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A method for identifying and quantifying Usage EcoDrifts

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Usage ecodriffs, which refer to non-optimal use of a product by the users, create additional environmental impact generators: energy overconsumption (real-time impacts) and abnormal wear and tear of parts of the product (delayed impacts). The goal of our study was to develop a method for identifying and quantifying UEDs of products that have a high environmental impact use phase. In this paper, we studied the case of different usages of a vacuum cleaner and their environmental consequences. We first conducted a survey to gather information on how people use the product. Then, we conducted experimentations to measure the consequences of the usages. We also explored how the testers responded to feedback inviting them to adopt a more sustainable behaviour. Results show that most of the users do not use the product optimally and cause additional environmental impact. Several usage ecodriffs were identified, causing both abnormal energy overconsumption and wear and tear of the product. The calculations show that Delayed Environmental Impacts, because their consequence is the early replacement of the whole product, are of much greater importance than Real-time Environmental Impacts.

1. Introduction

The use phase of products is the source of a great share of environmental impacts at a global scale (Ardente and Mathieux, 2014). As a consequence, in most developed countries, the majority of products placed on the market has to respect stricter and stricter norms regarding environmental performance when used (see Europe 2020 targets on climate change and energy). The focus on the environmental importance of the use phase of products is quite recent among the design community (Nissen, 1995). It has been a growing concern for the relevance of ecodesign projects where indicators regarding the efficiency of the use phase were needed (Cerdan et al., 2009). Products as well as services have been subject to these changes in the ways of designing them (Maxwell and Van der Vorst, 2003). These changes come along with the realization that even if a product has a very low impact manufacturing phase, its ecofriendly nature can be removed depending on its use phase's efficiency (Hauschild et al., 2005). Before that, the environmental impact of products has traditionally been understood as derived mainly from the life-cycle phases related to material transformation (McLeninghan, 1990). The use

phase concern later appeared in ecodesign strategies as a criteria among others inside ecodesign checklists (Vezzoli and Sciama, 2006; Waage, 2007). Such strategies now take into account the whole of the life cycle of products (Herrmann et al., 2005, 2007). Through the years, the use phase has been more and more considered as a key issue of ecodesign problems. Famous cases such as the shower faucet and the light bulb have been flagpoles for the recognition of the use phase as a crucial step of the life cycle. Many more cases can be found in the literature and have participated to the evolution of ecodesign strategies for a better use phase efficiency. The more recent user-centered design strategies have focused on two ways of bettering the environmental performance of products: first by influencing the product architecture using customer and environmental requirements, second by passing information to the users through feedback strategies regarding the best usage practices available (Lilley, 2009). On the product side for example, vacuum cleaners (that are the concern of our case study) are now subject to ecodesign requirements that set a minimum of 500 working hours for the motors and hoses. On the user side, to better the environmental performances, products are ecodesigned to be optimally used following prescribed usage patterns (Brezet and Hemel, 1997; Vezzoli and Manzini, 2008). However, there is no guarantee that users will do so. They might find their own ways to use the products and risk deteriorating the environmental performances (Tang et al., 2008). These non-optimal usages generate

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environmental impacts: first by causing unnecessary electrical overconsumption (Lilley, 2009; Tukker and Tischner, 2006), second by causing abnormal wear and tear of the product (and so forth the need of replacing it early) (Barré et al., 2013). If people were to use products in the best environmentally-friendly way, the impacts of the use phase would be smaller. Hence, researchers and designers need to concentrate on the non-optimal usages of products and find ways to counter them. They have to come to a better understanding of how people use products by studying their usage patterns. Then, by investigating what are the causes of these usages, they should be able to find the corresponding design solutions leading to better environmental performance.

Numerous studies show that environmental performance can be bettered by affecting the way people use their products (McMahon and Bhamra, 2012; Tukker and Tischner, 2006). Usages of products are also directly linked to how the products are designed (Norman and Draper, 1986). These problems are the origin of the Design for Sustainable Behaviour field of research (Pettersen and Boks, 2009) which has been fed by renowned authors such as Bhamra, Lilley and many others. They have identified many strategies to affect user's behaviour through product design (Lilley, 2009; Lockton et al., 2010). These strategies have been applied by many later authors such as Desmet (2000) and Tang et al. (2008) among others.

In this study, we call product usage which deviates from the best environmental practices available "usage ecodrift" (UED). UEDs do not have yet a common shared definition among the scientific community. Given their importance on the environmental performance of products use phase, it appears necessary to clarify this concept. Although the UED concept has already been studied in the scientific community under other names, studies have mainly focused on eco-driving learning (Jamson et al., 2015; Rolim et al., 2014), on household practices related to energy consumption (Santin, 2011) and on household practices related to water heating (Santin et al., 2009). The problem was also developed in studies focused on intervention strategies aiming at reducing household energy consumption (Gulbinas and Taylor, 2014; Jain et al., 2012, 2013). The goal of this paper is to develop a method for identifying and quantifying UEDs of products that have a high environmental impact use phase. We insist on the fact that delayed impacts (caused by wear and tear) have to be taken into account alongside with real-time impacts (energies and materials overconsumptions). By modeling the environmental impacts generated by these two sources, it is possible to calculate the environmental performance of the use phase for several different usage patterns (different combinations of UEDs). This allows us enlightening and prioritizing the design hotspots that must be corrected. By doing so, we aim to demonstrate that UEDs can be modeled to be taken into account during the design stage. There, they can be countered by choosing pertinent technological solutions.

To evaluate the pertinence of the UED concept, we chose the vacuum cleaner case study. We studied its usage by observing a panel of users and conducted several environmental evaluations of the product itself and of different usage scenarios. The results of the evaluations allowed us to conclude on the importance of UEDs for the use phase of the product.

In Section 2, the UED problem is developed. We show that UEDs are multiple and cause more or less impacts. They depend on usages that can be grouped creating user segments. In Section 3 we detail the research method in five points: (i) the reference usage definition, (ii) user segmentation, (iii) UED identification and experimentations, (iv) establishing UED models and (v) the environmental assessment of the use phase. Section 4 gathers the results obtained during the field and laboratory experimentations conducted for the study. Finally the results are discussed and future research problems are suggested.

2. The behaviour-centered design challenge

The concept of UED refers to two types of environmental impacts. The first type is "real-time impacts". In this case it is easy to make the link between the UED and the impact. For example electrical overconsumption is often caused by an obvious specific behaviour of the user. The second type refers to impacts caused by abnormal wear and tear (due to the user's behaviour) of parts of the product. Because the problem is likely to be invisible to users until the concerned part or component fails, they will not easily understand the relation between their behaviour and the environmental impact. This gap between UED occurrence and awareness/consequence is the reason we call these "delayed impacts".

Taking users behaviours into account during the design process is not easily done. For a given product, the diversity of users induces a diversity of usages and thus, a diversity of UEDs. This diversity is due to several factors such as need, culture, consent, etc. (Pierce et al., 2010). The context of use also has to be considered as it may influence user behaviour (Maguire, 2001).

Hence, designers are dealing with a triple UED-user segment-use context that, once uncovered, should allow them a global point of view of the use phase (Bhamra et al., 2011). In this paper, the work focuses on the two first points: UED and user segment.

2.1. The UED concept

Our definition of the UED concept is based on a previous research conducted by Serna-Mansoux et al. (2014b). The authors studied "variations of a sequence of tasks inside a usage scenario that causes additional environmental impacts". Here, the concept of UED encompasses the variations Serna-Mansoux et al. (2014b) studied. It not only takes into account real-time impacts (due to overconsumptions) but also delayed impacts (due to abnormal wear and tear) (Barré et al., 2013). The following definition is proposed: "For the usage of a product with a given functional unit, a UED is defined as a usage practice which, in comparison to a reference usage, causes: (i) an increase in energy consumption and/or (ii) an increase in materials consumption and/or (iii) abnormal wear and tear of the product (and so the need to replace it earlier), thus generating additional environmental impacts".

This definition underlines the fact that diverse behaviours can be associated with the diversity of users (Santin et al., 2009). Hence, instead of considering only an "average user" and an "average usage" (Santin, 2011), the concept requires to study a wider panel of usages.

2.2. Considering users and usages

A first step of the problem concerns the way people learn how to use products. Later on, it is not given that the usage pattern will stay the same throughout the whole use phase. Usage patterns are likely to be influenced both by internal factors (ecological engagement, free time, health, culture, etc.) and external factors (energy cost, air quality, etc.) (Sardianou, 2008).

If we simplify the problem with the hypothesis that the usage, once learned, stays the same throughout the whole use phase (Pierce et al., 2008), the first question is "how do people learn how to use products?" Nowadays, technology changes fast and people are accustomed to acquiring and trying new products. In the case of mobile phones, the user manual is barely read. Users prefer to discover the interface and the functionalities of their phone intuitively (Britton et al., 2013). Knowing that, how can designers be sure that users will gravitate towards eco-friendly usage? This will depend on the internal and external factors listed above, but also on the knowledge of the device's functionalities and their effects in

terms of environmental impacts (Gulbinas and Taylor, 2014).

Scientific studies have shown up four constraints likely to lead to UEDs.

- *Habit*: Pierce et al. (2010) demonstrated that most actions in everyday life are ruled by habit. These actions depend on unconscious mechanisms whereas conscious action is needed to change one's behaviour. Furthermore, habits can be strong enough to cancel out any incentive aiming to change the behaviour.
- *Beliefs*: many people do not know the environmental consequences of their daily actions (Bedford et al., 2011; Fischer and Newell, 2008; Lillemo, 2014).
- *Comfort*: Perrin and Barton (2001) show that sustainable behaviours are often rejected because they induce additional effort for the user.
- *Time*: just as for comfort, a new behaviour may be rejected if it is seen as too time consuming (Tonglet et al., 2004).

User behaviour is influenced by these four constraints simultaneously but some might be stronger than others. Grouping people according to their predominant behavioral constraints (and UEDs) is a way to segment users. Segment-specific technological solutions may then be developed to guide users towards a more eco-friendly behaviour (Buchanan et al., 2014).

2.3. User awareness and design solutions

A product fulfils various different needs for various different users. Cor and Zwolinski (2014) state that taking this diversity into account is essential for establishing an efficient eco-design strategy. Designers should use this diversity to design the technological solutions for the product. In the same time, the way users will interact with these technologies has to be thought through.

If real usage differs notably from the ideal usage conceived by the designer, the environmental impacts generated during the use phase may increase. To prevent this, the product itself can be a way to encourage a behavioral change since it is an interface between user and usage (Cor et al., 2014). In the literature are found several "product to user" eco-usage mechanisms with different levels of enforcement (Froehlich et al., 2010; Pierce et al., 2008; Wever et al., 2008). They are usually labelled as "eco-feedback" (which is only informative), "behaviour steering" (which provides incentives and "forced functionality" (which is highly enforced).

Out of the four constraints listed in part 2.2 of this paper, we hold that *belief* is the most important. Indeed, a user who does not understand the relation between his actions and their environmental impacts may be more difficult to guide towards more sustainable behaviour (Lilley, 2009). A sustainable frame of mind change is the prerequisite for inducing sustainable behavioral change (Burgers et al., 2015; Davis et al., 2009; Perrels, 2008). According to the Theory of Planned Behaviour (Ajzen, 1991), knowing that the user has control over his/her actions (if the product is well designed) and that social norms are clearly in favor of sustainable behaviour (Barreto et al., 2014), then only the user's attitude will influence their behaviour.

Since users need to be made aware of the existence of the UEDs, informing them with eco-feedback seems to be an appropriate way of influencing their attitude (Serna-Mansoux et al., 2014a). However, a major eco-feedback drawback is the lack of certainty as to whether the user will get the information or will react in the desired way (Buchanan et al., 2014). To improve the odds, designers must take into consideration the user's awareness process (Lidman et al., 2011; Serna-Mansoux et al., 2014b). When thinking of raising users' awareness, user-accepted product-solutions can be designed

(Bhamra et al., 2011). However, even when the behavioral change is accepted, it is necessary to ensure that the change is sustainable and will not fade over time (Scott et al., 2012; Serna-Mansoux et al., 2014a).

3. The UED methodology

To evaluate the impacts caused by UEDs, we set up a five step research protocol: (1) definition of usage of reference (UoR), (2) users segmentation, (3) identification of UEDs and experimentation, (4) establishing UED models and (5) environmental evaluation.

3.1. Step 1: definition of the UoR

The UoR is defined as the optimal usage free of all UEDs. It is the usage that offers the best environmental performance. The UoR is useful in two ways. First, to have a value to compare the environmental performances of the observed practices with; second, to have a targetable goal that can be used to orientate users' behaviour.

If the product is easy to use, simple tests, common sense and discussions with users and with the designers should be enough to define the UoR. Information may also have been published concerning the best usage practices (manufacturer recommendations, base-case scenarios from the norms, studies in the scientific literature, etc.). All this data is a precious help to have a broad view of the variety of usages of a product. Nevertheless, if finding the optimal usage of the product is not trivial and implies setting a greater number of parameters, techniques such as Design of Experiments (DoE) should be employed. DoE-like techniques should then allow determining the values of the usage parameters corresponding to the best environmental performance.

3.2. Step 2: user segments

A way to establish user segments is to explore directly the diversity of usages. To do so, a sufficient number of users and usage situations have to be observed. Data collection can be done in various ways. More important is the choice of the data collected and the ways of analyzing it. The data has to be pertinent to represent the diversity of usages. Then, using segmentation techniques allows establishing coherent users groups (for example probabilistic latent semantic user segmentation as described by Khobzi and Teimourpour (2015) and Wu et al. (2009)).

3.3. Step 3: UEDs identification and experimentation

UEDs identification requires a broad and objective vision of the diversity of usages. Furthermore, when a UED is identified, it is crucial to know its level of occurrence among the population of users. A good way to have these broad and quantitative views of usages is to observe a large variety of users in a large variety of situations. Before observation, protocols have to be set up to define when a usage is out of the UoR boundaries. We propose here a model of experimentation in order to identify the UEDs. The number of persons selected for the experimentation should be chosen depending on the diversity of users using the product.

Our experimentation consists in two use sessions separated by a feedback intermission and concluded by a debriefing. The first session consists in letting the person use the product as usual, without giving them any advice. Their behaviour and practices are observed during this session. The non-optimal practices that were observed during the first session and are absent of the UoR are considered as UEDs. Then, a feedback is given to the user directly to

be sure that the information is heard. It is the occasion of informing the user about the optimal usage of the product. The second use session allows measuring the reaction to the feedback. Finally, the debriefing is useful in order to know whether the user understood the feedback they were given and how they interpreted it.

In our method, measuring the UEDs parameters permits quantifying two of their negative consequences: overconsumption of energy and materials and decreased lifetime (LT) of the system.

3.4. Steps 4: usage models

Before performing the environmental evaluation of the system, it is necessary to apply the results found during the experimentations to the whole of the product use phase. To do so, for each UED, we quantify the overconsumptions and define, using experience from the manufacturer and the users, the value of LT decrease. Each UED is characterized by the levels of its negative consequences: overconsumptions and LT decrease. Usage models corresponding to the observed behaviours of the people in the user segments are then created. They consist in different combinations of UEDs (each UED with a specific coefficient), defined to correspond to the observed usage patterns.

3.5. Step 5: environmental evaluation

Since the UEDs and usages models are defined by overconsumptions and LT decrease, it is easy to assess their environmental consequences by applying them to the model of the product in a Life Cycle Assessment (LCA) software. This allows quantifying the environmental consequences of the non-optimal usages and identifying the hot spots that have to be dealt with in priority.

4. Results

4.1. Case study

Our case study concerns the usage of a household cordless vacuum cleaner. The choice of the vacuum cleaner case study is motivated by several points. First, it is a widely distributed product; meaning that studying the user population can generate much data. It includes a battery, which is a component known for possibly being critically affected by non-optimal usage. It requires several user-product interactions to optimally function.

The vacuum includes a dust canister (bagless system) and a dust filter. The control is a single three position slider button that is moved by the user's thumb when grabbing the handle. The three positions are (1) Stop, (2) Run (low power) and (3) Run (max power). The battery LT is 500 cycles.

We consider a functional unit defined using European norms as follows: "Run 500 vacuuming cycles on a 70 m² surface made of 70% hard floor and 30% soft floor". The vacuuming cycle is defined as a vacuuming session followed by a complete charge of the battery.

4.2. Usage of reference

The wireless vacuum cleaner is a fairly easy product to use. As a consequence, the optimal usage can easily be defined using common sense and conducting some tests. Here, the UoR has been defined by the research team after several tests, discussions and using some of the information provided by the manufacturer in the user's manual. The UoR has to guarantee the product to have a service life at least as long as the manufacturer's claim (here 500 cycles). The UoR elaborated is summed up and explained in the four following actions:

- *Use low power vacuum on hard floors and max power on soft floors.* Our tests showed that in a great majority of cases, low power was enough to vacuum hard floors and max power was necessary to vacuum soft floors with a satisfying result. The results of the vacuuming were assessed visually and by weighting the dust collected during the test (at least 95% of the dust had to be vacuumed with two strokes).
- *Empty the canister once the marked level is reached.* Even if negative effects do not appear right after the marked level is reached, we chose to keep this level as our reference as it is obvious for the users.
- *Clean the dust filter after 2 running hours.* The cleanliness of the dust filter being difficult to qualify with only a visual control, we chose to keep the value given by the manufacturer. This value was also confirmed by our tests.
- *Unplug the battery charger when the charge is complete.* We measured the electrical consumption of the charger when plugged whereas the battery is full. We observed that a residual consumption exists and, as a consequence, recommended to unplug the charger when the battery is full.

The UoR was verified to fulfill the functional unit defined previously. As a consequence, with the hypothesis of complete use efficiency (optimal stroke speed to pick the dust up), the UoR can be considered as the most environmentally efficient usage considering the given functional unit.

4.3. User segments

To identify user segments we conducted a survey among a population of users. We designed a questionnaire with 25 questions to characterize the respondent's usage practices. The questionnaire also allowed us to determine participants' environmental awareness. When designing the questionnaire, four user segments were foreseen: "Hygiene", "Comfort", "High-Tech" and "Eco-sensitive" (see description in the list below). The segmentation was done as follows: each question of the questionnaire was attributed with four scores (one for each segment). Depending on the answer of the respondent, points were added to the corresponding segment scores. In the end, the respondent was associated with the segment for which the score was the highest. The survey provided us with 350 completed questionnaires. The analysis of the results showed a segmentation of the population inside three segments (as the High-tech segment gathered less than 1% of the population, we chose to remove it from the study):

C1. Hygiene (40%): They are not interested by how much electricity the vacuum cleaner needs. It is an everyday tool that must be efficient. People in this group are efficient and well organized for doing chores. Some know about the environmental consequences of their actions but they do not consider this as a priority.

C2. Comfort (51%): Their priority is their well-being. Chores need to be done, the quicker the better. They favor easy-usage efficient products. Their choice tends towards silent and automatic products.

C3. Eco-sensitive (9%): They are concerned about the consequences of their everyday actions. They often seek advice to improve their behaviour. Their home does not need to be perfectly clean if this means consuming a lot of electricity.

4.4. UED identification and experimentation

We set up an experimentation to identify the UEDs and quantify their consequences. During a first session, we observed a panel of twelve persons (see Table 1) while vacuuming "as usual" a 10 m² room. The persons were chosen among the students and staff of the

Table 1

Characteristics of the participants with averages and, in parentheses, standard deviations.

Group 1	5 women and 1 man 3 from C1, 2 from C2, 1 from C3 Average age: 46,5 years old (7,3) Average dwelling surface: 72 m ² (27,1) Average number of persons in the household: 1,8 (0,8) Average vacuuming time (hours per week): 1,8 (1,7)
Group 2	5 women and 1 man 2 from C1, 3 from C2, 1 from C3 Average age: 45,7 years old (9,6) Average dwelling surface: 83 m ² (29,4) Average number of persons in the household: 3 (1,9) Average vacuuming time (hours per week): 2,3 (2,9)
Altogether	10 women and 2 men 5 from C1, 5 from C2, 2 from C3 Average age: 46,1 years old (8,1) Average dwelling surface: 77,5 m ² (27,7) Average number of persons in the household: 2,4 (1,5) Average vacuuming time (hours per week): 2 (2,3)

University of Toulon, France. The selection was made in accordance to the distribution of the user segments inside the population as seen in the previous section. The experimentation was monitored so that users can be observed without being disturbed by the presence of a member of the research team. Usage practices that deviated from the usage of reference were marked and, if relevant enough, labelled as UEDs.

Observation of users and comparison with the defined UoR led us to identify 5 UEDs:

- D1. Charging time management (battery left plugged in even when charged)
- D2. Dust filter cleanness (vacuuming with an obstructed filter)
- D3. Canister dust level (vacuuming even if the canister is already full)
- D4. Vacuum power management (always vacuuming using max power)
- D5. Preparing the room before vacuuming (wasting time moving furniture when vacuuming)

Not all users contribute towards these UEDs in the same proportions. The experimentation and the survey allowed us to identify UED tendencies inside the user segments. Proportions were established using observations as well as the answers to the questionnaire. These proportions are approximated in the following table (meaning that 50% of users from C1 is doing D1, 100% is doing D2, etc) (see Table 2).

After the first vacuuming session, users were given feedback with information such as:

- power consumption and its annual equivalence in euros and CO₂;
- the possible gains if adopting a more sustainable behaviour; and usage advice such as:

Table 2

UEDs distribution depending on user segment expressed in percentages of persons doing to the UED.

	C1	C2	C3
D1	50	100	0
D2	100	100	50
D3	50	70	50
D4	50	70	50
D5	50	100	0

- prepare the room before vacuuming to be quicker;
- use the different vacuum powers depending on the type of floor.

A positive evolution was observed after feedback for the three user segments. The following table lists the variations of the measured parameters (see Table 3).

Results show that for each segment the vacuuming time was shorter, the power consumption lower, there was less use of max power, there was more power switching, there were more stops and the room preparation was better. This experiment shows that it is possible to better the usage performances if the right advices are given to the users. However, it does not give information about the correct way of transmitting the information. Moreover, this experiment only shows the immediate effect of the feedback. Serna et al. (2014a,b) showed that these effects may decrease over time if the feedback is not renewed periodically.

4.5. UED models and environmental evaluations

4.5.1. UED models

After the experimentation, each one of the UEDs was reproduced in the laboratory in order to measure and calculate their environmental consequences caused by energy overconsumption and/or abnormal wear and tear.

- D1. We measure the electrical power used when the charger is plugged in even if the battery is fully charged. We consider that the charger stays plugged in 24/7 except when the vacuum cleaner is running.
- D2. We simulate filter obstruction by covering the filter with a piece of fabric to slow the airflow; we then observe the consequences on the electric motor and the battery.
- D3. The same observations are made after filling the canister completely
- D4. We measure electricity consumption at low power and max power
- D5. We consider that not preparing the room before vacuuming results in a 10% increase of running time.

The results of the measurements and calculations are listed in the following table. The electrical overconsumption is the difference between the reference usage electrical consumption and the value measured when reproducing the UED. The value is given for 500 cycles (vacuuming session and complete charge of the battery). The LT decrease is estimated using after-sales data gathered by the manufacturer and discussion with their engineers and designers.

4.5.2. LCA methodology

The environmental evaluations carried out for this study were conducted using the SimaPro v8.0.4.30 software and the EcoInvent v3.1 database. The LCAs were performed accordingly to the ISO 14040 and ISO 14044 norms (Guinee et al., 2010).

The goal of our study is to assess the environmental impact of the different UEDs and different combinations of UEDs identified. The functional unit is defined using European norms: "Run 500 vacuuming cycles on a 70 m² surface made of 70% hard floor and 30% soft floor".

We do not take into account in our LCAs neither the phases of transportation nor the end of life of the product. We consider that there is no maintenance.

The life cycle inventory of the vacuum cleaner was carried out in laboratory. A genuine vacuum cleaner was provided for the study. It was completely dismantled and each component was characterized and weighted. The impacts of the electrical consumption during the use phase were considered using the French energetic mix. The

Table 3
User performance after feedback taking account of segments.

	C1		C2		C3	
	Before	After	Before	After	Before	After
Vacuuming time (minutes)	4.48	4.42	7.72	6.11	6.93	6.11
Total time (minutes)	4.64	4.55	7.93	7.04	7.45	6.57
Electricity consumption (Wh)	4.01	3.86	6.17	4.82	5.12	3.51
Time at max power (%)	89	85	85	82	97	44
Number of power switches	0.60	1.46	0.15	0.17	0.27	0.56
Number of stops	0.40	0.40	1.25	3.75	0.33	2.00
Room preparation (1–5 bad to good evaluation)	1.80	3.00	2.00	4.00	1.66	3.00

data was compiled in SimaPro to perform the life cycle impact assessment.

The life cycle impact assessment was carried out using SimaPro with the IMPACT 2002+ method (Jolliet et al., 2003). The overall scheme of the IMPACT 2002+ framework is visible in Fig. 1.

Interpretation of the LCAs conducted for our study is given in the “Discussion” section of this paper.

4.5.3. 1st case: environmental impacts of UEDs alone

UED consequences, in terms of overconsumption and LT decrease, are translated into mathematical equations in order to calculate environmental impacts. We consider that the LT decrease of a product part induces the same LT decrease for the whole product. This means that if the battery is dead after only 400 cycles the complete product has to be replaced, generating additional environmental impacts (since the functional unit considers 500 cycles). These equations are established from the results displayed in Table 4 and are listed in Table 5. To keep equations simple, we used a single variable EI to represent the environmental impacts final score. The coefficients before EI_{VC} are the “number of vacuum cleaners” needed to complete the 500 cycles considering that the UEDs can cause a decreased number of cycles (for example, if the lifetime is reduced to 400 cycles, 1.25 vacuum cleaners, each with a LT of 400 cycles, will be needed to complete the 500 cycles). The coefficients before EI_{AEG} represent the increase of electrical consumption measured between the reference usage and the UEDs.

To calculate the environmental impacts of the vacuum cleaner, it

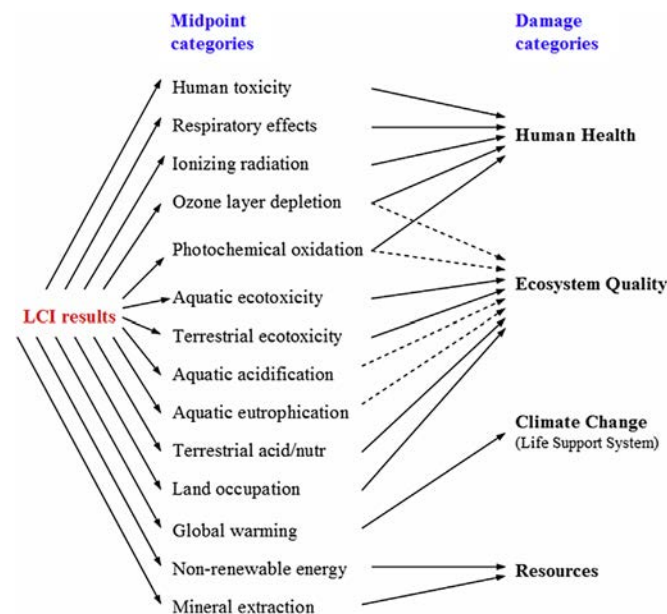


Fig. 1. Overall scheme of the IMPACT 2002+ framework, based on Jolliet et al. (2003).

was completely disassembled to obtain its bill of materials as shown in Fig. 2 below. Using the EcoInvent database, the LCA model of the vacuum cleaner was established according to the bill of materials.

Using the results from Table 4, we conducted environmental evaluations for each UED. The results are shown on Fig. 3 (electrical overconsumption alone, the value of the UoR being zero) and Fig. 4 (electrical overconsumption and early replacement of the product). On all the next figures are only visible the eight IMPACT2002+ midpoint impact categories with the highest scores. In Figs. 3–5, the numeric value written on the blue sections of each column stands for the value of the “Global Warming” impact expressed in kg CO₂-eq.

The results show a clear correlation between environmental impact and product LT. Because of early product replacement, UEDs D1 and D4 have the highest impact scores (+2.3 and + 1.6 Pt). Electrical overconsumptions alone (D3 and D5) do not generate a significant impact (from +140 to +350 μP t).

4.5.4. 2nd case: distribution of UEDs taking account of user segments

Taking into account UED distribution depending on user segments allows us to obtain results closer to real usages. It shows that because their usage practices are different, user segments will not all have the same environmental performances. To model these different usage practices, a sum of UEDs weighted accordingly to the results of Table 2 is attributed to each user segment. It must be noted that if the overconsumption impacts are simply summed up, it is not as simple for the lifetime decrease impacts. For the lifetime decrease we only take into account the UED that has the strongest impact. The equations modeling these usage practices are listed in Table 6 below.

The results of the environmental evaluations of the usage practices of the three user segments are displayed in the Fig. 5 below.

Fig. 5 shows that summing UEDs has heavy consequences. We can see that the score of segment 2 (C2 being the one with the most UEDs) is 64% (+4.1 Pt) higher than the ideal use score without UED (C0).

4.6. Design solutions

The results show that a product's usage may have heavy consequences in terms of environmental impacts. Most of these consequences can be foreseen and dealt with during the design process. To illustrate this idea, below we propose two solutions which would reduce UEDs in some measure.

First, the UED “power management” revealed that users often stay at max power even when not needed. After observation, it appears that the slider button used to power the vacuum cleaner up is a potential cause of this UED. With the current slider, it is easy to push from STOP to MAX POWER bypassing the LOW POWER

Table 4
UED consequences in terms of electricity overconsumption and LT decrease of product parts.

UED	Consequences	Electricity consumption	LT decrease
None	None	14.3 kWh	Battery LT of 500 cycles
D1: charge management	Charger plugged in 24/7	+3.3 kWh	Battery LT down to 360 cycles
D2: filter cleanness	Less vacuum power, hard on the motor, more running time	+1.3 kWh	Motor LT decrease of 10%
D3: full canister	Less vacuum power, more running time	+2.6 kWh	Measures didn't show impacts neither on the battery nor on the motor
D4: power management	Accelerated battery aging	+3.2 kWh	Battery LT down to 400 cycles
D5: room preparation	More running time	+3.1 kWh	No loss as the number of cycles stays the same

Table 5
Mathematical expressions of UEDs environmental impacts.

	Overconsumption	LT	Environmental impact (EI)
No UED	14.3 kWh	–	$EI_{D0} = EI_{VC} + EI_{Aeg}$
D1: charge management	+3.3 kWh	360 cycles	$EI_{D1} = 1.39 \times EI_{VC} + 1.25 \times EI_{Aeg}$
D2: Filter cleanness	+1.3 kWh	Motor - 10%	$EI_{D2} = 1.1 \times EI_{VC} + 1.1 \times EI_{Aeg}$
D3: Canister	+2.6 kWh	–	$EI_{D3} = EI_{VC} + 1.2 \times EI_{Aeg}$
D4: Power management	+3.2 kWh	400 cycles	$EI_{D4} = 1.25 \times EI_{VC} + 1.25 \times EI_{Aeg}$
D5: Preparation	3.1 kWh	–	$EI_{D5} = EI_{VC} + 1.25 \times EI_{Aeg}$

EI_{VC} : the environmental impact of the vacuum cleaner manufacturing.

EI_{Aeg} : the environmental impact of the vacuum cleaner electrical consumption without UEDs according to the functional unit.

EI_{Dx} : the environmental impact of UED n° x.

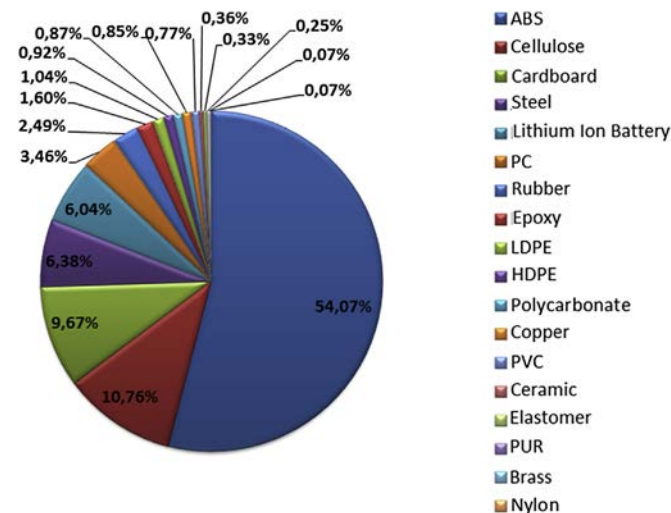


Fig. 2. Bill of materials of the vacuum cleaner.

position. Some users did not even notice the middle position of the slider. For this reason some of them overuse the vacuum's max power, thus generating more environmental impact. This issue is easily solved by modifying the control button.

Second, a consequence of some UEDs is the LT decrease of parts of the product. Making these parts easily replaceable would avoid throwing away the product when only one part is worn out. Furthermore, it would allow upgrading of the replaced parts and increase the product's attractiveness.

Nevertheless, not all the non-optimal usages can be corrected with simplistic design solutions. For example, the UED of power management is also a belief/habit problem (people often think that the low power position is not efficient) that may take a long time and complex incitation to be corrected permanently. Methods enabling designers to create these effective eco-usage awareness

strategies are still being developed by the sustainable usage research community.

5. Discussion

The case study chosen in this paper was a wireless vacuum cleaner. This choice was motivated by the fact that many household possess a vacuum cleaner and people see it from many points of view. For some it is a pleasure to keep the house clean, for some it is a chore. Hence, we were certain to easily gather a lot of user feedback and to establish different user segments. The fact that the vacuum cleaner is cordless is also important as devices with electric batteries are known to possibly age quickly if not used correctly. The results would probably have been totally different if the case study had been a wired vacuum cleaner.

The usage of reference included the few usage advices found in the user manual of the vacuum cleaner. However, a large part of it was established arbitrarily after discussion and tests. By doing so, it is well possible to come up with a usage of reference which is not environmentally optimal. The usage of reference has to remain flexible so that if better usage patterns are encountered they can be included in it. The usage of reference has to be clear of UEDs. Otherwise it is possible to miss them and to come up with false results.

Three user segments were defined using the results of the survey. The definition of the segments highly depends on the survey itself and on its analysis. Depending on the questions asked to the people surveyed and how the answers are interpreted, the results could have been different. The number of people surveyed may also play an important role. The survey took place in France, nationwide, where 350 people were surveyed. Hence, our study gives pertinent results for similar populations only. The results might be different considering a population with a great cultural gap.

Five UEDs were identified after observing the vacuuming sessions of twelve participants. The participants were chosen so that each user segment was equally represented. It is clear that a higher number of participants would have been essential to certify the

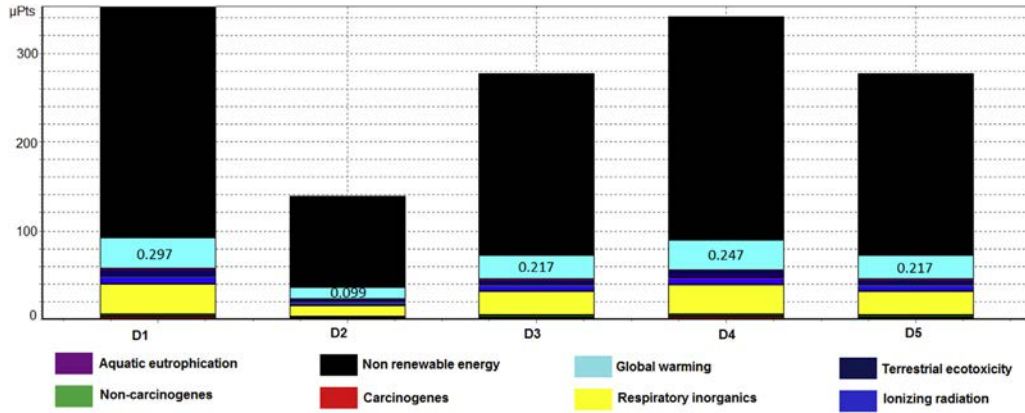


Fig. 3. Environmental impacts caused by electrical overconsumption of UEDs.

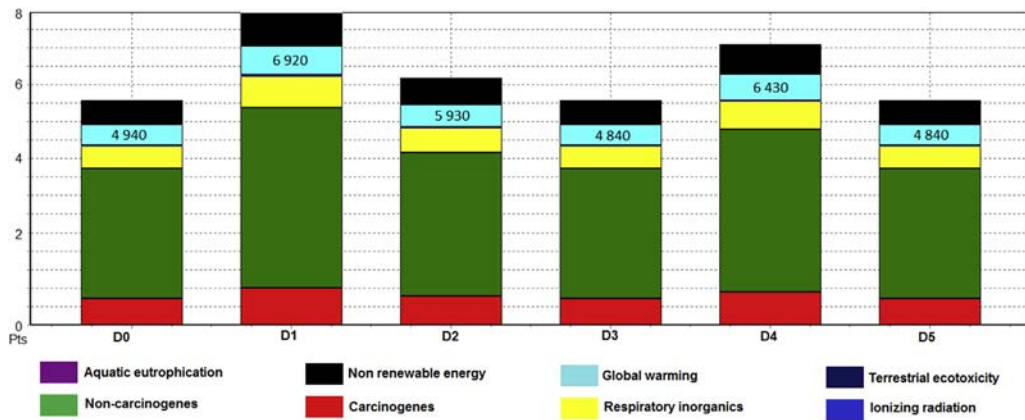


Fig. 4. Environmental impacts caused by UED overconsumption and early replacement of the product.

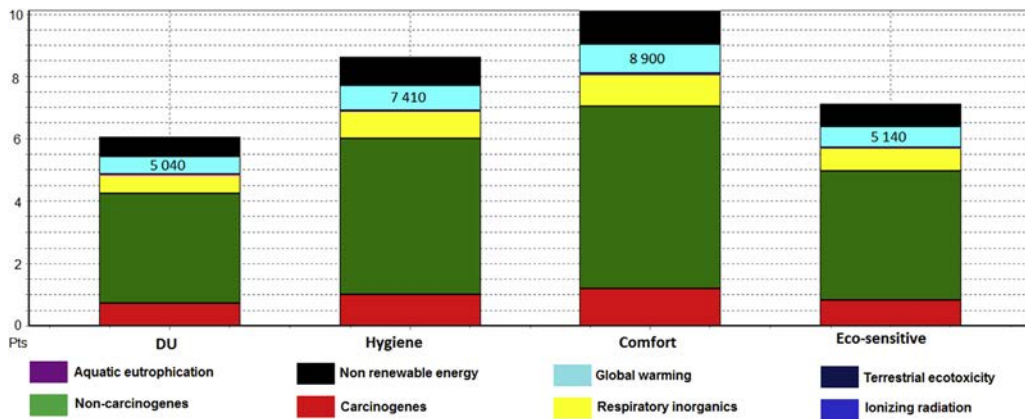


Fig. 5. Environmental impact of the usage practices of each user segment.

Table 6

Sum of the environmental impacts caused by UEDs for each user segment.

	D1	D2	D3	D4	D5	Sum
C1	50	100	50	50	50	$El_{C1} = 0.5 \times El_{D1} + El_{D2} + 0.5 \times El_{D3} + 0.5 \times El_{D4} + 0.5 El_{D5}$
C2	100	100	70	70	100	$El_{C2} = El_{D1} + El_{D2} + 0.7 \times El_{D3} + 0.7 \times El_{D4} + El_{D5}$
C3	0	50	50	50	0	$El_{C3} = 0.5 \times El_{D2} + 0.5 \times El_{D3} + 0.5 \times El_{D4}$

results. Unfortunately, the lack of adequate resources prevented us from extending the number of participants.

Feedback was given to the participants between their two vacuuming sessions. It was given in the form of usage advices written

on a sheet of paper. The feedback was well transmitted and accepted as it was sure the users would read it and were in a good disposition to try and better their behaviour. However, this case is not close to a real life situation. Knowing how people at home would react to different types of feedback regarding daily actions would be important data to get results closer to reality.

During the experimentations, we identified a UED which is not related to the product: “not preparing the room before vacuuming”. Even if it has no direct link with the product, we consider it is a pertinent UED as it has a great influence on the vacuuming task. This UED shows that only focusing on the product and its functions may not be sufficient. It would probably not have been detected without *in situ* observations. Therefore, studying the real usages from the users is showed to be useful.

UEDs were reproduced in laboratory as close to reality as possible. The losses due to UEDs of number of cycles for the battery and the motor are not easily calculated. The numbers used in our study are approximations established with help from the vacuum cleaner manufacturer. It was not possible to certify the numbers in laboratory as it would have been too time consuming to completely wear out several vacuum cleaners.

For the environmental evaluations we considered that if a UED caused a decreased number of cycles, another complete vacuum cleaner was needed to complete the 500 cycles. The environmental impact of the second vacuum cleaner was weighted accordingly to the remaining number of cycles to 500. The end of life of the products was not taken into account in the calculations.

6. Conclusion

Whereas most environmental use-phase studies only take into account real-time impacts caused by overconsumption of energy and materials, the delayed impacts also caused by UEDs can be of much greater importance. When causing abnormal wear and tear of product parts, UEDs' impacts can increase dramatically since, for many products, replacing the whole product is easier than replacing the worn part. In this paper, a methodology to identify and quantify UEDs and their consequences was elaborated. It was then tested on the cordless vacuum cleaner case study. First, the reference usage of the product was defined as the one with the best environmental performance. Second, a survey was conducted among the population of users to define user segments. Three were identified: hygiene, comfort and eco-sensitive. The definition of the segments was crucial as it influences the rest of the method up to the design solutions. It must be assured that the user segments represent parts of the user population that will need different intervention strategies to better their usage practices. Third, experimentation was conducted to quantify the UEDs from people of each segment. It was shown that depending on the segment, users have specific usage tendencies that can be represented by a weighted combination of UEDs. Every user may have its own personal weighting. However, the point is that such diversity cannot be taken into account when elaborating intervention strategies through product design. Reducing this diversity by considering pertinent user segments which gather people with similar weightings seems to be a good compromise. It is a way for bettering the practices of a maximal number of users with a minimal number of different intervention strategies (theoretically one for each user segment). Fourth, these UEDs were analyzed in laboratory to measure and calculate their consequences in terms of energy overconsumption and LT decrease. It has to be done the closest possible to reality to obtain realistic measurements. Fifth, from these consequences, environmental impacts values were calculated throughout the LT of the product. The results showed that UEDs, when summed up, can cause a raise up to 64% of the environmental

impact. It includes overconsumptions of energy but it is most of all caused by LT deterioration and the environmental cost of replacing the product early. In order to increase products' LT, designers must anticipate UEDs and the wear and tear they generate. It was finally shown that some easily found technological solutions can prevent some of the non-optimal usages. Furthermore, advanced intervention strategies such as ecofeedback may be of great efficiency for more reticent to change user segments. An evolutionary feedback may also permit a better persistence of the usage change through time. A difficulty may be to find a set of ecofeedback technologies working efficiently for the different user segments (which may each need a specific behavioral change strategy). However, as each intervention strategy may add environmental impacts to the product's account, it would be necessary to assess each one of them to determine their environmental profitability.

Contrary to the other life cycle phases of products which are often well-known, the use phase is defined by high uncertainties. Considering its importance, developing methods to help researchers and designers modeling it and assessing its impacts is crucial to design eco-friendly products. The use-phase model including UEDs described in this paper aims to be used in our future research, in a wider life cycle model for the ecodesign of products.

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