Environmental assessment of the durability of energy-using products: method and application

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ABSTRACT

Durability of products is generally seen to be a desirable goal. However, the extension of the lifetime of energy-using products is not necessarily the optimal strategy, as the efficiency of products generally decreases with wear, and their substitution by more energy-efficient products can be more environmentally beneficial in the long run. There is currently no standardised approach to resolving this conflict. The article describes an original method for environmentally assessing the durability of energy-using products in order to identify if and to what extent the potential extension of the product's lifetime could have life-cycle benefits. The method is based on the comparison, within a life-cycle perspective, of two scenarios of different lifetimes of a target product and its potential substitution with better performing alternatives. The method considers some key parameters of durability, including the product's lifetime, energy consumptions, impacts of lifetime extension and characteristics of the replacement product. The method can be used for ecodesign purposes by manufacturers or by policy makers. The applicability and robustness of the method are discussed, including limitations, difficulties and possible improvement. A general index and a simplified index have been introduced. The applicability and relevance of the simplified durability index is shown in two case-studies (of washing machines). The article shows that some life-cycle environmental benefits can be gained by extending the lifetime of the products. However, the benefits are variable, mostly depending on the selected impact category, the extension of the lifetime, the impact of repair, and the efficiency of the replacement product.

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1. Introduction

The concept of durability has been widely discussed in scientific literature. The durability of a product is generally related to the conservation of its properties. For example, Mora (2007) defined durability as "the characteristic of those objects or materials that maintain their properties over time". The focus on properties is especially common in standards defining the characteristics that the product/material should fulfil (e.g. the tensile strength of materials) and the testing conditions to identify them. Various ISO standards have been developed, for example concerning buildings and building components (ISO, 2009; ISO, 1998). These standards require that the estimated service life of the product (e.g. the timeframe during which the product satisfies the design conditions) meets or exceeds the design life of the product (e.g. the specified period of time for which the product is to be used).

Analogously, various standards regarding the durability of furniture (ISO, 2007; ISO, 2005) have been developed. These involve the standardised application of loads in order to observe the response of the product to external stress. In some cases, standards have been developed for a specific product group, modelling the probability of failure and the conservation of performance. This is the case, for example, of the CIE 097 standard, which introduced a standard method for the maintenance of indoor electric lighting systems (CIE, 2005). This method also represents an interesting example of the correlation of the durability with the functionality of the product, which in this case is the energy output of the device.

The concept of durability has sometimes been associated with the ecodesign of products for the selection of design solutions that extend their lifetime (Kostecki, 1998; Lounis et al., 1998). However, durability can be interpreted differently, for example by differentiating between "the product's economic life (determined by the opportunity cost) and product's technical life (determined by the duration of the product's ability to fulfil its technical function)" (Kostecki, 1998).

Although the use and the End-of-Life (EoL) of the products are not directly controlled by the manufacturers, the product's design can affect these phases and the lifetime of products, including the prevention of premature failures (Lounis et al., 1998) or simplifying repair and maintenance (Kostecki, 1998). Furthermore, the concept of "design for durability" is generally understood as the design of the product in order to extend its lifetime (Downes et al., 2011; Kostecki, 1998; Östlin et al., 2009; Rose, 2000; Veshagh and Li, 2006). The extension of products' lifetimes is likely to reduce the environmental impacts during their lifecycles and to lead to benefits largely resulting from 'avoiding' manufacturing and supply chain impacts (Downes et al., 2011).

The ISO technical report 14062 on "integrating environmental aspects into product design and development" defines "design for durability" as being related to "the product's longevity, reparability and maintainability, considering environmental improvements emerging from new technologies" (ISO, 2002). Furthermore, it states that (ISO, 2002) "when developing products, there may be considerable value in thinking in terms of functionality (how well the product suits the purpose for which it is intended in terms of usability, useful lifetime, appearance, etc.). […] When defining the product's lifetime as part of its function, increasing the durability and extending the services associated with the product can reduce adverse environmental impacts. It can also be beneficial to achieve a balance between the product's technical lifetime and its useful lifetime (i.e. how long a product is considered useful, before it is obsolete or no longer needed by the user)".

Increasing the durability of products may have the adverse effect of reducing the adoption of more environmentally beneficial technology with increased energy efficiency or emission controls (Veshagh and Li, 2006; VHK, 2011) and potentially interfering with the substitution with more energy-efficient solutions, as for example, for energy plants (Ardente et al., 2005) or for buildings and building materials (Ardente et al., 2011, 2006). Sneck (1981) also found that "negative aspects of excessive durability are caused by the use of unjustifiably durable and usually much more expensive materials, construction techniques or designs". Excessive durability can become counterproductive as the needs of the users may change to such an extent that the product is no longer suitable or the changed fashions (or competition from newer products) make old ones unacceptable (Sneck, 1981).

A possible strategy for the improvement of durability of products is their upgradability, which can slow product obsolescence and can reduce the environmental impacts and costs for users (Kostecki, 1998). Product upgrade features help avoid early obsolescence and increase the product's life by facilitating the replacement of electronic components or installed software, for example, while avoiding the unnecessary disposal of mechanical parts, such as the plastic housing, power supply and metal chassis. According to William and Sasaki (2003), the upgrading and reselling of some products, such as personal computers, are far more effective from an environmental standpoint than recycling. However, upgrading also has its limitations, mainly related to rapid and major technological changes (Kostecki, 1998).

According to ISO/TR 14062 (2002) "a balance is also necessary between extending a product's lifetime and applying the latest technological advances that may improve the environmental performance during use by taking into account possible upgrading during product development". ISO/TR 14049 (2012) also noted that "for long-lived products, such as refrigerators with lifetimes of 10 or 20 years, technology development may be a factor that cannot be disregarded. One refrigerator with a lifetime of 20 years cannot simply be compared to two successive, present-day refrigerators with a lifetime of 10 years. The refrigerators available 10 years from now are certain to be more energy efficient (i.e. lower energy input per functional unit) than the present" (ISO, 2012, p8). Therefore, the different efficiency levels of products should be included as part of the assessment.

1.1. Durability of products in the European product policies

The promotion of durable products is in line with current European policy strategies as underlined by the European Commission (EC): "moving away from a wasteful economy towards one based on durability and reparability of products is likely to create job opportunities throughout the product lifecycle in terms of, maintenance, repair, upgrade, and reuse" (EC, 2012). Furthermore, according to the European Union (EU) Ecodesign Directive (EU, 2009), lifetime extension must be considered as an appropriate strategy to improve the environmental profile of products. Possible Ecodesign policy measures include the setting of a minimum guaranteed lifetime, the setting of a minimum availability time for spare parts, and the promotion of the modularity, upgradeability and reparability of products (EU, 2009).

However, for energy-using products (EuPs) and energy-related products (ErPs), lifetime extension is not necessarily the optimal strategy due to decreasing efficiency of worn-out products as well as due to technological progress (Dewulf and Duflou, 2004).

The complex question of whether or not it is better to replace an inefficient EuP with a more efficient one more quickly has already entered the European policy debates about the Ecodesign of several product groups, as discussed for example in several studies (IZM, 2007; ISIS, 2007; AEA, 2009; VITO, 2009; AEA, 2010; VHK, 2011b).

The lifetime extension of some product groups can be environmentally beneficial, such as EuPs which have low impacts during their use phase (e.g. products which have very low energy consumption or operate with renewable energy sources), or products for which the production phase accounts for a significant share of their environmental life-cycle impact. According to Horie (2004), trade-offs also exist between the optimal product lifetime from the perspective of energy and cost objectives. For example, users often prefer to postpone the replacing of inefficient devices because the electricity cost savings that would be incurred with a new, more efficient model are relatively small compared with the purchase costs of new models. It is therefore recognised that a comprehensive assessment of durability is a complex task and it should include issues other than technical properties, including the functions, life-cycle environmental impacts and life-cycle costs of the product, and user behaviours.

Measures for improving durability have already been introduced into current European product policies. These measures fix a minimum lifetime of the products according to standardised methods. Some examples have been developed for the Ecodesign of indoor electric lighting systems (EC, 2009b) and vacuum cleaners (EC, 2013), and for the EU Ecolabel criteria on the upgradability[1] of televisions (EU, 2009a), notebook computers (EC, 2011a) and personal computers (EC, 2011b).

However, several stakeholders (including associations of consumers, Non-governmental organisations (NGOs) and representatives of Member States) recently highlighted the need for a more systematic assessment and integration of durability issues into EU product policies (DEFRA, 2011; VHK, 2011b; BIOis, 2013). Some authors have highlighted the need to further develop methods to better handle resource efficiency issues, including durability, in product policies (Dalhammar and Machacek, 2013).

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[1] These criteria prescribe that the product shall be designed so that key components can be easily exchanged and/or upgraded by the end-user.

1.2. Aims of the article

Based on the abovementioned societal needs and the unavailability of appropriate methods, the present article discusses and applies an original method for the environmental assessment of the durability of energy-using products (EuPs) in order to identify if and to what extent the potential extension of a product's lifetime could be relevant in terms of life cycle benefits. The method is based on the life-cycle approach (ISO, 2006) and focuses on the variations of some key parameters and impact categories.

The method is developed to be applied in the context of product development (including also the design phases until and including the market launch) and helps to address issues that could arise during the assessment of EuP (including data availability).

More particularly, the method has been developed in order to support policy makers for: i) the identification of product groups that could benefit from requirements concerning lifetime extension; ii) the setting of product requirements for some relevant product groups to be put on the market. The method has been subjected to a consultation process with several stakeholders involved in policy making discussions (including representatives of governments, industries, recyclers and NGOs) (Ardente and Mathieux, 2012a,b). Feedback from stakeholders has been also integrated to improve the method.

The method does not include additional issues of sustainability, such as economic or social/user considerations. Reuse of the product or its parts is also not considered.

It is highlighted that, according to the EU policies and literature review, durability is one of the key criteria for the Ecodesign of products. Other Ecodesign strategies can be applied to improve the environmental performance of the products (e.g. reusability/recyclability/recoverability, use of recycled materials, management of hazardous substances, dematerialisation). However, the present article focuses only on the analysis of the durability criteria, as a part of more comprehensive method for the assessment of the resource efficiency and environmental sustainability of EuPs (Ardente et al., 2013; Ardente and Mathieux, 2013).

An analysis of the methods and approaches for the assessment of durability, as discussed in the scientific literature will be given in the following section (Section 2). The proposed method will then be presented (Section 3), an example of its application to the washing machine product group will be given (Section 4) and the robustness of the method and its possible applications will be discussed (Section 5).

2. Methods for the assessment of durability of products

According to the scientific literature, the assessment of the durability of products can be subdivided into two main approaches: the forecast of the expected duration of products, and the assessment of the sustainability of the lifetimes of products throughout their life cycles.

The first approach is, for example, based on analysis of resistance to loads and failure models (including the prevision of the expected time before failures). This is a classical "engineering" approach to durability, which focuses on the physical durability of products. It is based on, for example, probabilistic/stochastic methods (Lounis et al., 1998; Ugwu et al., 2005), direct checking/testing and/or indirect assessment of durability based on product-specific standardised methods (Bravo and de Brito, 2012; EC, 2004; ISO, 2009; ISO, 2005; Medina et al., 2013; NAFI, 2003), use of technical datasheets and checklists (Takada et al., 1999; Veshagh and Li, 2006).

The second approach is more comprehensive and it can involve technical, environmental, social and economic issues in the assessment, and focuses on the ability of the product to meet the expectations of the users. Various methods have been developed according to the different scopes of the studies and the priorities of the analysts. The studies identified were mainly based on:

a. Life Cycle Assessment (LCA) (ISO, 2006) of different scenarios of the durability of products (Agrawal et al., 2012; De Saxce et al., 2012; Dewulf and Duflou, 2004; Horie, 2004; Cooper, 2005; Rüdenauer and Gensch, 2005, 2005b; Tasaki et al., 2013; WRAP, 2010). The methodological assumptions and the selected scenarios are set by authors for the specific case studies being considered;

b. Ecodesign methods and tools (Abeysundara et al., 2009; Brouillat, 2009; Downes et al., 2011; Östlin et al., 2009; Sundin and Bras, 2005; VHK, 2011). In these cases the assessment of durability was part of a more comprehensive analysis, which included the analysis of potential burdens/benefits of extending the lifetime of products (mainly based on the combination of life-cycle environmental and life-cycle cost issues);

c. Qualitative/quantitative analysis of the relationship between durability of products and their potential environmental impacts (Brook Lyndhurst, 2011; Hauschild et al., 2004; van Hemel and Cramer, 2002; Kostecki, 1998; Lindahl et al., 2006; Monteiro de Barros and Dewberry, 2006; Mora, 2007; Rosenthal, 2004; Walsh, 2009). These analyses are generally supported by expert judgements of authors (also supported by interviews and/or questionnaires) and by literature reviews.

In addition, it was observed that the majority of the methods mainly focus on the environmental assessment of durability issues. However, the differentiation between the 'engineering' and the 'environmental assessment' approaches is not strict and, in some cases, common views and contact points among the two have been observed, including material durability issues complemented by life-cycle considerations about impacts and costs, as for example in (Rose, 2000; Kagawa et al., 2006; Ugwu et al., 2005).

The relevance of lifetime issues in the life cycle of products has been also investigated by Tasaki et al. (2013). Authors focused on the consumer's point of view, who should decide whether it is worth replacing a product from an energy perspective before or after its average life. However, this approach differs from that used during the early stages of the life cycle (e.g. in the context of product development). In this case, analysts have to analyse the product at the early design stage and assess the impacts of potential strategies for lifetime extension. Such analysis is hampered by the lack of data on the impacts of processes for the extension of the lifetime (e.g. repair, cleaning) and on the impact of potentially replacing products.

Cullen and Allwood (2009) also highlighted the risk of directly using LCA to develop priorities for action, especially when the system boundaries of a product are not properly defined (i.e. defining comparable alternatives referring to different timelines). According to the same authors, decision makers are in danger of overemphasising the use-phase impacts and overlooking the impacts of indirect activities (Cullen, and Allwood, 2009). According to the authors, guidance and specific methods should be provided to avoid such risks.

Furthermore, Cooper (2005) stated that some studies proved that the lifetime extension of EuPs was not environmentally profitable as it is based on incorrect assumptions concerning the set of system boundaries. Cooper (2005) also denoted the general lack of studies on household products, using different life-span assumptions.

During our analysis of the scientific literature, various key methodological issues for a quantitative environmental assessment

of durability have been identified (listed in Table 1). Although several of these key issues have been included in various reviewed studies, a method for tackling all of them has not yet been identified.

In particular, it was not possible to identify a general structured and recognised method to analyse the environmental assessment of the durability of products. It was instead observed that methods in the scientific literature based on a life-cycle approach generally focus on case-by-case approaches (as e.g. in Abeysundara et al., 2009; Rüdenauer and Gensch, 2005b; Walsh, 2009; WRAP, 2010). Based on the analysis of the literature, there is a need for a method founded on a life-cycle approach (i.e. robust), that adheres to ISO standards (ISO, 2006) for the definition of comparable system boundaries (i.e. transparent), takes into account the key issues presented in Table 1 (i.e. comprehensive), is applicable to various products at the early stages of their life cycle (i.e. general), and is simple enough to bridge potential data gaps (including e.g. the impacts of processes for lifetime extensions or the impacts and efficiency of potential replacement products). However, it is highlighted that the method is not intended to provide a comprehensive and detailed LCA of the product, but aims to identify whether or not it makes sense to focus on the durability issues of a considered product.

3. Method for the environmental assessment of the durability of EuPs

The method for the environmental assessment of the durability of energy-using products (EuPs) is based on the comparison, from a life-cycle perspective, of different scenarios concerning the length of the lifetime of a target product and its potential substitution with better performing alternatives. In particular, the method is based on the comparison of two scenarios (Fig. 1). The "Base-case" Scenario (1) assumes that the product "A" is substituted, after its average lifetime "T", by the new product "B". The "Durability" Scenario (2) instead assumes that the lifetime of product "A" is extended by an additional time frame "X", and only afterwards it is substituted by the new product "B".

The differences between the impacts of the two scenarios are used to assess the benefits/drawbacks of the potential extension of the lifetime of the product.

The input data of the method can be affected by some uncertainties, especially when the assessment is performed in the
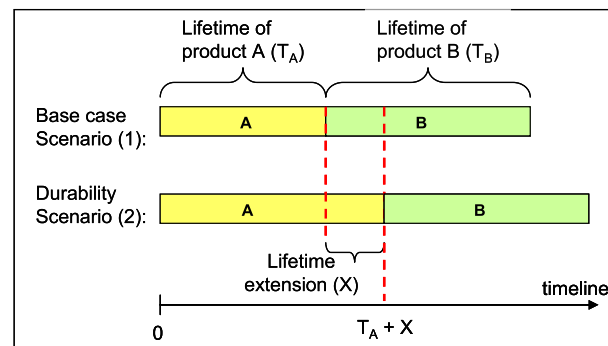
Table 1
Methodological key issues for a quantitative assessment method for durability.

Methodological key issues for durability	References
Consistent and transparent setting of the reference flow(s) for comparing the potential benefits/burdens	(Cooper, 2005; Abeysundara et al., 2009; WRAP, 2010)
Assessment and inclusion of the impacts of repairing	(Östlin et al., 2009; WRAP, 2010)
Clear set and declaration of the system boundaries in order to grant robust and transparent assessments	(Horie, 2004; Cooper, 2005; Rüdenauer and Gensch, 2005)
Variations in the lifetime and their influence for the environmental profile of products	(Dewulf and Duflou, 2004; Downes et al., 2011)
Trade-offs between the benefits related to the longer lifetime with potential drawbacks (e.g. due to loss of efficiency of the products)	(Downes et al., 2011; Tasaki et al., 2013; VHK, 2011; WRAP, 2010)
Broad selection of impact categories in order to avoid that the choice of categories could "drive" the analyst to certain conclusions	(De Saxce et al., 2012)
Use of a simple method, in order to support practical applications, by designers and policy makers, to a broad set of products. Sensitivity analysis of key parameters.	(Rüdenauer and Gensch, 2005)

Fig. 1. Setting of scenarios for the assessment of durability.

early stages of the product development process. In this case it is important to find out which of the available products is representative of the new product (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010).

The use of representative data for the product group can support the analysis and reduce uncertainties. For example, the parameter "X" has to be set by the analyst based on average lifetime information from manufactures and/or users, or based e.g. on previous experiences and statistical data.

It is highlighted that the value of "X" is fundamental to the method and, therefore, it is recommended that a sensitivity analysis of results be performed considering a possible range of different values.

3.1. Indexes for the durability of EuPs

In life-cycle approaches, in particular in LCA, it is necessary to set equivalent reference flows in order to compare two scenarios (ISO, 2006). As underlined by ISO/TR 14049, products can be regarded as being comparable in spite of differences in their lifetimes. This difference has to be taken into account in the calculation of the reference flow (ISO, 2012).

According to ISO/TR 14049 (ISO, 2012), the selected reference flow for the proposed method is the provision of a selected function of the product for a selected timeframe. If the product provides different functions, multi-functionality and allocation problems could emerge, which should be treated using different possible LCA strategies (Ardente and Cellura, 2012). However, for our purposes we have restricted the analysis to only one function of the product.

The timeframe is delimited by the initial time "0" (i.e. the start of the use of product "A") up to the time "$T_A + X$" (i.e. the extended lifetime of product "A"). The assessment of durability is therefore based on the difference of the environmental impacts arising in the two scenarios defined in Fig. 1, according to a selected environmental impact category "n". (The assessment should be run using different impact categories.)

In scenario 1, it is assumed that the impacts of the manufacturing phase and EoL[2] of product "B" are proportionally divided over the lifetime of the product "B". The impacts of the reference flow in scenario 1 are therefore calculated as follows:

$$I_{1,n} = P_{A,n} + U_{A,n} \cdot T_A + E_{A,n} + \frac{P_{B,n}}{T_B} \cdot X + U_{B,n} \cdot X + \frac{E_{B,n}}{T_B} \cdot X \qquad (1)$$

where:

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[2] The analysis considers only impacts due to disposal of the product. Potential environmental burdens and credits derived by other EoL treatments (e.g. recycling or energy recovery) are not accounted (as well as recycled materials used as inputs in the production).

- $I_{1,n}$ = Environmental impact (of category "n") for the base-case scenario [unit];
- $P_{A,n}$ and $P_{B,n}$ = Environmental impact (of category "n") for the production of "A" and "B" respectively [unit];
- T_A and T_B = Average lifetime of "A" and "B" respectively [year];
- X = Extension of lifetime of "A" [year];
- $U_{A,n}$ and $U_{B,n}$ = Environmental yearly impact (of category "n") for the use of "A" and "B" respectively [unit/year];
- $E_{A,n}$ and $E_{B,n}$ = Environmental impact for category "n" for the EoL (disposal in landfill) of "A" and "B" respectively [unit].

The impacts of the distribution (transport) during each phase (i.e. production, use, EoL) are included in the related terms. Distribution to consumers is included in the use phase.

In scenario 2, the lifetime of product "A" is to be extended. If the time extension 'X' is not too long, it can be assumed that there will be not substantial changes of the EoL treatment of product "A" at the two reference times ("T" and "$T_A + X$"). The environmental impacts of the reference flow are:

$$I_{2,n} = P_{A,n} + U_{A,n} \cdot (T_A + X) + R_{A,n} + E_{A,n} \qquad (2)$$

where:

- $I_{2,n}$ = Environmental impact (of category "n") for scenario 2 [unit];
- $R_{A,n}$ = Environmental impact (of category "n") for potential additional treatments (e.g. repair) related to the extension of the lifetime of product "A" [unit].

The difference between the two scenarios is:

$$\Delta_n = I_{1,n} - I_{2,n} = \left[\frac{P_{B,n}}{T_B} + \frac{E_{B,n}}{T_B} + (U_{B,n} - U_{A,n}) \right] \cdot X - R_{A,n} \qquad (3)$$

The term "Δ_n" in Formula 3 represents the environmental impact variation (of category "n") between the base-case and the durability scenarios [unit].

Please note that the results of Formula 3 are independent of the impacts due to the manufacturing phase and EoL of product "A" and of the impacts of the energy use of product A until the time "T_A". These impacts, in fact, affect equally both the two scenarios.

Formula 4 analyses whether there is an environmental benefit in prolonging the lifetime of the product:

$$\Delta_n = 0 \qquad (4)$$

From the analysis of previous formulas, it is observed that, if product "A" is substituted by product "B", involving the same (or even larger) energy consumption during its use "U", it will result that: $(U_{B,n} - U_{A,n}) \geq 0$. Therefore, there will be environmental benefits ($\Delta_n > 0$) when: $X > R_{A,n}/[P_{B,n}/T_B + E_{B,n}/T_B + (U_{B,n} - U_{A,n})]$.[3]

If product "A" is substituted by product "B", which consumes less energy during the use phase (in other words, is more energy efficient), it will result that:$(U_{B,n} - U_{A,n}) < 0$. Therefore, the environmental benefits due to the extension will be reduced by the loss in energy efficiency. In this case, it is beneficial to prolong the lifetime of "A" when $X > R_{A,n}/[P_{B,n}/T_B + E_{B,n}/T_B + (U_{B,n} - U_{A,n})]$, and this occurs when the following condition applies: $[P_{B,n}/T_B + E_{B,n}/T_B + (U_{B,n} - U_{A,n})] > 0$.

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[3] It is assumed that all the elements in Formula 3 are always non-negative and that the denominator does not equal zero.

When $[P_{B,n}/T_B + E_{B,n}/T_B + (U_{B,n} - U_{A,n})] \leq 0$, it follows that $\Delta_n \leq 0$. This means that the lifetime extension never produces environmental benefits.

Finally, in the special case where $R_{A,n} = 0$ (i.e. the lifetime can be extended with no or very limited impacts as for example, by the upgrading of some electronics via the installation of newer software), there will always be environmental benefits ($\Delta_n > 0$) when $[P_{B,n}/T_B + E_{B,n}/T_B + (U_{B,n} - U_{A,n})] > 0$.

It is also highlighted that the method mainly refers to EuPs (i.e. products that consume energy during the use phase). In fact, for non-EuPs the terms $U_{A,n}$ and $U_{B,n}$ are generally null (unless consumable materials are also included in the environmental balances) and the analysis would follow the previous condition 1 (concerning the potential extension of the method to other product groups, see the discussion in Section 4).

Finally, a general index of durability can be defined as the ratio between the environmental benefits and the life-cycle impacts of product "A", as follows:

$$D_n = \frac{\dfrac{P_{B,n}}{T_B} \cdot X + \dfrac{E_{B,n}}{T_B} \cdot X + (U_{B,n} - U_{A,n}) \cdot X - R_{A,n}}{P_{A,n} + U_{A,n} \cdot T_A + E_{A,n}} \cdot 100 [\%] \qquad (5)$$

The term "D_n" in Formula 5 represents the durability index for the impact category "n".

It is possible to set a "threshold of relevance (Y) [%]" over which the lifetime extension is deemed to be relevant for the scope of the analysis (e.g. ecodesign of a product to reduce a certain amount of impacts of potential life-cycle benefits to be achieved through some policy measures). It can be summarised that, if $D_n \geq Y$, it would be beneficial to extend the lifetime of the product.

Otherwise, if $D_n < Y$, it would be not beneficial to extend the lifetime of the product.

The threshold of relevance (Y) should be set by the analysts (designers or policy makers) according to their prioritisation of environmental impacts and potential achievable benefits. However the strategies to set these thresholds belong to the decision-making process and are beyond the scope of this article.

3.2. A simplified index for the durability of EuPs

The calculation of Formula 5 implies the knowledge of the two products "A" and "B". In particular, product "A" is the focus of the analysis, while "B" represents the higher efficiency substituting product (e.g. the benchmark product). This can be difficult to assess, especially considering that this type of analysis is performed in the context of development of product "A". However, in some cases it can be assumed that the manufacturing phase and EoL of product "B" will not differ substantially from product "A" (for example, in the case of products that are not affected by rapid technological change). In these cases, a simplified index can be introduced that refers only to the characteristics of product "A". The additional assumptions are:

1. The products "A" and "B" have the same average lifetime ($T_A = T_B = T$). This assumption is plausible for products that are not characterised by rapid technological change and on which fashion has a minor influence.
2. The products "A" and "B" have the same impacts during the production and EoL phases ($P_A = P_B = P$; $E_A = E_B = D$). This assumption is plausible for products that are constituted of similar materials and have a similar manufacturing process, and when no substantial technological changes apply.
3. The impact due to the use phase of product "B" is expressed as a function of the impact of product "A". In particular, it is assumed

that product "B", compared to product "A", would have lower impacts during the use phase of a certain percentage "δ", as follows:

$$U_{B,n} = \delta \cdot U_{A,n} \quad \text{with} : 0 \leq \delta \leq 1 \qquad (6)$$

The parameter "δ" allows the comparison of product "A" with a more energy-efficient product "B". For example, if it is assumed that product "B" has 20% lower energy consumption during the use phase compared to product A, then: $\delta = 0.8$.

The abovementioned assumption 3 is the most relevant for the assessment because it can largely influence the results. The value of "δ" should be carefully set (for example, based on trend projections of products in the market (ISO, 2012)). It is furthermore recommended that a sensitivity analysis be performed of values of "δ", due to potential uncertainties of the parameter.

Based on the three abovementioned assumptions, Formula 5 can be modified as follows:

$$D'_n = \frac{\frac{P_n}{T} \cdot X + \frac{E_n}{T} \cdot X - (1 - \delta) \cdot U_n \cdot X - R_n}{P_n + U_n \cdot T + E_n} \cdot 100 [\%] \qquad (7)$$

where:

- D'_n = Simplified durability index of the considered product for the impact category "n" [%];
- P_n = Environmental impact (of category "n") for the production of the product [unit];
- T = lifetime of the product [year];
- E_n = Environmental impact (of category "n") for the EoL (disposal in landfill) of the product [unit];
- X = Extension of the lifetime of the product [year];
- U_n = Environmental impact per unit of time (of category "n") for the use of the product [unit/year];
- R_n = Environmental impact (of category "n") for additional treatments (e.g. repair) necessary for the extension of the lifetime of the product [unit];
- δ = Percentage representing the lower impacts of the use phase of a new product that could substitute the case study product [%].

4. Analysis of the product group "washing machine": two case-studies

The assessment of improvement in durability should focus on products that have longer technological cycles, i.e. products that are less affected by frequent technological changes (Rose, 2000). For example, washing machines are, among the consumer durables, products with a relatively large technology cycle and hence are potentially relevant targets for 'design for durability' measures.

Although there are several case study applications of LCA to washing machine in the scientific literature, there is no common position about extending their lifetime. Various studies neglect the durability issues (Nielsen and Wenzel, 2002; Park et al., 2006; Cullen and Allwood, 2009). The European ecodesign preparatory study on washing machine generally stated that unnecessary energy consumption by products is influenced by over-aged appliances, but did not provide any specific figures (ISIS, 2007). Simon et al. (2001) stated that 90% of the environmental impacts of washing machines occur in the use phase, with the implication that improved energy use efficiency should be prioritised over lifespan considerations. On the other hand, Downes et al. (2011) concluded that improvements in energy efficiency (achieved through replacement) do not compensate for the impacts associated with the manufacturing of

new products. Similarly, some authors found that the substitution of old machines machine is convenient only when the most efficient products in the market are used as replacements (WRAP, 2010).

Due to this observed lack of homogeneity in the modelling and assessment of lifetime issues in LCA studies, the washing machine product group was found to be suitable for the application of the present method on durability. Two case studies of washing machines (WM1 and WM2) have been selected for the analysis of the durability. Furthermore, according to private communications from manufacturers, the impact of producing new washing machines is comparable to that of old devices. In some cases, also for some electronic components, manufacturers claim that impacts have even decreased (e.g. content of precious metals in Printed Circuit Boards). Therefore, the use of the simplified durability index (Formula 7) is considered as being suitable for this product group.

4.1. Case study products and assumptions

The input data and assumptions for the assessment of the case-studies are following illustrated.

The bills of materials of the two products refer to data from Rüdenauer and Gensch (2005), complemented by some communications from manufacturers and references.[4] WM1 represents the medium-low price segment of the market, while WM2 represents the high price segment.

The index "D'_n" is calculated for some example impact categories. It is generally recommended to use a multi-criteria approach using when established life-cycle indicators. However, in order to focus the attention on the application of the method, the presented results have been here restricted to three indicators that are considered to be representative of a larger set of impact categories: Global Warming Potential (GWP), Terrestrial Ecotoxicity (TE) and Abiotic Depletion Potential - Element (ADP$_{el}$). These three categories have been selected because GWP is generally dominated by energy consumption, ADP$_{el}$ is generally dominated by the manufacturing phase and TE is generally equally influenced by both of the life-cycle stages. These three indicators are also in line with the recommendations of the International Reference Life Cycle Data System (ILCD) Handbook (EC, 2010). Characterisation factors of the three impact categories are derived from Guinée et al. (2002) as implemented in the software GaBi (PE, 2011).

The average lifetime "T" for washing machines (WMs) is assumed to be 11.4 years (Rüdenauer and Gensch, 2005). The extension of the lifetime "X" is assumed to range from 1 to 4 years;

The energy consumption of the two WMs during the use phase is 133 kWh/year (1.52 MWh/lifetime), based on the assumption of 175 [cycles/year] of washing a 4-kg load. (Ardente and Mathieux, 2012a,b). Energy consumption for when the WM is on "standby" and "off" were excluded from the scope of the study;

The energy consumption of the substituting product "B" during the use stage is assumed to range from 100% to 70% of that of the product "A". It is highlighted that, according to the current European energy labelling of washing machines, the substitution of a device of class A to one of class A+ implies a 12% reduction in energy consumption, while substituting to a washing machine class A++ would lead to a reduction in energy consumption of about 22%. Changes in water consumption levels are not considered in the assessment of durability;

The life-cycle impacts of the production "P_n" phase and EoL "E_n" of the case-study products are calculated according to various life-cycle inventory databases (BUWAL, 1996; ecoinvent, 2009; ELCD,

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[4] Details about products' composition are illustrated in Ardente and Mathieux, 2012a,b.

2010; PE, 2011) (details of life-cycle impacts are provided in Ardente and Mathieux (2012a,b));

The life cycle impacts "R_n" for the additional treatment (i.e. repair) to extend the lifetime of the WMs are estimated as follows. Two scenarios are considered: "low-repair scenario – LRS" and "high-repair scenario – HRS", in which "R_n" varies:

- From 2.5% to 5% in the GWP impact category of the production phase;
- From 10% to 20% in the TE impact category of the production phase;
- From 10% to 30% in the ADP$_{el}$ impact category of the production phase.

The "low-repair scenario" can be considered to be representative of a minor intervention for the prolongation of the machine's lifetime (e.g. corresponding to the substitution of a low-impact part, such as the door). The "high-repair scenario" is representative of a major repair intervention (e.g. substitution of a main component such as the motor or a Printed Circuit Board).

Table 2 summarises the main assumptions behind the calculation of the Simplified Durability index D'_n; Table 3 illustrates the data about the life-cycle impacts of WM1 and WM2.

4.2. Results of the assessment of durability

The following Figs. 2 and 3 illustrate the simplified index for the two case studies in the LRS scenario, while Figs. 4 and 5 illustrate the HRS scenario. The Y axis plots the values of the D' index: positive values correspond to an environmental benefit (saving) associated with the lifetime extension.

From the analysis of these results, it is observed that the lower the energy consumption of the replacement product (i.e. with lower values of "δ"), the lower the benefit of extending the durability of the product in all scenarios (i.e. lower values of the durability index). In some cases (e.g. Fig. 2 for GWP) it is possible to identify a threshold of the value "δ" below which there is no benefit in extending the lifetime. This threshold is a function of the extension "X" of the lifetime (e.g. $\delta = 80\%$ for 4 years' lifetime extension of WM1). The benefits of WM2 are larger than those of WM1 for the GWP and TE impact categories. This is related to the higher impacts of the production phase/EoL of the WM2 case study.

In the low-repair scenario (Figs. 2 and 3) the environmental benefits of the TE and ADP$_{el}$ impacts are larger than those of the GWP. Furthermore, the slope of the "D'_n" index for TE and ADP$_{el}$ in the figures is lower than that of GWP due to the fact that these impacts are not largely influenced by the use phase. On the other hand, the benefits of TE and ADP$_{el}$ are largely influenced by the assumptions about the impacts of the repair activity.

It is also noticed that the parameter "R_n", which concerns the life-cycle impacts of the treatments for lifetime extension, is very relevant for some impact categories. For example, the benefits of the LRS scenario (Figs. 2 and 3) compared to those of the HRS scenario (Figs. 4 and 5) are higher for the ADP$_{el}$. In some cases, there is no benefit to be gained from extending the lifetime: for example,

Table 2
Summary of the assumptions for the calculation of the simplified Durability Index "D'_n".

Product "A" (WM1 and WM2)		
Average lifetime "T"	11.4	[years]
Energy consumption (during the use)	133	[kWh/year]
Total energy consumption for the use phase	1.52	[MWh]
Extension of lifetime "X"	From 1 to 4	[years]
Product "B" (replacement product)		
Energy consumption (δ) of product "B" compared to "A"	From 70% to 100%	

Table 3
Life cycle impacts of WM1 and WM2.

	Global Warming potential (GWP)		Terrestrial ecotoxicity (TE)		Abiotic depletion potential elements (ADP$_{el}$)	
	[kg CO$_2$ eq.]		[kg DCB$_{eq.}$]		[kg Sb$_{eq.}$]	
Life cycle impacts for WM1						
P_n	2.0E+02		2.7E+00		4.6E-03	
E_n	8.2E+00		2.6E-01		2.5E-06	
U_n	8.4E+01		1.9E-01		1.7E-05	
R_n	LRS	4.9E+00	LRS	2.7E-01	LRS	4.6E-04
	HRS	9.9E+00	HRS	5.4E-01	HRS	1.4E-03
Life cycle impacts for WM2						
P_n	3.1E+02		5.6E+00		1.3E-02	
E_n	1.2E+01		6.6E-01		2.9E-06	
U_n	8.4E+01		1.9E-01		1.7E-05	
R_n	LRS	7.7E+00	LRS	5.6E-01	LRS	1.3E-03
	HRS	1.5E+01	HRS	1.1E+00	HRS	4.0E-03

LRS – low-repair scenario; HRS – high-repair scenario.

in the HRS scenario for the WM2 (Fig. 5), benefits for the ADP$_{el}$ occur when the lifetime is extended for more than three years.

Concerning the potential benefits related to durability of WMs, it is observed that:

- The extension of the lifetime of the WM1 by 4 years (Fig. 2) can reduce the life-cycle GWP by 3%, compared to the replacement of the old product with a new one that is 10% more efficient in an LRS scenario.
- It can be observed that the lines crossing the *x*-axis comprise of values of $80\% < \delta < 85\%$ (Fig. 2). This means that, relative to the GWP impact, the extension of the lifetime of the WM1 from one to four years is environmentally comparable to the replacement of the old product with a new one that is 15–20% more efficient (LRS).
- The extension of the lifetime of the WM2 by 3 years (Fig. 3) leads to a saving of about 3% of the GWP impact category for the LRS scenario compared to the replacement with a product with $\delta = 85\%$. The extension of the lifetime by three years is furthermore comparable to the replacement of the old product with a new one that is 30% more energy efficient.
- The benefits are generally more relevant for some impact categories, such as ADP$_{el}$ and ET. For example, the extension of the lifetime of the WM2 by four years (Fig. 3) can reduce the life-cycle ADP$_{el}$ by about 25%, independently from the energy efficiency of the replacing product. However, in the case of large impacts of the repair activity (scenario HRS – Fig. 5), these benefits are 5% of the life-cycle ADP$_{el}$.

Comparing the results with similar studies in the literature on the same product group (as by WRAP, 2010; Rüdenauer and Gensch, 2005) the current analysis showed a larger variability in the concluding remarks. In particular, it is observed that the environmental assessment of the lifetime extension of a WM is influenced by the considered impact category and the variation range of the selected parameters.

5. Discussion

In the following, some key issues of the proposed method are discussed, focusing on the potential use of the method and its uncertainties.

5.1. Robustness of the assumptions and uncertainties of the method

The proposed durability method is generally influenced by some key parameters, mainly the average lifetime of the product/s

considered, the annual energy consumption, the impacts due to lifetime extension (e.g. repair) and the efficiency of the replacement product (as highlighted by various authors such as Downes et al., 2011; Östlin et al., 2009; Dewulf and Duflou, 2004). These input data can be affected by uncertainties, especially when the assessment is performed in the context of the product development. A useful contribution could derive from published studies of the product group (e.g. LCA). When possible, data should refer to information from associations of manufacturers that are representative of the product group (as done in the WM case study which referred to Rüdenauer and Gensch (2005)).

Some data, however, are intrinsically uncertain (e.g. the impact of carrying out a repair or the efficiency of replacement products). In these cases, it is recommended to analyse different scenarios based on sufficiently large variations of the key parameters, in order to assess the sensitivity of the results related to the initial assumptions.

The use of the simplified index allows for significant simplification of the calculations. In this case, in fact, it is not necessary to calculate the full life-cycle impacts of the replacement product. In particular, when the analysis is performed during the early stage of the development of product "A", it could be difficult to collect information about the life cycle of "new" product "B" (a difficulty also experienced in similar analyses, such as in WRAP, 2010). These difficulties rise especially for products that have a long average lifetime. Although simplified, this method is scientifically robust for the scope of the assessment, and it is based on assumptions that are plausible and generally adopted also by other studies in the literature. The use of the simplified index can be inappropriate in the case of products that are subject to rapid technological changes
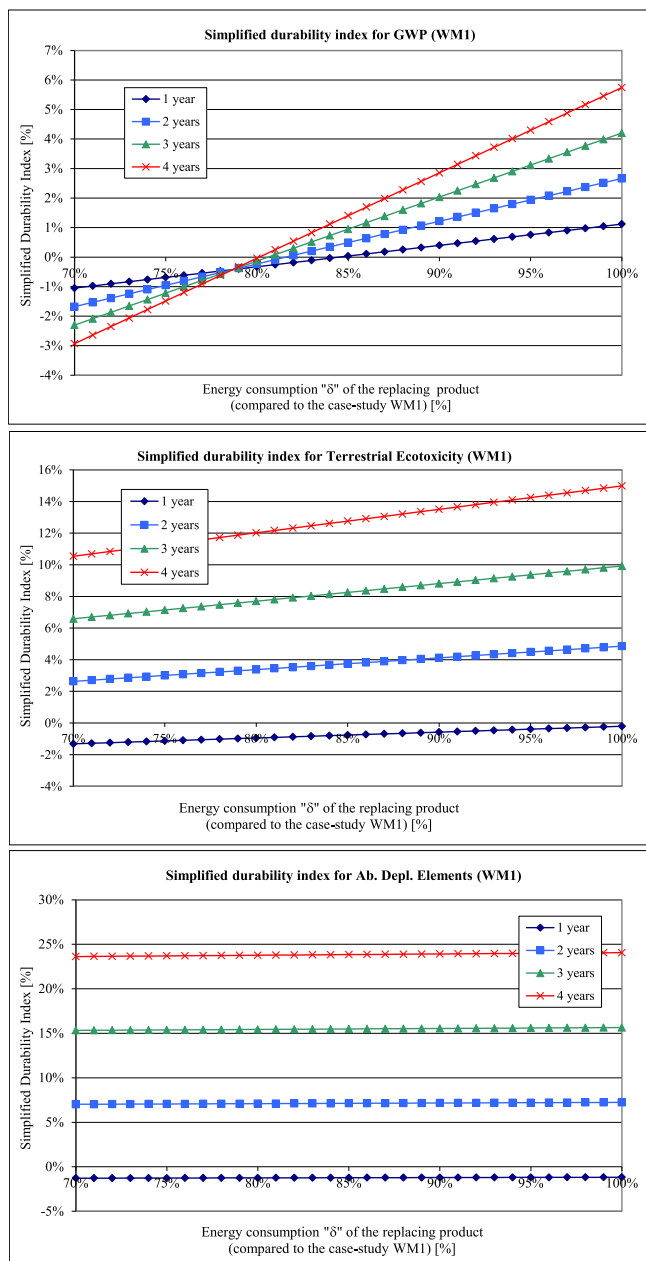

Fig. 2. Simplified Durability index for WM1 (LRS scenario) for various values of δ and for three representative impact categories.
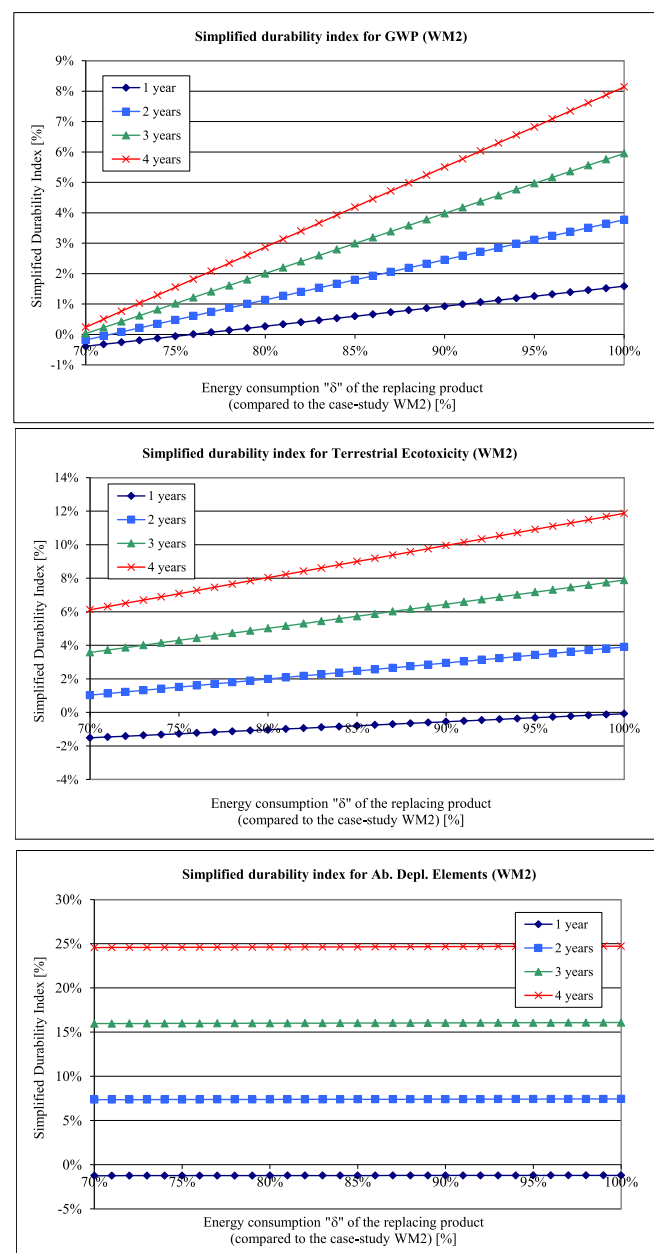

Fig. 3. Simplified Durability index for WM2 (LRS scenario) for various values of δ and for three representative impact categories.

(Kostecki, 1998). In such cases, the impacts of the manufacturing phase and EoL of product "B" could greatly differ from those of the base-case product. In such cases, it is recommended that the general index be applied. The impacts of product "B" could be estimated as a portion of the impacts of product "A". The assessment should also include a sensitivity analysis of the impacts of product "B" in order to assess potential uncertainties.

The method also introduced some key assumptions, such as the single functioning of the product. In the case of multi-functionalities (e.g. a washing machine that includes a drying system), the impacts of the product should be divided among the different functions according to common LCA rules, for example by the use of allocation factors (Ardente and Cellura, 2012).

Concerning the modelling of the EoL, the analysis considered the impacts of EoL disposal, while potential environmental burdens/credits due to the recycling/recovery of materials have not

been considered. As consequence of this, the terms "$E_{A,n}$" and "$E_{B,n}$" in the formulas refer only to disposal, and are assumed to be non-negative. In addition, only primary materials are assumed to be used in the production process. This choice was made because the assessment of durability illustrated here was part of a more comprehensive assessment, which also included other ecodesign criteria (such as recyclability of waste or recycled input materials (Ardente and Mathieux, 2013)). For these reasons, it was decided to keep the analysis of these issues separate. However, the inclusion of the potential benefits/burdens of recycling could be part of the further development of the method.

In addition, it is noted that the impacts of the additional treatments for lifetime extension "R" are considered to be independent of the extension of the lifetime "X". A more comprehensive assessment, for example using the general index for durability, could assume that maintenance for longer lifetime extensions would cause higher burdens.

The additional treatments could also include the upgrading of the product (William and Sasaki, 2003). In this case, a representative replacement product "B" should be carefully selected, which generally cannot be considered to have the same impacts on the manufacturing phase as product "A".

Impacts due to the energy consumption during the use phase can be also considered as variable parameters of the analysis instead of a fixed design assumption (as in Tasaki et al., 2013). This approach is, however, more relevant to support the decision making process of consumers more than designers. While the method has been specifically conceived for EuPs, it is potentially extensible to ErP, considering in this case the relationships with related energy systems. For example, a thermal insulation board is an ErP that can influence the thermal losses of buildings and/or the performance of heating/conditioning systems. The assessment of the durability of thermal insulation should also be accounted for in the environmental analysis of these related systems (Ardente et al., 2006).

The method is also potentially extensible to non-ErP (e.g. furniture). In this case, the terms "U_A" and "U_B" in Formula 5 related to the use phase should be related to the use of consumables (e.g. polishing and cleaning agents).

5.2. Possible applications of the method

The method could be used by different actors for different purposes, mainly at the early stages of the life cycle of EuPs (i.e. during the product development until and including the market launch).

As already argued in Section 1.2, the proposed method has been developed to support the product policy debate on the durability of EuPs and the setting of product policy requirements for some relevant product groups. This method has been discussed with stakeholders during a consultation process (Ardente and Mathieux, 2012a,b) and has been recognised as a useful tool for the assessment of lifetime issues of EuPs in the product policy process. Moreover, following this consultation, the implementation of the method for the preparation of European product policies is currently under discussion (BIOis, 2013). These initial positive feedbacks tend to prove the usefulness of the method in product policy discussion on durability.

Although not directly tested, the proposed durability indexes could be additionally used by manufacturers to identify and assess how the increased reparability/substitutability of some components would contribute to the overall life-cycle balance of the product. Durability strategies for newly designed products could be assessed, including incorporating the substitution of key components into the design (e.g. disassemblability of key components to be potentially substituted by spare parts), design for durable key
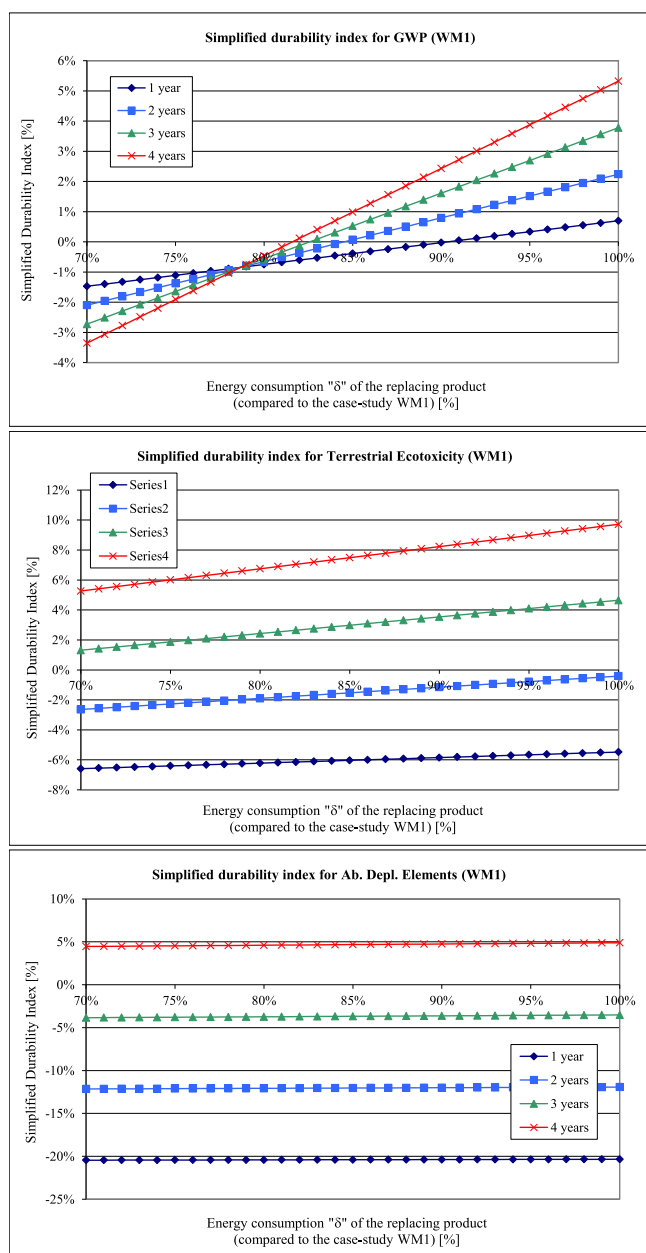

Fig. 4. Simplified Durability index for WM1 (HRS scenario) for various values of δ and for three representative impact categories.

components (e.g. with the use of more resistant materials), and provision of information for the optimal use and maintenance of the product.

As previously discussed, some uncertainties affect the analysis during the product development (especially when the potential replacement product "B" is not known). However, the method can drive the establishment and assessment of different scenarios in which parameters relevant to the analysis are modified within some possible ranges. The general index for durability is complete, and includes several product parameters. On the other hand, the simplified index allows some possible data availability problems to be overcome.

The method could also support the development of commercial strategies that require the design of durable products, such as for example the option of leasing products. Leasing firms retain the

ownership of the leased units and they can have the incentive to remarket products or to invest in designing more durable products, resulting in a lower volume of new production and disposal of products (Agrawal et al., 2012). The method could be used by such leasing firms to define the optimal extension of the lifetime or the best interventions to be made from an environmental life-cycle perspective. Such results could then be used to develop more environmentally friendly leasing offers.

However, the two latter aspects regarding the potential usefulness of the method during the design phase and for defining leasing strategies have not yet been tested with manufacturers.

6. Conclusions

This article presents a robust, transparent, comprehensive, general and still sufficiently simple method the environmentally assessing the durability of energy-using products (EuPs). It is based on the comparison, within a life cycle perspective, of two different scenarios concerning the lengths of the lifetime of a target product and its potential substitution with a better performing alternative. The method is not intended to provide a comprehensive and detailed LCA of the product, but aims to identify whether or not and to what extent it makes sense to focus on the durability of a considered product.

The method integrates all the key parameters that have been identified in the scientific literature on the subject. In particular, it includes the impacts of extending the lifetime of the product and key characteristics of the replacement product (such as life cycle impacts, lifetime length and energy efficiency).

Furthermore, the method is developed to be applied at the early stages of the EuPs development (including design and placement on the market) and it addresses potential problems that could arise (including the definition of a set of system boundaries and data availability).

The method provides two durability indexes: a general index (Formula 5) and a simplified index (Formula 7). Although simplified, we argue that this method is scientifically robust for the scope of the assessment (based on assumptions that are plausible and generally adopted by other relevant studies in the literature). It is highlighted that the general index for the assessment of durability is also applicable when additional data about the case-study products are available (e.g. through estimations and/or extrapolations).

Uncertainties and potential improvements of the method have been identified and discussed. In particular, the application of the general index (including a sensitivity analysis of input parameters) is recommended for product groups characterised by rapid technological change (concerning the manufacturing, use phase or EoL treatment of the product).

The simplified durability index has been applied to two washing machine case studies. This product group has been identified as being relevant for the analysis because of the large lack of homogeneity observed in the scientific literature about the modelling and assessing of lifetime issues. From the analysis, it is concluded that the extension of the lifetime of washing machines can produce some environmental life-cycle benefits (such as the abiotic depletion potential), even if it would delay replacement with more energy-efficient products. However, the achieved benefits are variable, mostly depending on the selected impact category, the extension of the lifetime, the impacts of repair and the efficiency of the replacement product. The case studies also show that the method can address the need for a more systematic assessment of durability aspects in product policies, as it can serve the policy debate on the setting of durability requirements for EuPs.
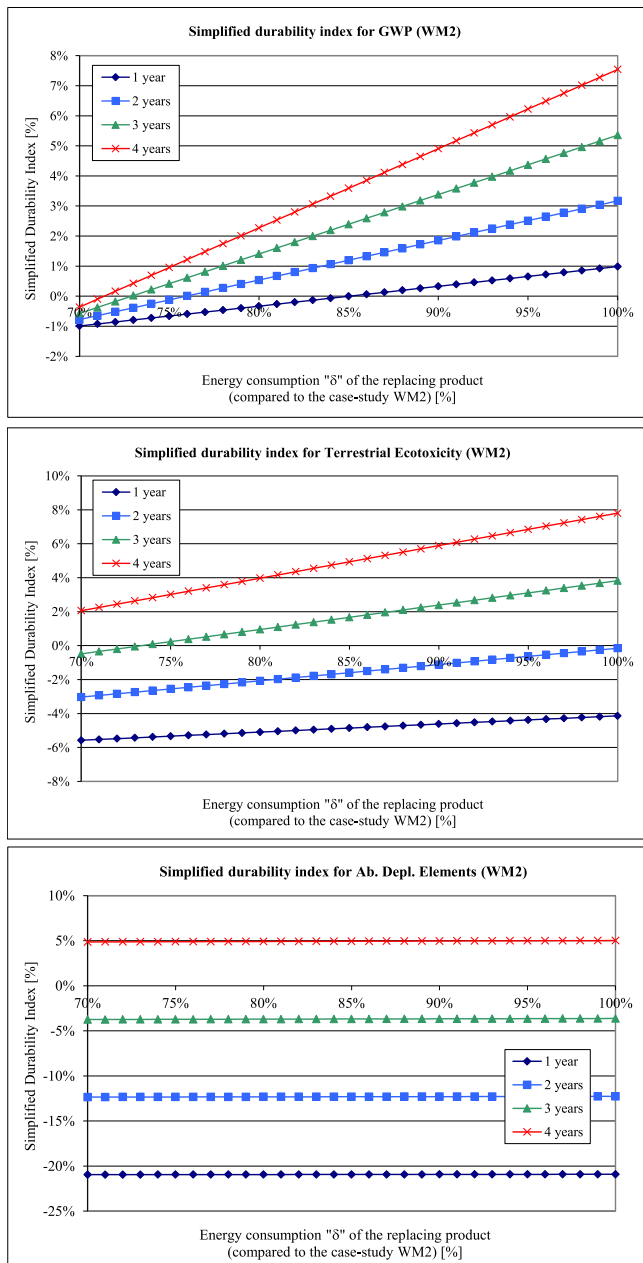

Fig. 5. Simplified Durability index for WM2 (HRS scenario) for various values of δ and for three representative impact categories.

Disclaimer

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