DURABOT: THE TOOL TO INTRODUCE DURABILITY IN THE DESIGN PROCESS

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ABSTRACT

The extension of the product lifecycle is crucial in the application of Circular Economy principles. However, when Energy Related Products are concerned, managing a durable product does not necessarily mean dealing with sustainable products. This happens because components and/or materials are affected by aging and lead to increased requirement of resources to run (i.e. electricity); there are certain trends that, although distinct from the previous facts, balance the effects of aging, i.e. energy grid mix decarbonization. In the present work an approach that considers both the economic and environmental consequences of durable products is proposed. The Durabot tool has been developed to accomplish the environmental analysis. The work overcomes the main literature criticalities: enables the assessment of environmental consequences of durability ; the evolution of energy grid mix is introduced; the environmental consequences of durable products in different lifecycle scenarios can be assessed during the design phase; therefore, the components to substitute and to make accessible are identified. The tool is intended to be used aiming at design for product lifecycle extension, maintaining both economic and environmental convenience

Keywords: Research methodologies and methods, Sustainability, Decision making, Design to X

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Cite this article: Cappelletti, F., Menchi, G., Rossi, M., Germani, M. (2023) 'Durabot: The Tool to Introduce Durability in the Design Process', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.152

1 INTRODUCTION

Ensuring environmentally sustainable production and consumption patterns is becoming an increasingly relevant need for most societal actors (primary industries, citizens, businesses, policymakers, third-sector organizations) (Alejandre et al., 2022). Therefore, the need arises to link environmental sustainability with multiple strategies that emerge in the Circular Economy (CE), such as recycling, reusing, remanufacturing and lifetime extension for impact reduction.

1.1 Durability

Enterprises recurrently consider durability; nevertheless, the affinity between durability and environmental sustainability is not always valid; it depends on the nature of the product.

From a general perspective, environmental sustainability is the ability of systems and activities to maintain a particular entity or resource (Ciccarelli et al., 2022). According to Iraldo et al. (2017), durability refers to the ability of a product to endure its lifetime. From products requiring energy or other sources during their lifetime, durability is comparable to sustainability. However, concerning Energy Related Products (ErP), preserving and using a product for a long time does not always leave a positive mark on the environment due to components degradation and consequent loss in performance.

Consequently, durability needs to be assessed to understand whether and when durable also means environmentally sustainable. Several indexes spread in the literature. Some approaches assess efficiency by comparing two or more scenarios by applying standards, such as CEN/CENELEC EN 45552 (Rodriguez and Favi, 2022; Schischke, 2022). Some authors prefer assessing the sustainability of durability from the economic and environmental perspective by comparing sale and servitization or other Business Models (BMs), as Kanatli et al. (2021) or Iraldo et al. (2017). Others couple technical information on products' lifetimes, failures, stresses, and degradation mechanisms with Life Cycle Assessment (LCA) and Life Cycle Costing (CC) considerations (Alfieri et al., 2018). When durability question is faced, it is essential that LCA also comprises all the aspects of the product lifecycle, including undesired factors, such as wear, aging, deterioration, as products durability relies on those factors to guarantee a long-lasting lifetime (Cappelletti et al, 2022).

By defining the research gaps and research agenda regarding product durability, Mesa et al. (2022) highlight the need for developing more design methods and indicators to measure, determine, and predict product durability in different lifecycle scenarios.

Alfieri et al. (2018) present an approach and a method to assess how to increase the durability of ErP and evaluate the associated impacts. The authors assess the benefits associated with the durability of a product through LCA-based indices. The approach might find practical application in identifying design options aimed at improving the durability of a product, even though it allows a static comparison between two scenarios.

1.2 Durability assessment tool

The scarcity of resources and the urgency to exploit them persuade the public into thinking that the more a product lasts, the better it is, as lower resources are employed to produce a new one. However, the question is more complex, especially for ErP products:

- Their components and/or materials are affected by aging.
- The energy grid mix, especially in European Countries, aims at full decarbonization; using a higher percentage of renewable resources to produce electricity makes the unitary environmental impact of energy consumption less impacting.

Those factors have opposite trends on product durability and environmental sustainability. Due to every product's peculiar features, it is impossible to predict if it is less impacting to maintain the old product or substitute it with a new one. The chance to upgrade the old product should be a noteworthy, proactive option (Khan et al., 2018). Haines-Gadd et al. (2018) investigate strategies that help develop more emotionally engaging product experiences, as the consumer, with choices and preferences, highly interferes with durability (de Ayala, 2021).

Mesa et al. (2022) highlight the strict relationship between durability and its boost derived from innovative circular BM and servitization practices. They identify 9 topics associated with product durability, such as fatigue, failure, reliability, sustainability and eco-design, lifecycle assessment/thinking, product service systems.

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To the best of the authors' knowledge, no tools are intended to assess the durability of products under the environmental sustainability perspective that also considers the whole product lifecycle.
The preferable lifecycle phases to evaluate durability are the design phase (Richter et al., 2019), the End of Life (EoL) (Sihvonen, 2017) when lifetime extension strategies are implemented, and the maintenance phase, when the convenience of replacing a module/component or the whole product is evaluated. Kirkizoğlu and Karaer (2022) analyze three alternative models for a durable goods manufacturer's after-sales service channel structure in the scenario where the customers evaluate the total cost of ownership of a product when they make their purchase decision.
In this context, the present paper develops a method and related tool to evaluate durable products' environmental sustainability. The tool supports the design phase as it preventively allows the assessment of durability and environmental consequences under different circumstances. Furthermore, it proves helpful in identifying which components have the highest priority of reachability to be substituted, as their aging may affect the whole product's environmental performance. The tool allows the comparison of scenarios regarding the product lifecycle phases and enables the assessment of environmental consequences of durability and how it varies when specific parts of the product are substituted. The work traces back its spark from the previous study of Cappelletti et al. (2022), where the correlation between durability and environmental sustainability is assessed by comparing two refrigerators. In that study, the authors introduced the refrigerators aging and adjusted the durability index proposed by Ardente et al. (2014), affirming that: i) it is necessary to introduce an analytical description of product performance over time and ii) this introduction makes specific simplifying hypotheses inapplicable in the index.
Starting from those results a specific tool has been developed. By doing so, the primary literature gaps are filled because:

- The environmental consequences of durability are evaluated considering product evolving performances in time (i.e., worsening functionalities).
- External factors (i.e., the evolution of the energy grid mix) that partially mitigate the increase in environmental impact due to wear and aging are introduced.

The tool enables the measurement and prediction of environmental consequences of durable products in different lifecycle scenarios during the design phase.
The approach followed in identifying the tool's main functionalities and structure is presented in Section 2; Section 3 follows, where the tool is used in the case of professional espresso coffee machines; Section 4 discusses the obtained results and critically comments the tool; ultimately, Section 5 closes the work.

2 METHOD

In the critical phase of design, multiple factors must be considered. As CE is spreading, the alternatives for lifetime extension strategies are considered and durability often tips the balance and makes clear which are the most convenient. In this work, the focus is on the environmental perspective and the main goal is to provide support for the design phase so that critical components for durability may be identified and their design improved so that they can be easily assessed to be upgraded, remanufactured, or substituted. However, the environmental driver must couple the economical one. In Figure 1 the proposed approach is presented. It aims at considering the economic and environmental aspects, based on a lifecycle thinking approach: both costs and environmental performances are assessed throughout the whole lifecycle to support the development of a durable and environmentally sustainable product.
The economic evaluation is made from the consumer perspective because the user will go for product or component substitution. The $Durability'€$ formula proposed by Cappelletti et al. (2022) has been used (Eq. 1), as it compares the life cycle cost of the product and component substitution cases: if the index is higher than 0, it means that is more convenient to substitute only some parts of the product, while if it is negative, the entire product replacement is advisable.

$$Durability'€ = \frac{Pur_{B_T} + EoL_{B_T}}{T} X + Use_{B_X} - Use_{A_X} - Main_{B_p} \quad (1)$$

where:

- Pur_{B_T} is the price (present value) of product B [€].
- EoL_{B_T} is the cost (present value) of disposing product B [€].

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- Use_{B_X} and Use_{A_X} is the cost (present value) of using the products B and A respectively during the period X [€].
- $Main_{B_p}$ is the cost (present value) of the maintenance due to component(s) p substitution [€].

2.1 Durability index

The tool is based on the durability index proposed by Ardente et al. (2014) and edited by Cappelletti et al. (2022). Considering the outlined limitations, the external factor of the energy mix evolution is also introduced. The durability index D_n compares the environmental impacts of repairing a broken product (A) by changing or fixing the malfunctioning component and replacing it with a new, updated, and improved product (B). From the results achieved by Cappelletti et al. (2022), the main limitations have been explored and external factors, such as the evolution of the energy grid mix, have been introduced. In the present work, the extended, adapted formula for the durability index has been considered when developing the tool (Eq. 2).

$$D'_{n_{ext}} = \frac{\frac{P_{B,n}}{T_B} X + \frac{E_{B,n}}{T_B} X + \left(U_{B,n,X} - U_{A,n,X}\right) - R_{A,n}}{P_{A,n} + U_{A,n}\, T_A + E_{A,n}} 100\ [\%] \qquad (2)$$

Where:

- $P_{B,n}$ and $P_{A,n}$ are the environmental impacts for the n impact category of material and manufacturing phase of product B and A respectively [n unit]
- T_A and T_B are the expected lifetime of products A and B respectively [years]
- X is the time product B's lifetime is extended for [years]
- $R_{A,n}$ is the environmental impact, for the n impact category, for additional treatments (e.g., repair) necessary for product A's lifetime extension [n unit]
- $U_{A,n,X}$ and $U_{B,n,X}$ are the use phases environmental impact, for the n impact category, of product A and B, respectively, during the X years [n unit]
- $U_{A,n,T}$ is the use phase environmental impact, for the n impact category, of product A for the period T [n unit]
- $E_{A,n}$ and $E_{B,n}$ is the EoL phase environmental impact, for the n impact category, of product A and product B respectively [n unit].

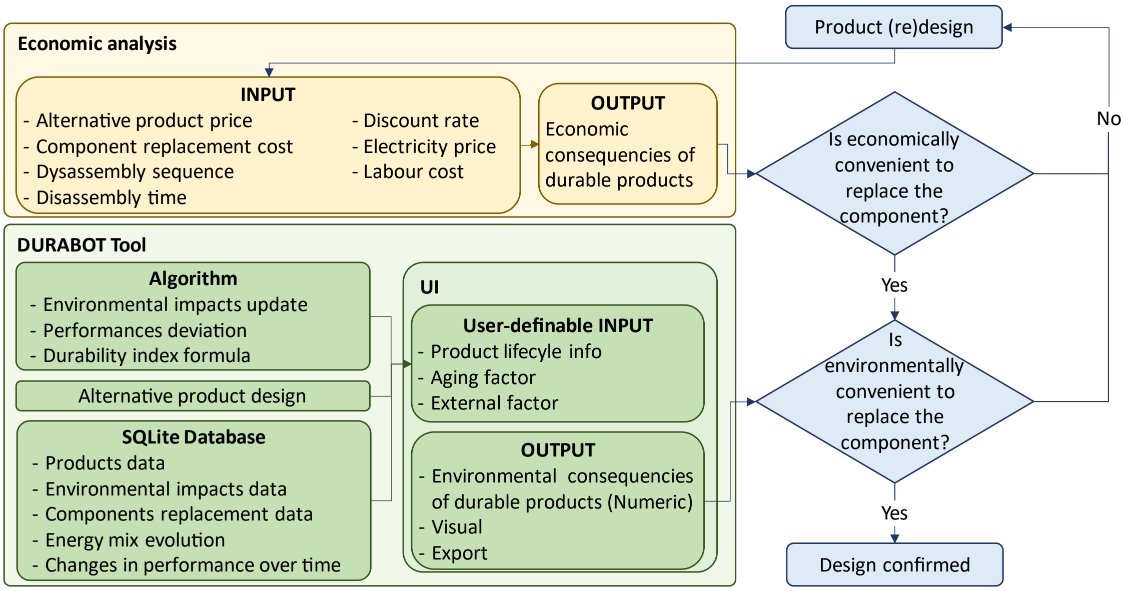

Figure 1. Workflow and Durabot architecture

During the design stage, only partial information may be available; thus it is possible to consider the revised, simplified formula where the impacts related to the production (P_n) and EoL (E_n) phases have the same value for product A and product B. However, when the evolution of the energy mix and/or the product's performance change over time are considered, product A and product B use phases may

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have different values, and there is no relationship between them. For this reason, the value of the environmental impacts related to the use phase must remain distinct (Eq. 3).

$$D'_{n_T} = \frac{\frac{P_n}{T_B} X + \frac{E_n}{T_B} X + \left(U_{B,n,X} - U_{A,n,X}\right) - R_n}{P_n + U_{A,n}\, T_A + E_n} 100\ [\%] \quad (3)$$

All these factors have been considered when working on an automated solution so that each of them can be customized as much as possible. Hence, such an automated solution has been named Durabot.

3 DURABOT

The Durabot tool is a handy and easy-to-use software that allows users to quickly assess whether it is more convenient to substitute a product or to undergo the repairing process from an environmental point of view. Its simple yet immediate interface guides the process by suggesting the requested inputs and providing graphs that mirror the outputs. Furthermore, the calculation is executed in real-time so that it is possible to quickly test with several different input values and impact types to achieve a better result.
The interface is divided into three main areas, as shown in Figure 3.

- The first area (top left, yellow) contains the inputs: some are direct, some are chosen from lists and others are calculated according to the inserted inputs.
- The second area (bottom left, orange) shows the main output, D_n being the durability index, and some intermediate outputs, such as $U_{A,n,X}$, $U_{B,n,X}$, $E_{A,n}$.
- The third area (right, green) is dedicated to the graphs: they show the trend of the durability index as the differential initial energy efficiency between product A and product B decreases and as the overall product lifetime (T) increases.

3.1 Input area

The input area is composed of two columns: the left is used for numeric inputs, while the right one allows users to choose the products on which the analysis should be conducted. The numeric inputs on the left column include the product's lifetime and energy consumption ratio. The tool is intended to be used for multiple products: the user can retrieve information from previously analyzed products or insert and modify additional ones. The multiple-choice inputs on the right column allow the selection of the products themselves, the impact category, the component to replace and the aging factors. Finally, the three boxes on the bottom of the left column are automatically calculated or read from the database based on other inputs provided by the user:

- Energy Consumption B can be retrieved as a function of Energy Consumption A (Eq. 3)

$$\text{Energy Consumption B} = \text{Energy Consumption A} * \delta \quad (3)$$

- R Factor A and B are read from the database based on the chosen.

In some cases, the user might be unsure about what should be inserted in some requested fields: for this reason, every input box has been provided with a tooltip that suggests the required information just by dragging the mouse cursor on it. However, the description provided in the tooltip is relatively brief, so a more detailed one could be needed. By clicking on the info button (on the top-left of the input area), a new panel will open with two links to documents that explain the whole process thoroughly.

3.2 Intermediate and final output area

This area contains either the input for the durability index, that are product and case-dependent, and the main output. This area comprises two parts: one contains the environmental impacts related to the lifecycle phases and the specific timeframes X and T related to Product A, while the second is related to Product B.
As previously mentioned, the outputs are calculated as all the input boxes are filled in; as any of them is modified, new outputs are immediately calculated and shown. The output boxes also have the same suggestion feature in the input fields.
The intermediate outputs, which are further employed as input for the durability index, are obtained through the algorithms and reading of the data stored in the SQLite database. This contains basic information about the products, their impacts, and replaceable components. It is read at the beginning of the execution and every time a new product or component is added or modified via software.

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The database stores default data and user-inserted data. The unitary environmental impacts of energy consumption belong to the first group. Following the future trends of the European energy grid mix (Capros et al., 2016), the energy mix is supposed to increase the use of renewable energy resources; a discretization time of 5 years is considered. When the user creates or edits products (that means that environmental impacts for all the lifecycle phases are inserted for the Climate Change [kgCO2eq], Water use [m3] and Mineral Resource Scarcity [kgCUeq]), this information is also stored in the DB. In accordance with the values inserted in the input area, the dependent inputs are retrieved. Ultimately, the D_n is calculated and shown for the single case related to the input parameters inserted.

3.3 Graphs area

The graphs area has a main space where the graphs are displayed, a menu to select the graph to show and an export button. The selectable graphs are:

- "Variable Delta", which shows how D_n changes by changing δ. Durabot shows multiple lines per each case: each dotted line represents the trend of D_n as X value increases (1, 3 and 5 years are shown by default and an additional one, for the X value selected by the user).
- "Variable T", which shows how D_n changes by changing T. Also in this case, the dotted lines represent the trend of D_n as X value increases (1, 3 and 5 years are shown by default and an additional one, for the X value selected by the user).

A yellow cross also considers the user-defined δ value in the first graph and T value in the second graph, thus showing the actual D_n result, which can also be read in the related output field. The graphs should thus be interpreted as extensions of the executed calculation. The importance for the graphs to show multiple X-scenarios consists in presenting a wide overview of the possible cases. In fact, regardless of the punctual D_n value that describes a specific case, the trends for a set X (varying δ) or between different X may have high variability. In the first type graph all the lines are monotonous, increasing function. For certain products, their slope is high: this means that also small differences in energy efficiency may determine the convenience of substituting the product or the component. When the lines have a slope close to zero, the dependency on energy efficiency is lower. Moreover, the differential value between different X values may lead to having very tight lines (when the use phase is much higher than the remaining phases) or lines spread over a wide area of the graph (when the lifecycle phases' impacts are comparable). The export button can be used to save a complete version of an executed calculation. It exports the graph axes values and every input and output present in the software itself, in an open source and easily manageable file format (.csv).

4 CASE STUDY

The main functionalities of the tool have been tested in the case of a professional espresso coffee machine equipped with three coffee-dispensing groups. The production occurs in Italy; in the present case the use phase is assumed in Europe. The case investigates whether the replacement of certain product parts makes the lifetime extension of the product sustainable from the economic and environmental perspective when compared to substituting the full product with a new one, able to absorb 10% lower energy during the use phase. The main product structure is maintained, but the focus is on energy efficiency.

4.1 Economic analysis

The expected lifetime for the considered professional coffee machine is 7 years. The analyzed scenario supposes the failure to occur at year 4: after the substitution, the product is used for additional 3 years (X). As uncertainties may affect the design phase, a range is given for the economic inputs, summarized in Table 1. The selected target components are chosen according to the work proposed by Cappelletti (2021) and applied by Rossi et al. (2022): such target components are the main boiler and the resistance. The economic analysis also considers the assembly and disassembly costs, having 30€/h as labor cost. Future expenditures have been actualized with 10% interest rate. The economic analysis reports high convenience for substituting the components rather than the entire product, both for the boiler ($Durability'$€_min $= 1{,}9E3$ and $Durability'$€_max $= 3{,}7E3$) and the Resistance ($Durability'$€_min $= 3{,}1E3$ and $Durability'$€_max $= 3{,}8E3$). The environmental aspect needs to be assessed.

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Table 1. Inputs for economic analysis

Input	Product B [€]	Energy [€/kWh]	Boiler, spare part [€]	Resistance, spare part [€]
Min	8000	0,3	200	70
Max	10000	0,5	250	130

4.2 Durabot

An LCA was conducted from the Bill of Materials (BOM) and the CAD 3D model of the product. It was supported by the commercial software SimaPro 8.0, equipped with the EcoInvent database. The results were obtained according to the ReCiPe Midpoint (H) method. For the sake of conciseness, only results for the Climate Change indicator, expressed in kgCo2eq are shown (Figure 2).

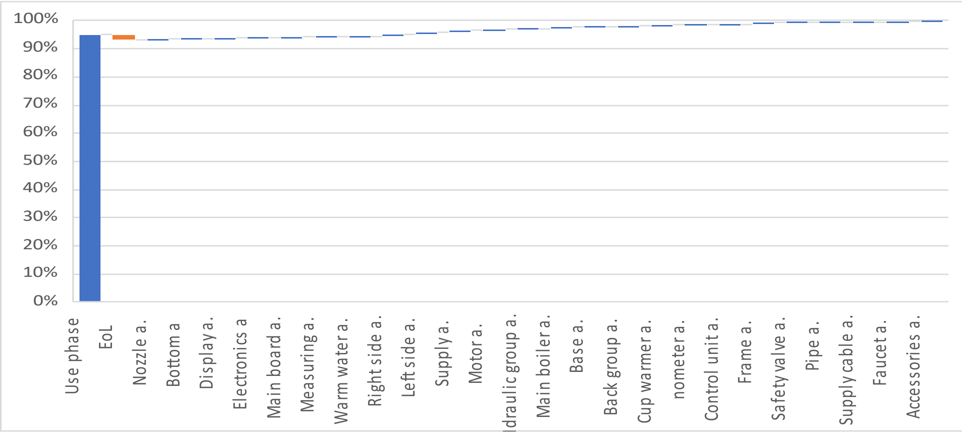

Figure 2. LCA analysis results [kgCO2eq]

The use phase retains more than 90% of the overall environmental impacts. Being the phase so impactful, the baseline scenario and the one with evolving energy mix have been considered and compared in the Durabot tool. In Figure 3, the baseline scenario is analyzed, and the yearly energy consumption does not change over time. First, the input area (yellow-marked) has been filled in with data from the considered coffee machine product, component to replace and aging parameters. Secondly, the intermediate and final output area (orange-marked) has been checked to retrieve the index value. Last, the graph area (green-marked) has been analyzed to confirm the index distribution.

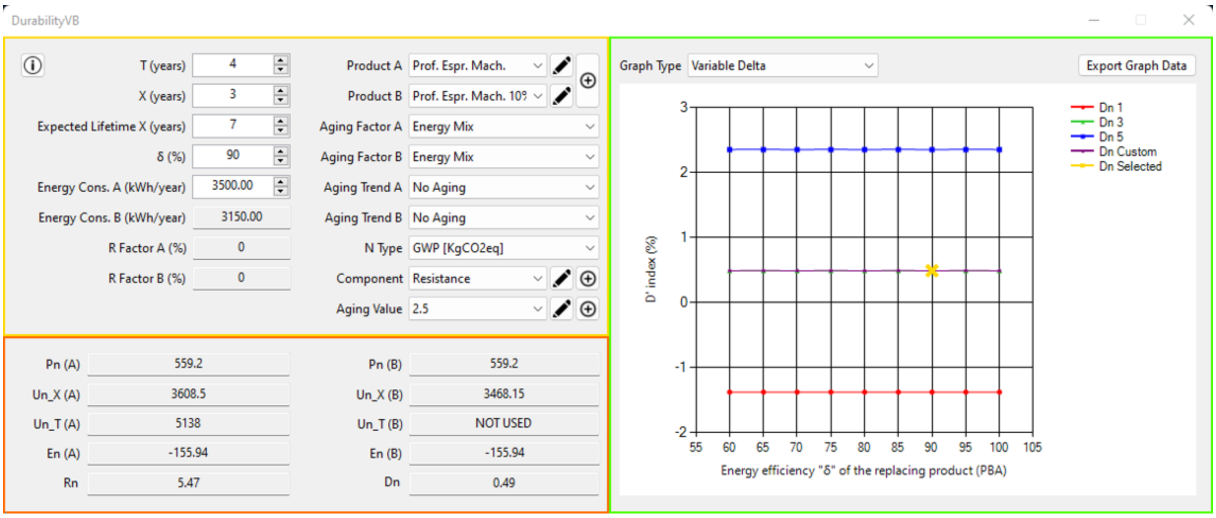

Figure 3. Main Durabot interface

The graphs area shows the first type of graph: the relative energy efficiency between the two products changes. Figure 4 illustrates the case where the energy mix varies. The potential convenience of replacing only certain parts of the product from the full one derives from two main factors: the

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inefficiency of product A is partially balanced by the decrease of unitary impact of the energy consumption and the production of the more efficient product B causes a certain quantity of emissions.

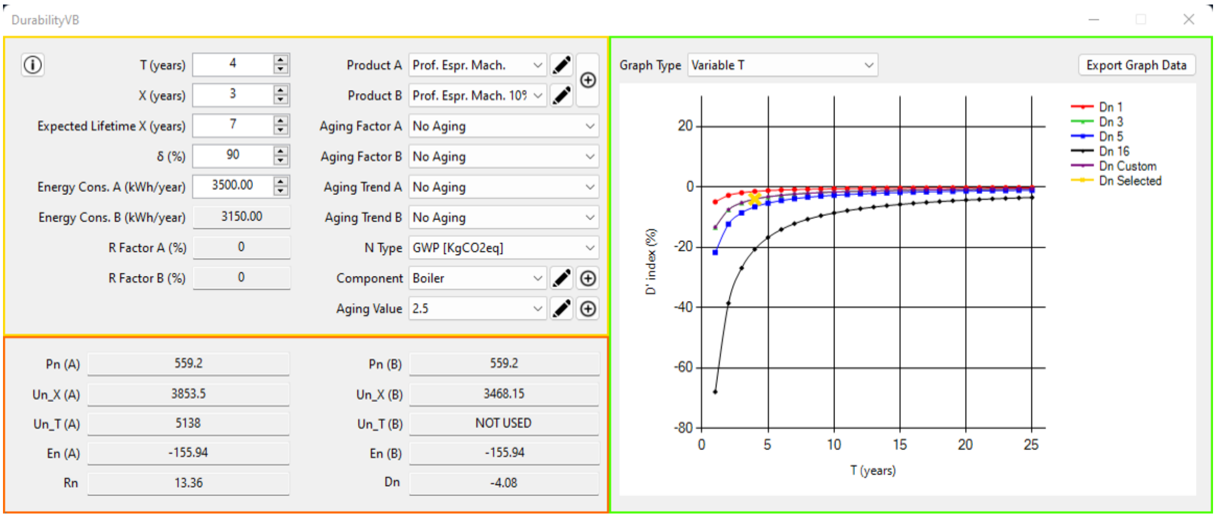

Figure 4. Main Durabot interface; energy mix evolving with time

5 DISCUSSION

The present work presents and applies an approach to support the design of durable products. The proposed approach and the related tool evaluate the environmental and economical aspects of durability, since to ErPs durable doesn't always mean sustainable. The work fills the gap outlined by Mesa et al. (2022) as it provides indicators to measure, determine, and predict product durability in different lifecycle scenarios, applicable to the design phase. The Durabot tool has been developed so that different scenarios can be analyzed and compared in a simplified way. In the present case study, it has been employed in a professional coffee machine durability analysis. Its use phase largely retains the main lifecycle environmental impacts and the boiler and the resistance are taken as target components.

From the environmental perspective, replacing components of product A instead of the full product is always convenient. However, the convenience is much higher if the energy and maintenance costs increase (disassembly, substitution, and re-assembly of the spare part).

As far as the baseline scenario (fixed energy mix in time) is considered, both the component's substitution is not convenient from the environmental perspective. This means that, besides the environmental burden due to the production and disposal of product B, the 10% lower energy absorption balances and overcomes those impacts. Furthermore, the graph shows how the index remains constant when changing δ (Figure 5): this is due to the fact that the use phase is far more impacting index-wise than the other phases. Such graphs are a sample reproduction of those automatically generated by Durabot (in this case, Figure 5 represents the "Variable Delta" graph described in 3.3).

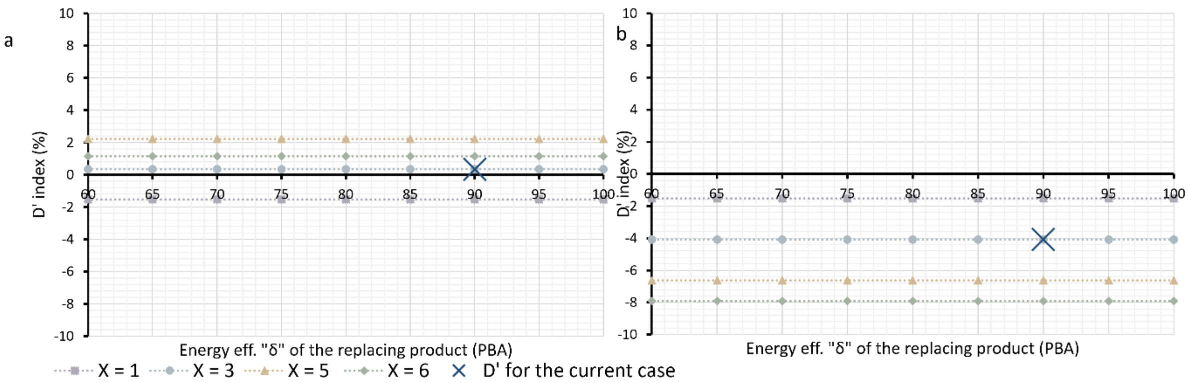

Figure 5. Durability index with varying (a) and fixed (b) energy mix (a), spare part: boiler

On the other hand, when the improvement of the energy mix is considered, both the boiler and resistance substitution ensure a lower environmental burden if product A is kept running (Figure 6).

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However, the design of the product may be investigated to increase D_n, for example, by designing the boiler and the resistance so that their manufacturing environmental impacts may be reduced. This may shift the X=1 case towards the positive axis, as it currently has the opposite trend.

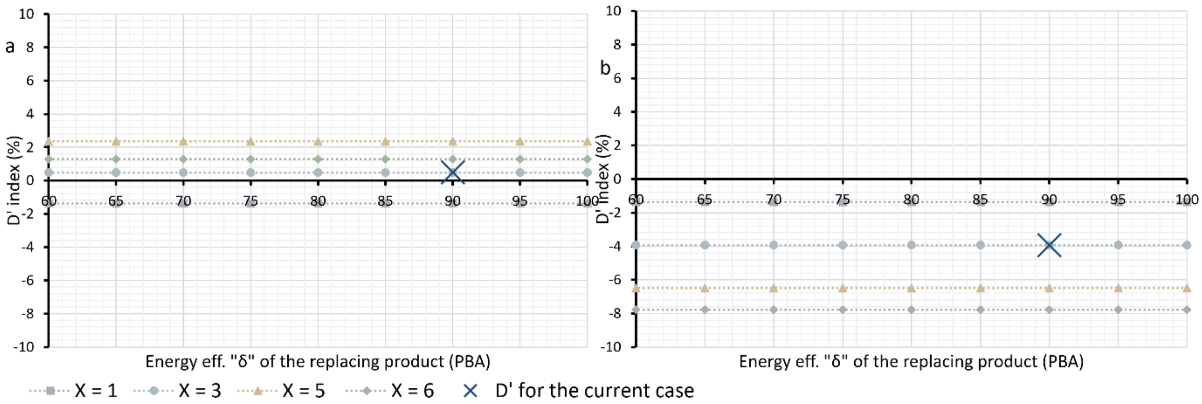

Figure 6. Durability index with varying (a) and fixed (b) energy mix (a), spare part: resistance

The lifecycle impacts of the coffee machine highly depend on the use phase impact. This is the main reason why all the scenarios present relatively low slopes.

Durabot currently allows the durability evaluation for three impact categories, although it is limited to their analysis. Multiple indicators must be considered, which might yield different results and trends. Cappelletti et al. (2022) applied the rationale further developed in the Durabot tool for refrigerators: the Climate Change impact category and the Water Use have opposite trends, regardless of the aging factor considered. The expected applications to multiple case studies by Alfieri et al. (2018) would enable the comparison of the approaches. A current limitation is the necessity to manually add every product or component, which may prove difficult in case many different cases have to be analyzed.

The functionalities of Durabot have been developed to provide a tool that easily encourages enterprises to do better in the context of durability, through its high usability, accessibility and results interpretation. At the moment, ErP durable is not always sustainable in the vast field. Durabot can support the design of products towards the duality of durability and sustainability so that resources extracted to create new products can be reduced and those already in the market may stay in longer lifecycles.

6 CONCLUSION

The concepts of durability and environmental sustainability are interchangeable for products whose use phase does not require a high quantity of resources. The terms become distinguished realities for ErPs, or goods with long use phases or merchandise/services whose functionality requires more than one flow. The substitution of critical components highly affected by aging may redeem the affinity of the two terms. In the present work, the Durabot tool has been developed: by doing so the main literature gaps were filled because i) the tool enables the assessment of environmental consequences of durability considering product evolving performances in time (i.e., worsening of functionalities); ii) external factors are introduced (i.e., the evolution of energy grid mix); iii) the measurement and prediction of environmental consequences of durable products in different lifecycle scenarios during the design phase are enabled. The Durabot user can identify which components are convenient to substitute for extending the product lifecycle and consequently acting on its design to ensure component accessibility. The maintenance man and/or product user would also apply the presented approach. Durabot enables a complete evaluation of component substitution right at the moment when the failure occurs.

Future versions of the Durabot tool may include a better products management system, the ability to evaluate more than one environmental impact at a time, and a procedural interface to enable support for a wide range of analysis products, even from different manufacturers, fields and with different durability formulas. This would allow it to be used in designing contexts and thus make it general-purposed and flexible. One more feature is the automatic import of products and components from famous LCA databases so that there would be no need to add them manually one by one.

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