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Combining life cycle assessment and online customer reviews to design more sustainable products – Case study on a printing machine

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Abstract

Life cycle assessment (LCA) is a standardized methodology to quantify the environmental footprint of products, processes, and systems. While LCA is an internationally accepted tool to highlight environmental hotspots, it lacks in providing concrete guidance to practitioners (e.g., product designers, material engineers, industrial managers) to reduce the ecological impact of their products. In parallel, a tremendous amount of product reviews is written each day online by actual users of the product. We may reasonably assume that these online product reviews contain valuable information to designers that can lead to improving the sustainability of the products they develop. In the present study, we investigate and experiment how the deployment of LCA combined with the mining and interpretation of online customer reviews could lead to the design of more sustainable products. The proposed approach is applied to a basic printing machine where LCA results are combined with the information collected from sustainability-related online reviews to identify sustainable design leads for the next generation of eco-designed printers. For discussion and validation purposes, the results are compared with a new-generation printer having an environmental certification, the EPEAT ecolabel.

Keywords: Sustainable design ; life cycle assessment ; data-driven design ; product reviews ; case study

1. Introduction

The integration of sustainability concepts in the early phase of product design is essential for the actual sustainable production, use, and end-of-life of products and processes [1]. Within the range of eco-design tools developed and fine-tuned in the past two decades, life cycle assessment (LCA) is the most acknowledged and widely spread methodology for environmental impact assessment in academia and industry, supported by the ISO standards 14040 and 14044 [2]. Yet, LCA results are often challenging to interpret to concretely find eco-improvements, i.e., solutions (e.g., alternative materials, product architectures, or production processes) that would ultimately lower the environmental footprint of products.

In parallel, a tremendous amount of product reviews is posted online every day. This is both (i) a convenient way for customers to make their voice heard, and (ii) an opportunity for designers to improve the features of their products [3, 4]. Meanwhile, the recent advance of digital tools (e.g., web scrapping) and artificial intelligence-based techniques (e.g., machine learning) enables researchers and industrialists to extract, proceed, and analyze large datasets of such online reviews. Recently, a couple of researchers started to leverage such techniques to extract meaningful information from online reviews for product improvement and innovation.

For instance, El Dehaibi et al. [5] identified and extracted customer perceptions of product sustainability from online reviews, and modeled these perceptions of product sustainability using machine learning (ML) natural language

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processing (NLP) techniques to determine which of these features are associated with positive and negative sentiments. Additionally, in a previous study analyzing the reviews of three technical and electronic product categories, Saidani et al. [6] pointed out that 15-20% of online reviews are likely to mention product sustainability-related information and are therefore valuable for sustainable design. Among the sustainability-related design learnings that could be elicited from product reviews, one could cite: (i) the life duration, and wear and tear (e.g., an early failure) of specific parts; (ii) the positive or negative perceptions of sustainable features; the non-sustainable use pattern(s) of a product supposed to be sustainable like an apparent energy over-consumption. In a complementary fashion, the authors [7] started to discuss the opportunities and challenges of deploying ML and NLP techniques [8] to automate the generation of sustainable design insights from online product reviews.

In all, the research gaps and contribution to knowledge are twofold: (i) the exploitation of product reviews to generate sustainable leads for the design of products, (ii) the combination of machine learning techniques (automating this process on thousands of reviews) with LCA to quantify the potential improvements on the environmental impact. In this line, the overarching aim of this research project is to leverage the capabilities of machine learning techniques, tools, and algorithms in complement with life cycle assessment to design more sustainable products. While Rolnick et al. [9] explored how climate change can be tackled with ML in various topics (such as climate simulation models, energy scheduling, optimization, and automatic monitoring with remote sensing), the application of ML tools to design more sustainable products is still overlooked. Chiarello et al. [10] also identified a gap in the application of data-driven tools (e.g., NLP) for the assessment of the sustainability of designs (e.g., using LCA). With this background, the research question guiding the present study is how complementary are life cycle assessment and product reviews mining to provide potential and possibly trustable sustainable design leads.

2. Materials and methods

2.1. Research approach

The overall research process carried out in this study is depicted in Fig. 1. First, an LCA is performed to calculate the environmental footprint of the product and identify eco-hotspots. In parallel, online product reviews are mined and analyzed to better understand the product usages and discover limitations, defects, and potential improvements on product sustainability. Concretely, both approaches are tested on the same product, a basic printer, to discuss the complementarity of the sustainable design insights obtained. The results are then compared with a new-generation printer having an environmental certification. The characteristics of the two printers are given in Table 1. OpenLCA has been used for the comparative LCA part, and Jupyter Notebook for the NLP part. The working environment used to conduct this study is further detailed in the next sub-sections.

Table 1. Comparison of the specifications of the two printers

Specifications	Generic printer	EPEAT certified printer
Dimensions	18.26 x 15.35 x 9.0 in	18.11 x 13.43 x 9.21 in
Weight	17.9 lb = 8.12 kg	18.04 Ib = 8.18 kg
Package weight	22 lb = 9.98 kg	22.88 Ib = 10.38 kg
Power consumption	See Table 2	See Table 2

Note that these two products have been chosen based on the following selection criteria: technical and/or electronic product of a minimal technical complexity; sufficient number of reviews (i.e., superior to several hundreds); product with environmental certification and its conventional counterpart (i.e., with similar characteristics); ability to estimate the life cycle inventory.

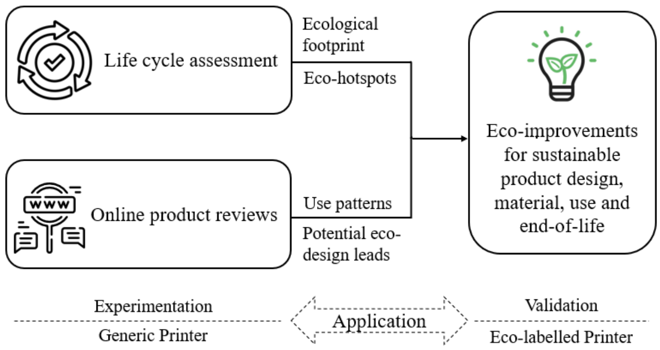

Fig. 1. Synopsis of the research approach

2.2. Life cycle assessment

The environmental impact of each printer is evaluated by using the LCA methodology. LCA is a tool to determine the environmental impacts of a product, process, or activity throughout its life cycle: from the extraction of raw materials through to processing, transport, use, and disposal [2]. LCA can be used as a valuable decision-support tool and as a gateway to environmental improvements. According to the ISO standards 14040-44 [2], a LCA comprises four principal stages: (i) goal and scope definition; (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA); (iv) interpretation of results. At this last stage, the outcomes of the LCI and LCIA stages are interpreted in order to find hotspots and compare alternative scenarios. The goal of the present LCA is to quantify and compare the environmental footprint of an eco-labeled printer with its conventional counterpart over the entire lifecycle. The scope and system boundaries of the LCA are illustrated in Fig. 2. It includes the impact associated with the material extraction, processing, and assembly of the printers, as well as their electricity and ink consumption.

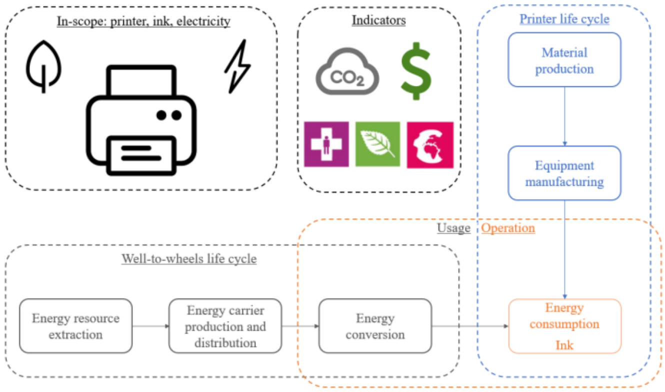

Fig. 2. Scope and system boundaries of the LCA

The functional unit (FU) for this LCA has been defined according to the guidelines provided by the European Joint Research Center [11], including the five key elements to include in its proper definition: (i) verb (functional analysis): print; (ii) what (form of the output): copies (pages); (iii) how much (magnitude): 10 pages every two weeks (i.e., 1300 copies over five years, corresponding to 13 cartridges replacement); (iv) how well (performance): with a speed of 10 pages per minute (copies distribution: 55% black and white; 45% color); (v) for how long (duration, time horizon of the analysis): 5 years. The working mode distribution is the following: every two weeks, 1 minute of printing, 15 minutes in ready mode, 45 minutes sleep mode, and 7 hours in manual-off mode.

The life cycle inventory for these two printers has been built using primary data from the original equipment manufacturer available online in their product material content information datasheet [12] and completed with data from previously published LCA of printers [13, 14]. The life cycle impact assessment has been conducted using the OpenLCA software version 1.10, the ecoinvent database 3.7, and the LCIA methodology ReCiPe (H) 2016.

2.3. Mining online product reviews

The steps of the machine learning and natural language processing pipeline deployed here are the following: (i) data extraction and pre-processing; (ii) classification (i.e., is this review contained sustainability-related info? Yes / No); (iii) aspect-based sentiment analysis; (iv) interpretation for sustainable design leads. The product review mining procedure was designed using a python script to automate the extraction of product reviews from Amazon website, combined with a dictionary of sustainability-related to classify the reviews in two clusters. This procedure was implemented in python using Jupyter Notebook.

More precisely, first, online product reviews have been used data scrapping techniques and a ready-to-use Jupyter Notebook template available on-demand. In all, thousands of reviews have been extracted and pre-processed.

Second, for the classification of the reviews into two clusters, as illustrated in Fig. 3., two options were considered: (i) to build an automated classifier based on an *ad hoc* dictionary (see after), (ii) to train a classification model based on labeled reviews. For this first use case, the first option was selected to get initial results with unstructured and unlabelled reviews. Authors' expertise in eco-design coupled with a review of relevant literature has been used to build a dictionary of 160+ sustainability-related words (available on-demand) that could be used by customers to describe directly or indirectly the sustainability performance of products. For instance, El Dehaibi et al. [5] provided a list of topics to look for in reviews for each sustainability pillar. Te Liew et al. [15] classified an inventory of sustainability concepts by term of occurrence. Böckin et al. [16] made an inventory of product system characteristics assumed to be relevant for resource efficiency and durability in product design.

Third, aspect-based sentiment analysis [17] has been performed on a sample of reviews that potentially contain relevant sustainability-related information by identifying product features linked to sustainability-related comments. Eventually, interpretations are made by the authors on the relevance of such reviews to get meaningful sustainable design insights in complement to the LCA results.

Fig. 3. Automatic classification of thousands of reviews in two clusters

3. Results and discussion

3.1. Life cycle impact assessment and eco-hotspots

The LCA results for the 18 ReCiPe midpoint indicators for the printer, highlighting the distribution of impact among: material extraction and production, component processing (i.e., fabrication and assembly), and usage of electricity and ink, are charted in Fig. 4. It shows that the major part of the footprint is attributed to the use phase. Therefore, according to this main LCA result, original equipment manufacturers should focus on energy- and ink-efficient solutions to significantly reduce the environmental footprint of the printing machines they develop over their lifecycle.

Regarding the main contributors in the material category, two materials account for two-thirds of the total carbon emission in this category, namely, (i) acrylonitrile-butadiene-styrene copolymer (or ABS) with a carbon footprint of 21.69 kg of CO_2 eq., and (ii) polyphenylene sulfide with a carbon footprint of 2.7 kg CO_2 eq. Here, the substitution of such plastics with bio-based plastics could be a promising eco-friendly solution.

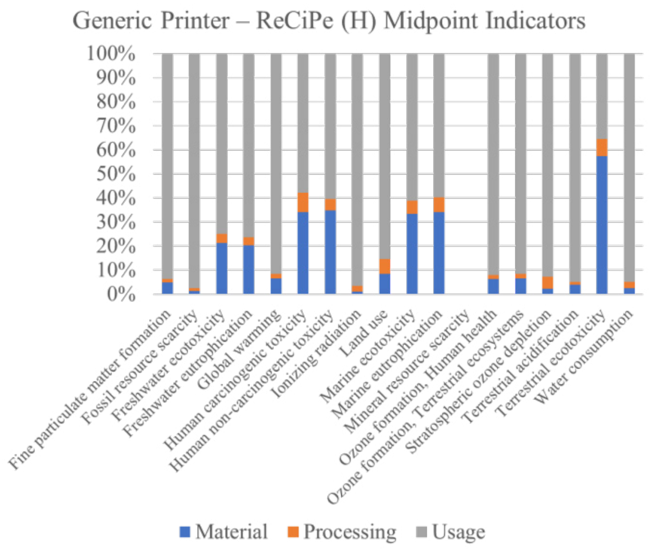

Fig. 4. LCA results

3.2. Complementary insights from product reviews and identification of sustainable design improvements

Overall, we can argue that one could have predicted the trends of the present LCA results and that the eco-improvements mentioned in the previous section, solely based on the LCA findings, are rather generic without providing more concrete or precise sustainable design solutions. Thus, it becomes interesting to complement these findings with feedback from a vast pool of users publishing thousands of critical reviews online on this product.

First, we extract potential sustainability-related reviews based on keyword matching, using our dictionary of sustainable design keywords, as described in sub-section 2.3. For example, for the sustainability-related word “broken”, an excerpt of a potentially relevant review including this keyword is: “Something is rattling around inside the printer, and there was a piece of broken plastic from the corner of the case”.

Then, to identify more specific reviews insightful for product design, we select the reviews that include both product features and sustainability-related information, combining the product features and specifications of this printer (namely, 'print', 'copy', 'scan', 'fax', 'speed', 'resolution', 'cartridge', 'security', 'ink', 'power') with our dictionary of sustainability keywords. For example, here is a review containing the sustainability-related word “broken” and the product features “ink” and “cartridge”: “When I tried the printer in the first days, I started getting stripes and then no black ink printer after few pages; the ink tank indicator was not telling me that the ink was done (it marked as less than held), probably because of the tiny size of the cartridge, and I thought the printer was broken.” Here is another example with the keywords “maintenance” and “print”: “I print infrequently (75 pages in four months according to the printer utility) and was always frustrated that each time I attempted to print a document it ran through a maintenance cycle of clean / unclog / align; all of which uses a lot of ink.”

Next, aspect-based sentiment analyses are performed on sentences that include both product features and sustainability-related information to estimate the perception (positive or negative) of customers on the features they value or not, and how they can be related to sustainable design. In all, commendable sustainable design solutions (i.e., recommended and/or valued by users) for the generic printer are the following: the combination of plastic for the printer to be light with a metallic frame to increase its robustness and durability on the mobile parts; the user-friendliness of replacing key mobile parts (design for modularity); and a double-sided printing capability to save ink and paper.

3.3. Comparison with the eco-labeled printer

In this sub-section, both the LCA results and additional insights from online reviews for the generic printer are being compared with the next generation of printers from the same family. This new-generation printer owns the EPEAT ecolabel. EPEAT products are specifically assessed against criteria including energy use and have a reduced sustainability impact across their lifecycle. The energy consumption of both printers, according to the same functional unit (FU) defined in sub-section 2.2. is detailed in Table 2. The associated impact reduction in favor of the EPEAT certified printed is illustrated in Fig. 5. through the global warming potential indicator (carbon footprint reduced by around one-third).

Table 2. Working mode and energy consumption of the printers.

Mode	Generic printer Power (W)	EPEAT printer Power (W)	Generic printer Total energy over FU (kWh)	EPEAT printer Total energy over FU (kWh)
Printing	27	21	58.5	45.5
Ready	5.5	5.8	178.75	188.5
Sleep	1.21	1	117.975	97.5
Manual-off	0.29	0.08	263.9	72.8

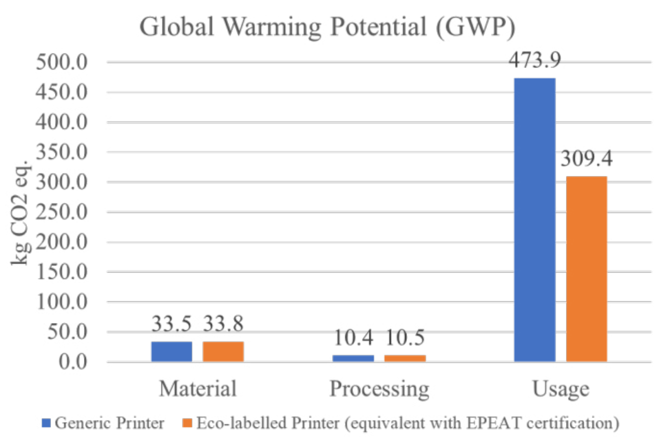

Fig. 5. Comparison of the carbon footprint of the two printers

The original equipment manufacturer also states that their new version (EPEAT printer here) is up to 14% smaller than its predecessor (generic printer here). However, looking at the total mass (see Table 1) and bill of materials [12] of the two printers, the EPEAT printer is actually slightly heavier, which translates to a marginally higher environmental impact allocated to the material and processing phases. Last but not least, in direct relation to the sustainable design leads elicited in the two previous sub-sections, the newly wireless EPEAT printer (i) "comes with a code to redeem eight months of Instant Ink based on printing 100 pages/month, so you can save on ink and get it delivered to your door", to cite how it is advertised by the original equipment manufacturer; and (ii) is made from recycled plastics and other electronics, up to 15% by weight of plastic.

In future works, it will be interesting to compare the online customer reviews between the generic printer and its eco-labeled alternative and understand further how customers value or are sensitive to environmental claims, how they are rating products in terms of sustainable performance, and if further eco-design leads could be generated from these reviews.

4. Conclusion, current limitations, and perspectives

The present research built on the increasing potential of online reviews and natural language processing techniques for sustainable product design. Practically, this study explored how online product reviews analyzed combined with LCA could foster the design and development of new generations of products more sustainable.

On the one hand, LCA is key to quantifying the environmental impact of products, identifying eco-hotspots, and validating environmental certifications, but it presents some shortcomings in the identification of sustainable alternatives for designers.

On the other hand, feedback from real-world users through online reviews (including, e.g., complaints, failure reports, recommendations, wishes, improvement ideas, or even repair practices) is a potential source of inspiration to aid designers in developing new products that tackle with sustainability issues.

The developed approach, combining LCA and ML/NLP techniques on product reviews, for sustainable product design, is first original and could therefore influence and inspire future design methods of using such techniques and leveraging feedback from product reviews to design sustainable products. On this basis, deploying the developed approach, it could be expected that the next generation of products will be more durable/sustainable by integrating the feedback of consumers/users, e.g., on actual defects, early failures, or unexpected wear and tear of key components.

As far as limitations are concerned, we must also be wary of user misperceptions that are not always correlated with low environmental impact (e.g., a plastic shell that may appear less strong than metal but is ultimately more durable). We therefore need to develop a more sophisticated methodology (see Fig. 6) that would allow us to move sustainable design insights from potential to reliable (perhaps by verifying them with complementary LCA simulations). This will then allow us to robustly combine data science and quantitative methodologies for assessing environmental impacts in engineering design and product sustainability [10, 18].

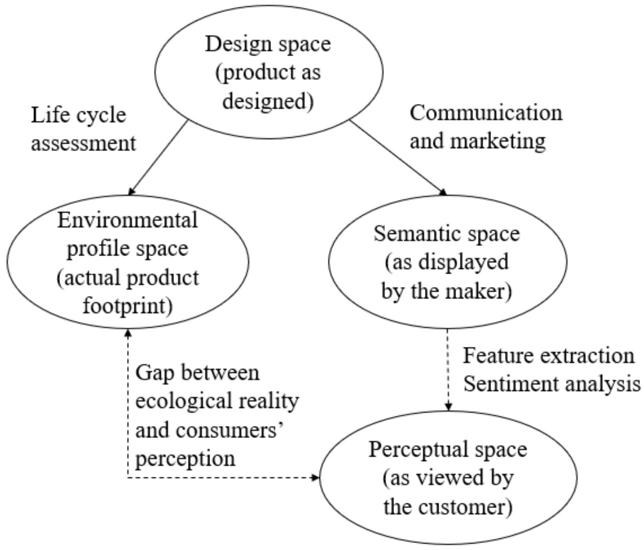

Fig. 6. Links between design, environmental and semantic spaces of products

An exciting line for future studies would be to use more specialized or expert-level customer review websites like iFixit.com or Backmarket.com. In the latter, a direct reference to the amount of e-waste saved is available in the product description [19]. For instance, Nasiri et al. [19] investigated the significant factors in consumer perceived value about purchasing refurbished smartphones mentioned in online customer reviews on two major online marketplaces: Amazon.com and Backmarket.com.

Last but not least, another perspective for future research on these topics will be to further illustrate how artificial intelligence tools could support LCA [20], e.g., to address data deficiencies, scenarios exploration, or impact estimation.

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