0.95	1.75	2.54	3.34	4.13
	79 %	0.00	1.43	2.15	2.87	3.59	4.30	-0.64	0.80	1.51	2.23	2.95	3.67
	78 %	0.00	1.28	1.92	2.56	3.20	3.84	-0.64	0.64	1.28	1.92	2.56	3.20
	77 %	0.00	1.12	1.69	2.25	2.81	3.37	-0.64	0.49	1.05	1.61	2.17	2.74
	76 %	0.00	0.97	1.45	1.94	2.42	2.91	-0.64	0.33	0.82	1.30	1.78	2.27
	75 %	0.00	0.81	1.22	1.63	2.04	2.44	-0.64	0.18	0.58	0.99	1.40	1.80
	74 %	0.00	0.66	0.99	1.32	1.65	1.98	-0.64	0.02	0.35	0.68	1.01	1.34
	73 %	0.00	0.50	0.76	1.01	1.26	1.51	-0.64	-0.13	0.12	0.37	0.62	0.87
	72 %	0.00	0.35	0.52	0.70	0.87	1.05	-0.64	-0.29	-0.12	0.06	0.23	0.41
	71 %	0.00	0.19	0.29	0.39	0.48	0.58	-0.64	-0.45	-0.35	-0.25	-0.16	-0.06
	70 %	0.00	0.04	0.06	0.08	0.10	0.11	-0.64	-0.60	-0.58	-0.56	-0.54	-0.52

D_n [Total freshwater consumption] – LRS scenario								D_n [Total freshwater consumption] — HRS scenario					
		'X' [hours]						'X' [hours]					
		0 h	100 h	150 h	200 h	250 h	300 h	0 h	100 h	150 h	200 h	250 h	300 h
δ [%]	100 %	0.00	3.79	5.69	7.58	9.48	11.37	-0.17	3.62	5.52	7.41	9.31	11.20
	99 %	0.00	3.63	5.44	7.25	9.07	10.88	-0.17	3.46	5.27	7.08	8.90	10.71
	98 %	0.00	3.46	5.20	6.93	8.66	10.39	-0.17	3.29	5.03	6.76	8.49	10.22
	97 %	0.00	3.30	4.95	6.60	8.25	9.90	-0.17	3.13	4.78	6.43	8.08	9.73
	96 %	0.00	3.14	4.70	6.27	7.84	9.41	-0.17	2.97	4.53	6.10	7.67	9.24
	95 %	0.00	2.97	4.46	5.94	7.43	8.92	-0.17	2.80	4.29	5.77	7.26	8.75
	94 %	0.00	2.81	4.21	5.62	7.02	8.43	-0.17	2.64	4.04	5.45	6.85	8.26
	93 %	0.00	2.64	3.97	5.29	6.61	7.93	-0.17	2.47	3.80	5.12	6.44	7.76
	92 %	0.00	2.48	3.72	4.96	6.20	7.44	-0.17	2.31	3.55	4.79	6.03	7.27
	91 %	0.00	2.32	3.48	4.63	5.79	6.95	-0.17	2.15	3.31	4.46	5.62	6.78
	90 %	0.00	2.15	3.23	4.31	5.38	6.46	-0.17	1.98	3.06	4.14	5.21	6.29
	89 %	0.00	1.99	2.98	3.98	4.97	5.97	-0.17	1.82	2.81	3.81	4.80	5.80
	88 %	0.00	1.83	2.74	3.65	4.56	5.48	-0.17	1.66	2.57	3.48	4.39	5.31
	87 %	0.00	1.66	2.49	3.32	4.16	4.99	-0.17	1.49	2.32	3.15	3.99	4.82
	86 %	0.00	1.50	2.25	3.00	3.75	4.49	-0.17	1.33	2.08	2.83	3.58	4.32
	85 %	0.00	1.33	2.00	2.67	3.34	4.00	-0.17	1.16	1.83	2.50	3.17	3.83
	84 %	0.00	1.17	1.76	2.34	2.93	3.51	-0.17	1.00	1.59	2.17	2.76	3.34
	83 %	0.00	1.01	1.51	2.01	2.52	3.02	-0.17	0.84	1.34	1.84	2.35	2.85
	82 %	0.00	0.84	1.26	1.69	2.11	2.53	-0.17	0.67	1.09	1.52	1.94	2.36
	81 %	0.00	0.68	1.02	1.36	1.70	2.04	-0.17	0.51	0.85	1.19	1.53	1.87
	80 %	0.00	0.52	0.77	1.03	1.29	1.55	-0.17	0.35	0.60	0.86	1.12	1.38
	79 %	0.00	0.35	0.53	0.70	0.88	1.06	-0.17	0.18	0.36	0.53	0.71	0.89
	78 %	0.00	0.19	0.28	0.38	0.47	0.56	-0.17	0.02	0.11	0.21	0.30	0.39
	77 %	0.00	0.02	0.04	0.05	0.06	0.07	-0.17	-0.15	-0.13	-0.12	-0.11	-0.10
	76 %	0.00	-0.14	-0.21	-0.28	-0.35	-0.42	-0.17	-0.31	-0.38	-0.45	-0.52	-0.59
	75 %	0.00	-0.30	-0.46	-0.61	-0.76	-0.91	-0.17	-0.47	-0.63	-0.78	-0.93	-1.08
	74 %	0.00	-0.47	-0.70	-0.93	-1.17	-1.40	-0.17	-0.64	-0.87	-1.10	-1.34	-1.57
	73 %	0.00	-0.63	-0.95	-1.26	-1.58	-1.89	-0.17	-0.80	-1.12	-1.43	-1.75	-2.06
	72 %	0.00	-0.79	-1.19	-1.59	-1.99	-2.38	-0.17	-0.96	-1.36	-1.76	-2.16	-2.55
	71 %	0.00	-0.96	-1.44	-1.92	-2.40	-2.88	-0.17	-1.13	-1.61	-2.09	-2.57	-3.05
	70 %	0.00	-1.12	-1.68	-2.24	-2.81	-3.37	-0.17	-1.29	-1.85	-2.41	-2.98	-3.54

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European Commission
EUR 27512 EN – Joint Research Centre – Institute for Environment and Sustainability

Title: Technical support for Environmental Footprinting, material efficiency in product policy and the European Platform on LCA – Durability assessment of vacuum cleaners.

Authors: Silvia Bobba, Fulvio Ardente, Fabrice Mathieux

Luxembourg: Publications Office of the European Union
2015 – 149 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online)

ISBN 978-92-79-52710-4

doi:10.2788/563222

LB-NA-27512-EN-N

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doi:10.2788/563222

ISBN 978-92-79-52710-4