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Investigation of a Process to Eco-Design LED Lighting Products

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Abstract: To date, many studies have been carried out to develop new approaches and methods to eco-design products. However, these have not been implemented and adopted by industry as much as they should. A better understanding of real-world industrial eco-design and development processes, and the eco-design tools applied during these, could inform the development of more effective and applicable eco-design methods and tools, for generic as well as for specific product categories (e.g., LED lighting products). This paper addresses this issue by describing and examining a real-world process followed to design and develop a LED lighting product by a lighting manufacturer, via case study research. The case study involved direct participatory observation to gather the data and provided new insights about the stages of the design and development process, as well as the tools applied, which were examined and discussed to inform the improvement of existing methods and tools, or the development of better new methods and tools.

Keywords: eco-design; eco-design methods; eco-design tools; eco-design process; eco-design process models; LED lighting products; lighting products

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1. Introduction

There is a considerable body of knowledge and publications (including standards) for practical guidance about how to integrate environmental considerations into design processes via eco-design methods and tools, to design generic [1–10], and specific (EEE: Electrical and Electronic Equipment) categories of products [11,12]. In addition to this, many published research studies focused on the analysis and development of eco-design methods and the integration of eco-design tools in design processes for generic products [13–16] and LED lighting products [17,18]. However, all these existing methods, approaches, and tools still have not achieved the full expected impact in industry [19,20], and hence in the environment, which means they are not being used or applied as much as they should. This is a long-term issue which remains to be addressed.

Many research studies [19,21–31] have pointed out potential barriers and issues which might have prevented their wider implementation. For example, a study [19] focused on the implementation of eco-design practices in Europe found the limited practical application of eco-design practices in Europe [19]. Other studies [21,23,24,31] highlighted the significant gap between theory and practice of eco-design, or the challenges faced to implement sustainability requirements in the early stages of the product development processes in organizations [22], and other studies [25] focused on the identification of factors to increase the implementation of eco-design in industry. Although all these studies have identified a varied number of reasons (e.g., lack of consumer demand, lack of regulations to support their implementation, lack of upper management support) as to why they have not been implemented more often, some of these issues are out of the control of developers and manufacturers, and the scope of this paper. However, some of the reasons identified in previous studies [19,24,26,30,31] are related to the nature of the existing methods, approaches, and tools developed, and their suitability for their application-operationalization within current industrial design processes. This means that many of the current methods, approaches, and tools might be further improved to enhance their adoption, so a better understanding of eco-design processes and the tools used within these processes is necessary to inform the improvement of existing methods and tools, as well as the development of new more suitable and effective eco-design methods and tools, which might enhance wider adoption of these by industry.

This paper addresses the following question: *How can the application of eco-design methods and tools to design LED lighting products be increased in industry?* To answer this question, we need a better understanding of real-world eco-design processes and the tools used within them, to obtain new insights about potential issues that might be hampering their implementation, and how these could be improved. That is why this paper focuses on the description and examination of the process, (including the tools used within it), followed to design and develop a LED lighting product with low environmental impact by a lighting products manufacturer. The aim of the study is to increase the understanding of the design and development processes (including the tools applied) used to design LED lighting products with low environmental impact, to inform the improvement of existing eco-design methods and tools, or the development of new ones. Although the findings are more relevant to a specific category of products (LED lighting products), some of the findings can also apply to eco-design methods and tools for generic products.

The paper is structured in the following sections: (2) Methods: which explains the methods used to collect the data, (3) Description of the Eco-design and Development process: which describes and examines the eco-design process, and the eco-design tools applied during the process, (4) Discussion: which discusses the eco-design method and tools used, and highlights the main limitations of the study, and (5) Conclusions: which summarizes the key new insights of the research.

2. Methods

2.1. Case Study Research

Case study research [32] was selected to describe and examine a real-world single-case based on the process followed to design and develop a LED-based lighting product with low environmental impact, by a lighting manufacturer [33].

2.1.1. Background

The design and development of the lighting product was initiated by the lighting manufacturer since it wanted to include a new eco-lighting product in its commercial catalogue, supported by funding from the EU [34]. The company has its own in-house design and development team but they had no previous experience or knowledge about how to design and develop eco-lighting products, so the product was co-designed and developed with an experienced eco-designer, who also described and examined the process stages and tools applied during the process. The lighting manufacturer is an SME (Small Medium Enterprise) located in Spain, which designs, develops, and manufactures lighting products for domestic and contract markets.

The researcher played an active role during the study, by observing and participating in the process as a product designer. This allowed him to describe and examine the design and development process, as well as the tools used during the process. In addition, it enabled the researcher to see the problems of implementing eco-design methods and tools in real-world industrial situations, which can help to understand better the needs and barriers related with the wider adoption of eco-design methods and tools.

2.1.2. Research Design

The aim of the case study was to increase the understanding of eco-design processes and eco-design tools used to design and develop LED lighting products with low environmental impact, and the objectives were to: (1) Describe and examine the design and development process (stages) followed to reduce the environmental impact of the lighting product, (2) Identify and examine each of the tools applied during the process.

The case study research method applied had the following characteristics:

- Unit of analysis: The process followed to design and develop a LED-based lighting product with low environmental impact.
- Type of event: The event subject to study was based on a contemporary real-world design and development process conducted by a product designer with a lighting manufacturer.
- Timeframe/duration of event: Longitudinal study: 2 years.
- Data collection method: Direct participatory observation.

3. Description of the Eco-Design and Development Process

The process followed to eco-design and develop the LED lighting product is described in Figure 1, which describes: (1) the design process stages (e.g., PDS, concept design, embodiment design), and (2) the tools (e.g., SM, SP) applied during the process.

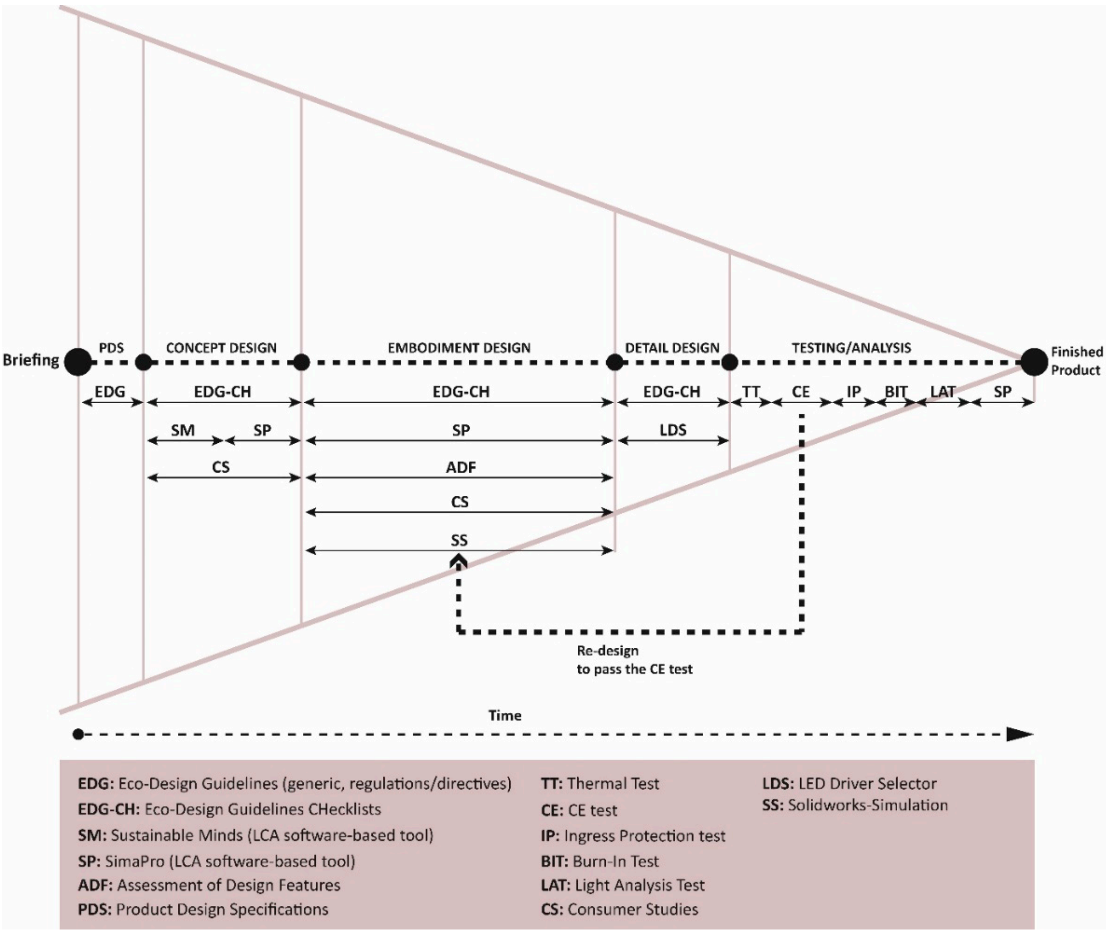

Figure 1. Descriptive model of the eco-design and development process. Reprinted with permission from J.L. Casamayor (2016). 2016 J.L. Casamayor.

The process starts with the 'briefing' of the product, which is materialized into the finished lighting product at the end of the process. The process has been shaped as a funnel because at the beginning there are less constraints so the design space (or design options) is ample. However, as the process proceeds and the product is defined in more detail, the design options are reduced.

The process was framed based on the already known design process stages described in key design and development methods literature [35–38], which typically comprises the following stages: PDS (Product Design Specifications), concept design, embodiment design, detail design, and testing. These stages are usually related to the grade of definition of the product. In each of these design stages, different tools were applied in order to support the product designers' decision-making processes. As it happens in any design process, the product is subject to a continuous synthesis and analysis iterative process, until the product is completely defined. In eco-design processes, one distinctive characteristic of the analysis is the additional assessment of the environmental impact of each design decision, this is why eco-design tools need to be applied during the process.

The tools applied during the process, shown in Figure 1, are briefly explained below, based on the design process stage where these were applied, and then examined and discussed in more detail in the next section (Section 4: Discussion).

- EDG (Eco-Design Guidelines) and EDG-CH (Eco-Design Guidelines Checklists): Eco-design guidelines are tools used in eco-design processes to provide best practice, generic or specific, (e.g., related with a specific aspect: recycling), design guidelines to reduce the environmental impact of the product. Some are generic, and some product category specific. In this paper, the ones that apply to LED lighting products were considered. Eco-design guidelines can be 'converted' into checklists so they can be used at each stage of the design process to check if the eco-design guidelines stated in the Product Design Specifications (PDS) are achieved in each design iteration of the process. There are many handbooks and manuals [1–12] that provide eco-design guidelines and checklists to reduce the environmental impact of generic or specific categories of products. Eco-design guidelines can also be based on compliance-related directives (e.g., WEEE [39], RoHS [40]). Many companies (e.g., Siemens [41], Motorola [42], Alcatel [43]) have also developed their own proprietary eco-design guidelines and checklists (which are not always published) which have been developed to suit their own internal processes.
- SM (Sustainable Minds): Sustainable Minds [44] is a software-based tool to carry out streamlined Life Cycle Assessment (LCA) of products. It has been developed for product designers (non-LCA experts) in mind, and it allows for easy-fast environmental impact assessment (screening) of design options and products, making it very suitable for design activities. It can be used with existing CAD tools, since BOM (Bill of Materials) of products can be imported directly from CAD tools into SM. The interface has been designed for designers, so it is easier to use and operate than other more scientific-oriented LCA software-based tools such as Simapro [45]. SM uses TRACI 2.11 [46] Life Cycle Impact Assessment (LCIA) method, to carry out the environmental impact assessment.
- SP (SimaPro): Simapro [45] is a software-based tool used to carry out LCA of products, services or processes. It can carry out the environmental impact assessment using different LCIA (Life Cycle Impact Assessment) methods (e.g., ReCiPe [47]) and is provided with several databases (e.g., Ecoinvent [48]). This tool has been developed for LCA experts, and requires a learning process, as well as background knowledge about LCA to be able to use it and understand-interpret its results. It is a common tool used to provide detailed LCA results and can be used to inform EFP (Environmental Footprint), EPD (Environmental Product Declaration) or other environmental impact reports of products, processes, or services.
- ADF (Assessment of Design Features): This tool is used to assess the environmental impact of the design features, which cannot be assessed with LCA. For example, the LCA cannot detect or assess if a specific assembly design option will allow easy dismantle for recycling at the end of life or not. This tool focuses on assessing specific design features which can affect the product environmental impact, but which are not captured with an LCA.
- TT (Thermal Test): Thermal tests are used to test the temperature inside the lighting product whilst functioning, over a specific period of time. This is to ensure that the temperature inside the lighting product housing will remain within certain limits during its functioning, to avoid overheating and premature ageing, or failure, of the

components and housing material, which would shorten the lifespan of the lighting product. A thermocouple device [49] is usually used to carry out the temperature measurements.

- CE (CE test): The CE mark test [50] is used to obtain the CE mark which is necessary for certain products which are going to be commercialized in the European Economic Area (EEA). It ensures that products meet EU safety, health, and environmental protection requirements. To obtain it, it is necessary to follow these 6 steps: (1) Identify the applicable directive(s) and harmonized standards, (2) Verify product specific requirements, (3) Identify whether an independent conformity assessment (by a notified body) is necessary, (4) Test the product and check its conformity, (5) Draw up and keep available the required technical documentation, and (6) Affix the CE marking and draw up the EU Declaration of Conformity. These 6 steps may differ by product as the conformity assessment procedure varies.
- IP (Ingress Protection test): The IP test [51] is used to classify and rate the degree of protection provided by mechanical casings and electrical enclosures against intrusion, dust, accidental contact, and water. The IP tests varies its requirements depending on the IP code required, which is defined by two digits (e.g., IP 34) the first one (e.g., 3) indicates the solid particle ingress protection, and the second one (e.g., 4) indicates the liquid ingress protection. The lighting product must pass specific IP tests (e.g., IP 34) to reduce the possibility of components' failure due to external environmental effects (i.e., moisture, water).
- BIT (Burn-In-Test): The BIT is used to detect faulty components and systems which could lead to premature failure of the lighting product, or premature degradation of components leading to lower performance of the lighting product. The test typically consists of switching on the lighting product for a specific period of time (e.g., 7000 h) continuously, to verify the product system and sub-systems have no manufacturing flaws or lower performance levels over time.
- LAT (Light Analysis Test): The LAT test is performed to analyze the light performance and light parameters of the lighting product, as well as its power consumption. This test is necessary to know the light parameters (e.g., luminous flux, power consumption, color correlated temperature, and light distribution) of the lighting product. Once these parameters are known, it is possible to obtain the luminous efficacy of the lighting product, its Light Output Ratio (LOR), its power consumption and its light distribution. This analysis is also necessary to inform the final environmental impact assessment (with an LCA) of the final lighting product. Several tools are used during this test: Goniometer [52], illuminance meter [53], colorimeter [54], power meter [55], ProSource [56], and Photometrics Pro [57].
- CS (Consumer Studies): CS are used to gather feedback from consumers about the lighting product features and usability. Data from consumers were gathered via focus groups and structured interviews, supported by 2D renders and 3D fully functional 1:1 scale prototypes of the lighting product.
- LDS (LED Driver Selector) [58]: It is used to select the optimum LED driver model for a specific LED model, to optimize the energy efficacy of the lighting product.
- SS (Solidworks-Simulation): SS [59] is used to virtually model and simulate the lighting product. The simulation in this case was focused mainly on structural and thermal simulation of the housing of the product and the passive heat sinks to inform its design and optimization.

The process shown in Figure 1 is described in detail below, explaining *what* tools were used in each stage of the process, and *how* these were applied during the process:

3.1. Product Design Specifications (PDS) Stage

This section describes the tools used during the PDS stage of the design process.

3.1.1. Tools Used

Two types of eco-design guidelines (EDG) were utilized: Generic Eco-design guidelines and Eco-design guidelines based on 3 EU directives: RoHS [40], WEEE [39] and ErP [60].

3.1.2. How the Tools Were Used

Generic eco-design guidelines were used to ensure the PDS included eco-design specifications (e.g., use of recycled material, easy disassembly) that could reduce the environmental impact of the lighting product. Eco-design guidelines based on directives and regulations were also used to ensure the lighting product could comply with RoHS, WEEE and ErP directives, which are applicable to lighting products. All these eco-design guidelines were included as a list of design recommendations related with different areas (e.g., materials selection, manufacturing processes selection, maintenance, use, recycling) in the PDS.

3.2. Concept Design Stage

This section describes the tools used during the concept design stage of the process.

3.2.1. Tools Used

Generic eco-design guidelines checklists (EDG-CH), eco-design guidelines checklists (EDG-CH) based on three directives (RoHS, WEEE, ErP), two types of LCA-based software tools: Sustainable minds (SM), and Simapro (SP), and consumer studies (focus groups) were applied.

3.2.2. How the Tools Were Used

Eco-design guidelines (both types) were used as checklists to support decision-making in every design iteration. This meant that every time a new design decision had to be made or several design options had to be considered, the option that complied with more eco-design guidelines was selected. In addition to this, LCA-based software tools were also used to assess and compare the environmental impact of different design options (e.g., materials, manufacturing processes, and finishes selection) and concepts. Two types of LCA-based software tools were used: Sustainable Minds and Simapro. Sustainable Minds was used to assess early concepts and to create 'what if' scenarios to know which material or manufacturing process had lower environmental impact. It also provided approximated impacts of each concept life cycle stage. Simapro was used to assess the final selected concept, to understand which were the life cycle stages and components with the highest impact for further eco-design improvement. A consumer study (with focus groups) was conducted to obtain lighting experts' feedback about the eco-features of the lighting product. This consisted of distributing printed images (3D virtual model) of the final concept, and a questionnaire, to 7 lighting experts, representing different types of roles and organizations from the lighting industry. The 7 participants were the following: (1) Lighting designer; (2) Lighting designer; (3) Architectural lighting designer; (4) Professor and researcher of Eco-design and LED lighting; (5) Chief Physician at a University Hospital and researcher in light and health/wellbeing; (6) Vice President of lighting company; (7) Founder and adviser of lighting company. The questionnaire contained 15 open-ended questions related to the product, and the purpose of this, was to, in addition to get the organizations representatives feedback (answers), to guide the focus group discussion. The focus group basically concluded that eco-design features, such as being 100% recyclable and using recycled materials, were very good arguments for public consumers (e.g., councils, public organizations) who may have green procurement policies in place, and sometimes have an allocated budget to pay extra to purchase this type of low environmental lighting products. For the private market (e.g., general consumers), these features were of less importance from a pure sales point of view. In relation with company branding and marketing these features were considered an important design feature. Recycling is an additional extra feature (used in marketing) besides other general environmental arguments such as the use of LEDs to reduce energy consumption, and the avoidance of unfriendly or toxic materials which are included in other lighting technologies such as fluorescent-based lighting products.

3.3. Embodiment Design Stage

This section describes the tools used during the embodiment design stage of the process.

The embodiment design stage focuses on the further definition of the final concept selected in the concept design stage. This stage is a continuous design iterative process of the final concept to define it in more detail and to reduce its environmental impact further at the same time. The role of the assessment, at the end of each design iteration, is to find areas (design features) that can be improved further to reduce the impact. Assessment was conducted with LCA-based software tools, the 'assessment of design features' tool, and eco-design guidelines checklists simultaneously.

3.3.1. Tools Used

During the embodiment design stage, generic eco-design guidelines checklists (EDG-CH), eco-design guidelines checklists (EDG-CH) based on three directives (RoHS, WEEE, ErP), one type of LCA-based software tool (SM), modelling and simulation tools (SS), the 'assessment of design features' tool (ADM), and consumer studies (CS: structured interviews) were applied.

3.3.2. How the Tools Were Used

The Eco-design guidelines (both types), applied at the PDS stage, were used as checklists to support decision-making processes in every design iteration. In addition to this, an LCA-based software tool (Simapro) was used to assess and compare different versions (prototypes) of the final concept, and to find out the environmental impact of the product life cycle stages and components. Solidworks was also used to model and simulate the mechanical and thermal properties of the housing of the product, and the heat sink to optimize the amount of material used in both. For example, the housing of the lighting product was modelled and simulated to reduce the thickness of the housing walls, and the passive heat sink was modelled and simulated to optimize the amount of material needed to cool the LED.

Another tool used was 'Assessment of Design Features'. This tool was used to assess the lighting product design features (e.g., energy efficacy, disassembly) in order to know which design features could be improved further in the next version (design iteration) in order to reduce the environmental impact of the lighting product. The assessment was mainly conducted by the product designer; however, this was complemented by (manufacturing and marketing) input from the lighting product manufacturer. Consumer studies (structured interviews) were also conducted to obtain feedback from the consumers. Unlike the first consumer study (focus groups) conducted during the concept design stage, this study used a functional physical prototype which consumers could physically see and use. This prototype was a very similar 1:1 scale replica of the final lighting product that would be manufactured in future stages. The study consisted of asking 28 consumers randomly selected in a lighting trade-fair (where the prototype was exhibited) to answer a close-ended questionnaire (8 questions) in a face-to-face short interview during an exhibition of the lighting product in a trade fair. The questions were designed to gain feedback about the eco-features of the lighting product to confirm their acceptability by the end consumers, as well as obtaining suggestions (needs-wishes) about how the product could be improved according to their preferences.

3.4. Detail Design Stage

This section describes the tools used during the detail design stage of the process.

At the detail design stage, the core architecture of the lighting product has been defined already, and the role of the eco-design guidelines checklists is to ensure that the selection of the parts and components' final specifications (e.g., quality, finish, tolerance) contribute further to reduce the environmental impact of the product, and also to refine the final design features of the product. The boundaries between the embodiment and detail design stages sometimes can be difficult to differentiate, and although they are both mentioned in design methods, in future eco-design methods, they could be integrated into one single stage called detail design.

3.4.1. Tools Used

Eco-design guidelines checklists (EDG-CH) related to the following areas: (1) Energy efficiency, (2) Reliability, (3) Recycling, and (4) Reparability. In addition, eco-design guidelines checklists (EDG-CH) based on the RoHS directive, and the LED driver selector (LDS) were used.

3.4.2. How the Tools Were Used

Eco-design guidelines checklists were used to specify (screen) the quality (i.e., type) of the final components selected, and the finish used in the parts and the joints. These guidelines focused on several areas: (1) Energy efficiency: This consisted of a list of guidelines (e.g., selection of high efficacy light sources and high-power factor dimmable drivers) to make the product more energy-efficient, (2) Reliability: This focused on guidelines to increase the reliability of the product to extend its useful lifespan (e.g., components used should pass specific certifications: IP certification, quality certifications such as ENEC [61], minimum light source/drivers lifespan rates, (3) Recycling: This supported the selection of adequate finishes and joints, in order to facilitate recycling at the end of life of the product, and (4) Reparability: This supported the selection of components that could be repaired and have a long life (e.g., selection of well-known brands with long warranty maintenance service/upgrades, selection of detachable modular components). The LED driver selector on-line web-based application was also used, to find the optimum match between the LED and the LED electronic driver, to make the LED-LED driver system more energy-efficient. Eco-design guidelines checklists from RoHS directives were also used to ensure all the electronic components complied with RoHS directive to avoid toxic materials.

3.5. Testing, Analysis and Certification Stage

This section describes the tools used during the testing, analysis and certification stage of the process.

3.5.1. Tools Used

The following tests were applied: Light analysis test, thermal test, burn-in test, IP test, and a CE mark test. Different tools and methods were used in each test. In the light analysis test the following tools were used: Goniometer, illuminance meter, colorimeter, power meter, and the software tools: ProSource and Photometrics Pro. In the thermal test a digital voltmeter and thermocouple adapter were used, and in the IP test, an IP test environmental chamber was used.

3.5.2. How the Tools Were Used

The tests were conducted consecutively in this order: (1) Thermal test, (2) CE mark test (3) IP test, (4) Burn-in test, and (5) Light analysis test. The thermal test was conducted introducing a thermocouple inside the housing containing the LED driver and the housing containing the LED and heatsink, for a period of 7 h (with hourly readings), to ensure that the temperature inside the housings of the driver and the lighting modules was below the allowed thresholds which could damage the housing material and electronic components, thus reducing the lifespan of the product. This was done to confirm the thermal simulation results performed initially (detail design stage) with Solidworks-Simulation (SS). The CE mark test was performed because it was necessary to commercialize this type of particular type of product in the EU, and was carried out by an external organization. The test consisted of the assessment of the product based on (mainly) safety criteria. The IP test was conducted by an external organization and consisted of exposing the product to specific environmental conditions in an environmental chamber. Once the tests had been passed, after re-design of some parts, the product was subjected to a burn-in test to reveal any manufacturing fault in the components and/or a bad design of any sub-system. Finally, the light analysis test was conducted using the goniometer, illuminance meter, colorimeter, power meter, and the software tools: ProSource and Photometrics Pro, to obtain the lighting product performance parameters (e.g., luminous flux, power consumption) related with the performance of the lighting product. These parameters were used to: (1) Inform the final life cycle assessment (LCA) using an LCA-based software tool (Simapro), (2) test the performance of the product, (3) to inform consumers about the performance of the lighting product, and (4) check the luminous efficacy and light output ratio (LRO) of the lighting product to ensure high energy efficiency.

4. Discussion

This section discusses the design process that was followed and described in the previous section, and the tools used during the process. First, it discusses and compares the eco-design process followed in this study with the design process usually followed by the same company to design non-eco lighting products, to identify the areas (related with eco-design processes) which could cause the lack of wider implementation of eco-design methods and the tools used within these. Then, it discusses the *effectiveness* and *usability* of the tools used during the design process, and assesses and compares them to identify what features of each of these tools could be hampering their wider adoption in design processes followed by product designers. The discussion is mainly focused on the eco-design tools that are directly used by product designers to inform their design decisions, since the paper is aimed at improving eco-design tools and methods, and some tools used during the design process such as tests and consumer studies have been used and studied already in other studies related with non-eco-design processes.

4.1. Design Process

When the eco-design process followed is compared with the (non-eco) design process (Figure 2) previously followed by the company, it can be observed that, although the previous design process follows the same process stages, it involves the application of less (eco-design) tools which are now required in the new eco-design process. The tools which were not applied in the previous design process are highlighted (in Figure 2) in grey color, and the tools that were applied are in black color (Figure 2).

In the non-eco-design process previously followed by the company the following tools (Figure 2, highlighted in grey), which were applied in the eco-design process, were not applied: EDG, EDG-CH, SM, SP, SS, LDS, TT, BIT, LAT. There are other tools (IP test, CE test) that were applied before depending on the type of product, and others (CS, ADF) which were applied in a different manner. For example, although Consumer Studies (CS) were also applied before, they were only used to inform the briefing of the product (PDS stage), but not at the embodiment stage (via prototypes). The CS carried out previously consisted of information gathering (feedback) from commercial representatives and shop owners about consumer preferences, so these were not formally designed studies targeting directly end consumers such the ones applied in the eco-design process presented in this paper. In addition, the information gathered was focused on consumer preferences, such as price, aesthetics and performance, rather than environmental related information. ADF was also applied previously, but mainly focused on one aspect: the assessment of disassembly of the product. IP test (and certification) was applied depending on the type of lighting product application. For example, for lighting products which have to be used outdoors, or in bathrooms, the IP test was applied. However, for lighting products to be used indoors (e.g., bedrooms), it might not be required, and hence it is not applied. The CE mark test is only applied for lighting products that will be sold in high amounts, otherwise the company provides its own independent certification. TT tests have not been typically applied previously because the company did not use LEDs before (i.e., they used incandescent and fluorescent light sources), and TT are more applicable when LEDs are used, since LEDs are more prone to thermal issues so thermal testing is necessary. The use of LEDs (typical in eco-lighting products) usually requires thermal tests, which is why they are more usually applied in eco-design processes of lighting products. LAT tests are not typically used in the company's previous design processes because the company's market is mainly domestic, where 'light distribution' (which is obtained through LAT) parameters are usually not required by the domestic consumer market. In addition, this type of analysis is necessary when using LEDs (since these are directional light sources), which have not been used by the company before in the development of their lighting products, this is why this type of tests have not been applied previously.

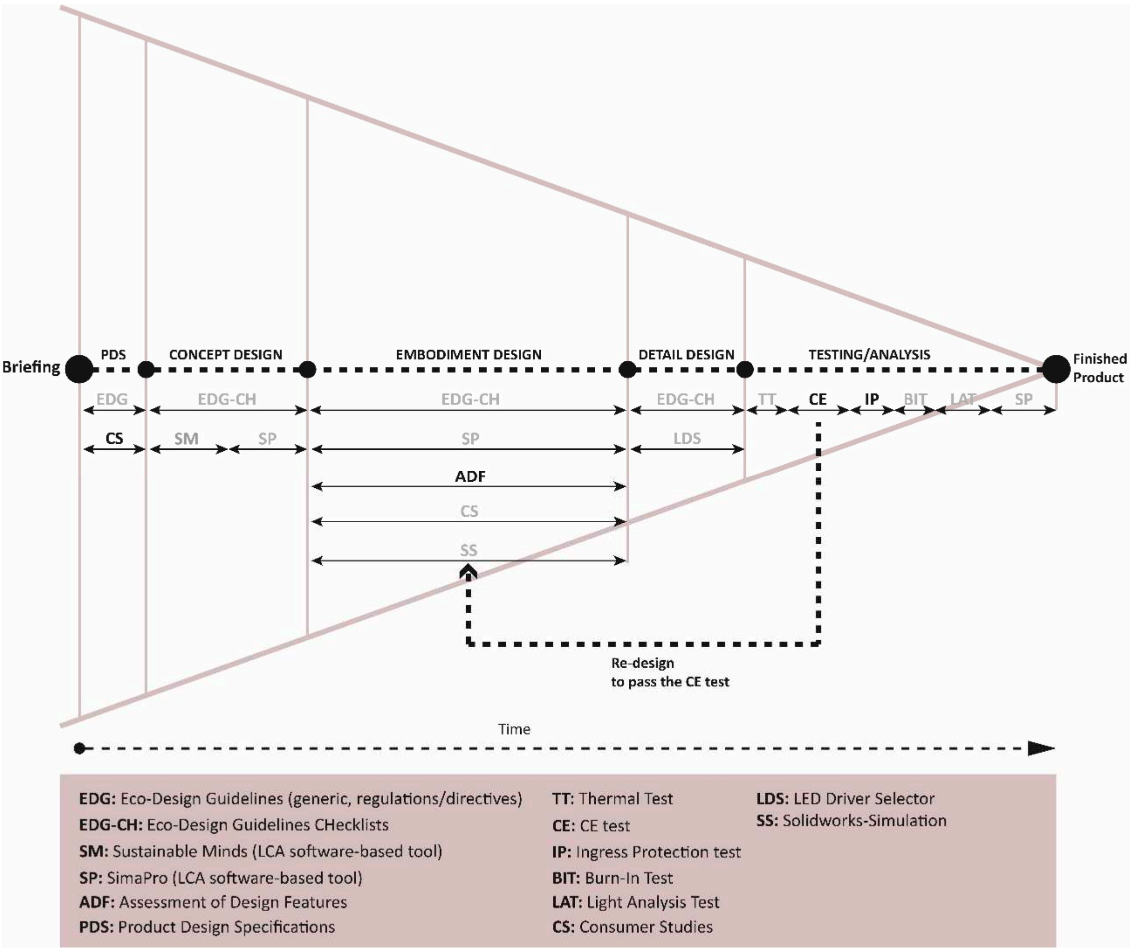

Figure 2. Descriptive model of company's non-eco design and development process. Reprinted with permission from J.L. Casamayor (2016). 2016 J.L. Casamayor.

The application of fewer tools in the previous design and development process followed by the company means that now product designers need additional time for learning and applying these new tools in eco-design processes compared with their previous non-eco-design processes. It also means that the company needs to have access to these new tools, so they have to, either purchase them, or outsource them (when these are not free) to external suppliers, thus having to spend additional costs compared with their previous design and development processes. Sometimes, these additional tools (e.g., software licenses or specific tests) may have prohibitive costs, which are outside the reach of companies with limited resources, thus representing a barrier for the implementation of eco-design methods and tools, despite the company's willingness to implement them. Other times, the lack of in-house expertise to use them, or the lack of time, may also represent barriers for their implementation.

The eco-design tools used in the previous non-eco-design process followed by the company, and the new eco-design process applied in this study are compared at each process design stage (Table 1) to identify and analyze their differences (in terms of tools application), and to discuss the potential implications of these differences in their wider implementation.

Table 1. Comparison of tools used in non-eco-design and eco-design processes.

Design Process Stages	Tools Used in Non-Eco-Design Process	Tools Used in Eco-Design Process
PDS	CS (Consumer Studies)	EDG (Eco-design Guidelines)
Concept design	None	EDG-CH (Eco-design Guidelines Checklists) SM (Sustainable Minds) SP (Simapro)
Embodiment design	ADF (Assessment of Design Features)	ADF (Assessment of Design Features) SP (Simapro) CS (Consumer Studies) SS (Solidworks-Simulation)
Detail design	None	EDG-CH (Eco-design Guidelines Checklists) DS (Led Driver Selector) EDG-CH (Eco-design Guidelines Checklists)
Testing/Analysis	CE (CE mark tests) IP (IP certification tests)	TT (Thermal Tests) CE (CE mark tests) IP (IP certification tests) BIT (Burn-in Test) LAT (Light Analysis Tests) SP (Simapro)

The eco-design tools used in the previous non-eco-design process are tools that can improve the environmental performance of a lighting product indirectly (e.g., tests increase reliability and hence extend the lifespan of the product), but which can also be used to design and develop non-eco-lighting products. For example, consumer studies, CE marks, and IP tests are also conducted in many non-eco-design processes. ADF is the only tool that is usually not used in non-eco-design processes, since it is usually focused on assessing and improving eco-design features that can improve the environmental performance of the lighting product. In this case, the company usually applies it in its non-eco-design processes to improve disassembly to facilitate repair. However, the more specific tools used for eco-design (EDG, EDG-CH, SM, SP) were not applied, since there are no eco-design requirements in conventional lighting products briefings, and these tools are only useful to assess the environmental impact of the full product or parts, and/or to provide guidance about eco-design guidelines and recommendations, all of which are used to satisfy eco-design requirements in briefings. This means that these tools are not required in conventional design processes which do not have eco-design requirements. In addition, these tools do not provide other non-eco-design related functionality advantages (e.g., quality or cost improvement), which could be used as an added value, or justification, to apply them in the design process (like tests do).

4.2. Tools

4.2.1. Eco-Design Guidelines/Checklists

Eco-design guidelines are very easy and fast to apply, and they can cover different areas such as disassembly, material selection, or recycling. In addition, the application of these does not require extensive knowledge about environmental issues, and it does not require to gather data about the product life cycle, which often is not available in the early stages of the design process. They can be applied as checklists in each stage of the design process, to assess each design decision in each design iteration to ensure each design decision satisfy all the requirements specified by the checklists. Eco-design guidelines are particularly useful at the beginning of the design process when we are eco-designing a new product.

Eco-design guidelines can provide 'general' design recommendations about how the final lighting product should be, or what environmental-related requirements each design decision should embody (e.g., use of recycled materials), but they cannot assess the environmental impact of different design decisions (i.e., design features), or concepts, so, they cannot support in selecting what design feature or concept variant has less environmental impact.

The incorporation of EDG in the PDS stage is critical, because it is at the beginning of the development process, when environmental-related design requirements will have the highest impact and it will be easier to implement. However, one of the problems found with the use of eco-design guidelines at this stage is that the specifications or recommendations provided are too general and are not provided in a format which is quantifiable. For example, guidelines recommend to use recycled materials, but the amount and type is not quantified or there is no indication of how these should be quantified when applied. It would have been more effective to specify the total amount of recycled content of the lighting product (e.g., the lighting product should contain 90% of recycled material and 100% should be recyclable) to have a benchmark for comparison at the end of the design iteration. Therefore, all the eco-design guidelines should be provided with quantifiable targets (if possible) at the PDS stage, which can then be compared and checked in each design stage.

Several matrix-based tools, such as green quality function deployment matrix [5], MET [6], MECO [6] and ERPA [62], were also trialed, although they were not selected and applied in the process in the end. The conclusion was that there was not enough information about the design concepts to fill-in the cells of the matrixes. In addition, the type of information asked was too specialized (e.g., environmental-related data) to be understood and retrieved by a product designer (particularly without previous eco-design knowledge). Since the information, available for the product designer to fill-in the cells, was many times unknown, or had to be based on very rough estimations, the results could not be considered robust enough or reliable. The other problem is the subjectivity of the assessment using this tool. For example, if the matrix had been filled-in by different users to assess the same concept the results would have probably been different, which confirms the subjectivity of the results using this type of tool. The conclusion is that using this type of tool can take too much time (since it is necessary to find the information required), and the results might not be reliable since a lot of information is not available, and the assessment results will depend on the product designer knowledge about environmental issues, so it is not advisable to use them. The eco-design guidelines using checklists, on the other hand, were easy to use to support decision-making along the concept design process.

4.2.2. LCA-Based Software (Sustainable Minds and Simapro)

Sustainable Minds and Simapro are both LCA-based software eco-design tools, but they have been created for different purposes. Sustainable Minds has been developed for product designers, whilst Simapro has been developed for LCA experts. Sustainable Minds is easier to use and requires less data (from the product life cycle) to complete the assessment, but the accuracy of the results is lower since it focuses on streamlined assessments, so it is more useful for general 'screening' design options or concepts. It also allows the possibility to conduct 'what if' scenarios (e.g., what if it is selected aluminum instead of PET?) easily, so different, materials, manufacturing processes, concepts, or the same concept in different versions can be compared easily. On the other hand, Simapro is a more advanced LCA tool, but it is also more difficult and time-consuming to learn and apply. It also requires a larger amount of detailed data from the product life cycle, as well as previous knowledge about the basic principles of the LCA method in order to use it and be able to understand and interpret the results of the assessment. However, it also provides more accurate and comprehensive results, with the possibility to use different life cycle impact assessment methodologies and model complex end of life scenarios to simulate possible different end of life scenarios of the product. Sustainable Minds is more suitable to assess early-stage concepts (i.e., concept design stage) when the product is not very defined yet and there is not enough information about the product life cycle. Once the lighting product is more defined and there is a physical prototype available, then Simapro software can be used and will provide more accurate results. There seems to be a need for an LCA-based software tool that has extensive databases, extensive life cycle impact assessment methods, and advanced modeling scenarios capabilities such as Simapro, whilst being oriented to eco-designers' activities and needs.

LCA-based software tools are also very useful to support product developers' decision-making processes regarding materials and manufacturing processes comparison and selection, but attention has to be paid to the databases (background data) and life cycle impact assessment methods selected in the assessment, since some have been developed based on specific countries/continents data and application and using them in another context (e.g., product manufactured in other country) may provide misleading results.

It was found that Simapro is a very suitable tool to conduct detailed LCA; however, at the early concept design stage there is not enough information about the concepts to inform a full detailed LCA with Simapro. Checklists, based on the eco-design guidelines specified, can be used instead of LCA-based software tools to roughly assess and compare concepts. Simapro is easier to apply and more effective when the product is more defined and therefore there is more information about the product life cycle data. In these cases, the assessment results can be used to compare or benchmark products, or to assess a reference product which has to be eco-redesigned. In this case there is complete information about all the product life cycle stages, and the assessment can identify the areas with higher impact where eco-design interventions are needed. When assessing the final version of a product the results can also inform an eco-label or similar environmental impact information of the product, for consumers or suppliers information.

4.2.3. Solidworks-Simulation

Solidworks-simulation is a tool used in non-eco-design processes, so it does not require new skills for product designers who use it to do simulations usually. The usefulness of this tool is that it allows to virtually simulate how the product will function which helps product designers to optimize the amount of material required in the housing and in the heat sink. Often it is used more material than it is required in many parts and components because no simulation has been carried out to check if the amount of material used is optimum for the application. Using this tool, resource efficiency in the product can be achieved, whilst maintaining the required functionality. Since Solidworks also allows solids modeling and environmental impact assessment through the same application (with version: Solidworks-Sustainability), it is a suitable design tool, since it can cover several functionalities (modeling, simulation, and environmental impact assessment) required for eco-design.

Although Solidworks software was used in this stage to model and simulate the lighting product, it was not the 'sustainability' version, which, in addition to modelling and simulating the product, can also simultaneously assess the environmental impact of each design iteration implemented in the product within the same software. Although the environmental impact results provided using Solidworks-Sustainability are not very detailed, this is a highly recommendable tool for the concept and embodiment design stages, because it shows the environmental impact of each design decision made in Solidworks software in real-time, as well as providing the environmental impact of each life cycle stage and components. The only disadvantage of this tool is that product designers need to use this particular software during the design process, and that the LCA results are not as comprehensive and detailed as the ones produced with Simapro. The utilization of this type of CAD-LCA tool would avoid the use of time-consuming LCA-based software tools such as Simapro (in the embodiment design stage) every time the lighting product needed to be assessed after creating/improving the concept in each design iteration, which would accelerate and simplify the eco-design process.

Another advantage of CAD-LCA tools (e.g., Solidworks-Sustainability) is that once the product is modelled in CAD there is no need to input the information into other software. In addition, the information of the product is extremely accurate because it is based on the Bill of Materials (BoM) from the CAD model.

4.2.4. LED Driver Selector

The LED driver selector is an online web application which is easy to use and does not require previous knowledge to use it. It is also very useful to find the optimum match between LEDs and LED drivers, which is key to make the LED-LED driver sub-system energy-efficient. The key elements to make a LED lighting product energy-efficient are: (1) the LED, (2) the driver, (3) the LED-LED driver setting, and (4) the optical elements (e.g., reflector, lens), and this tool helps to address one of these. It would be beneficial to have this functionality embedded into the design software (e.g., Solidworks), so it would not be required to use another application, so all the design work could be carried out with the same software, thus saving time and effort.

4.2.5. Assessment of Design Features

The advantage of this tool is that it allows you to assess (qualitatively) the design features (e.g., assembly architecture) of the lighting product, which affect its environmental impact (e.g., end of life disassembly for recycling), but which cannot be assessed and detected by a life cycle assessment (LCA) conducted with LCA-based software tools. It can be utilized in each design iteration during the embodiment design stage in order to reduce the environmental impact of the lighting product further after each iteration. The only requirement is that a concept (e.g., CAD model), or preferably, a functional prototype is required in order to be assessed. This tool can complement the life cycle assessment (LCA) of the product conducted with LCA-based software (e.g., Sustainable Minds or Simapro).

The utilization of this tool requires knowledge about eco-design, that is, about the issues or design features (e.g., use of smart sensors to reduce energy use, type of light sources used, disassembly process) that can affect the environmental impact of the product. Unlike LCA-based software tools, which provide environmental impact results independently of the user's knowledge judgement, the assessment carried out with this tool requires some personal judgement from the user, which will be biased by their previous knowledge about eco-design.

4.2.6. Tests and Certifications

All the tests and certifications utilized at the testing stage can be considered eco-design tools, because, indirectly, they contribute to increasing the reliability and hence durability of the lighting product. The light analysis test also contributes, indirectly, to reducing the environmental impact of the lighting product, by providing information about the lighting product performance (e.g., luminous flux, power consumption) which is necessary to inform life cycle assessments (LCA) (through LCA-based software tools). LCAs are, at the same time, necessary to obtain Environmental Product Declarations (EPD) [63] and Eco-labels [64], to inform consumers about the environmental credentials of the products. Information about a lighting product's performance (in particular, light distribution) is also required by architects and interior designers who design installations and spaces with lighting products. These professionals need to know the light performance of the lighting product so they can match the lighting product performance with the lighting needs of the space they design. Light (and energy) is often wasted because there is no information about the light performance of the lighting product. This information is provided in EULUMDAT/IES photometric files (obtained with the goniometer), which contains all the photometric data about the lighting products. These files are obtained in the light analysis test and can be exported to different CAD and light design software such as DIAlux [65]. Light analysis results can also provide data to obtain the lighting product efficacy and light output ratio (LOR), which have to be obtained to assess the energy-efficiency and efficacy of the lighting product. One of the drawbacks of these tests is that they are time-consuming and expensive, thus extending the duration of the design and development process and the cost of the process. In large companies, some of these tests may be conducted in-house, but in small companies, these tests and certifications are usually outsourced. In both cases, however, the product designers typically do not have to apply these tools directly or have knowledge about the standards and methods required to conduct them, so usability issues are not applicable in this case. However, they need to integrate them in their design and development processes, and know what the design requirements are so that the product can pass these tests, and this can be achieved through the incorporation of eco-design guideline–checklists from the very beginning of the process (e.g., PDS stage).

Product safety requirements (e.g., CE mark test) can be a barrier to develop eco-design lighting products in some occasions. For example, the lighting product was designed to be extremely easy to dismantle (following eco-design guidelines), however this did not allow the lighting product to pass the CE mark-safety tests, due to being considered unsafe for users to dismantle a product that conducts current so easily, so it had to be re-designed to make its disassembly more difficult. Tests usually mean that products have to be re-designed several times to pass the tests, thus extending the design process, and sometimes leading to conflict between the test design requirements and the eco-design guidelines best practices.

Although there are test-quality certifications for lighting products (e.g., ENEC) already, which are very effective in ensuring longer durability and reliability of the product, it has been observed that an EU eco-label, specific for (LED) lighting products, would help to provide more and better information about the environmental credentials of the product, which would help their commercialization and comparison by customers and suppliers. It would also help to create environmental performance criteria (e.g., guidelines) to be used as a guide during the design and development process.

IP tests are usually outsourced so product designers are not directly involved in conducting these, so no additional knowledge and skills are required to apply this tool. The only issue is that design requirements related with IP tests should be considered and included early in the design process (e.g., PDS stage) to ensure the products pass the test the first time, since failure to pass the test means the re-design of the product (extra time) and having to pass the test again (extra cost). IP tests are very effective in increasing the durability of the lighting product since electronics are very sensitive to environmental factors and IP tests can ensure the proper sealing of the housing protecting the electronic components inside, thus extending the lifespan of the product, and avoiding lower performance due to damage caused by external environmental factors.

Burn-in tests can be carried out in-house or being outsourced. When carried out in-house the test does not require specific knowledge and skills and it is easy to apply. The duration of the test can vary depending on the standards followed or company requirements. This test is very effective to detect faulty components and sub-systems, or to detect performance below the expected thresholds, which can (both) reduce the lifespan of the product.

After the end of the design and development process it was concluded that additional tests and certifications could have enhanced the environmental performance of the product. A comprehensive disassembly test would enhance the disassembly of the lighting product, to facilitate repairs, upgrades, and recycling during its use (e.g., repair, upgrade) and end of life (e.g., recycling) phases; an Environmental Product Declaration (EPD) certification could have provided more complete and standardized environmental impact information, about the lighting product to be used for benchmarking purposes by consumers and suppliers.

4.2.7. Consumer Studies

Consumer feedback during the design process is very effective to enhance the acceptance of the product by the end consumer. This feedback can be obtained via focus groups, interviews, questionnaires, or other social science-based research methods. Although consumer studies are also used in non-eco design processes, this is particularly important for eco-products, because certain eco-features of products (e.g., use of recycled materials) may not be perceived positively by consumers, and this may reduce the sales potential of the product for the company, who may then decide to stop manufacturing eco-products.

The application of several (e.g., focus groups and interviews) types of consumer studies at different stages of the design process are also beneficial because the consumer can give feedback about the product at different product definition stages. For example, although it is important to receive feedback from the consumer during the concept design stage, the product is not very defined at this stage, and the consumer cannot see it or use it physically, so they cannot evaluate the product fully. However, at the embodiment design stage, the consumer can see the product physically and use it, which allows them to check usability, performance, and other features that cannot be evaluated in a virtual 3D initial model (concept design stage).

The problem with consumer studies is that they usually increase the number of product design specifications, which sometimes, conflict with other eco-design product specifications specified in the PDS. For example, consumers may think that the finish of the eco-product is 'rough' and 'does not look clean or new'; however, a glossy coating (as suggested in the consumer study) can reduce the recyclability of the product. Consumer studies, like tests, can increase the quality and acceptability of the product in the market but they also add new design requirements, which sometimes conflict with eco-design guidelines best practices, leading to design requirements prioritization and tradeoffs.

The application of consumer studies is well established in other non-eco-design and development processes so it does not require specific new skills, so this method should be easy to apply by product designers with no experience in eco-design who are familiar conducting consumer studies.

4.2.8. Assessment of Tools

Seven of the eco-design tools, directly used by product designers, discussed in the previous section are (qualitatively) assessed and compared in this section (Table 2) based on a number of criteria. This assessment aims to identify what features of each tool might be hampering their wider implementation, and is based on the application of the tools during the case study.

The qualitative assessment technique applied consists of assessing each tool based on a four-point scale qualitative qualifier (e.g., none, low, medium, high), to show the likenesses of each tool to satisfy each criterion. The criteria used are: Learning time, which assesses the time it takes to learn how to use each tool before they are used. Cost, which assesses the cost of each tool. Usability, which assesses how easy to use each tool is, focusing mainly on interface-related usability. Environmental science knowledge required, which assesses what level of knowledge about environmental science or eco-design is necessary to use the tool. Time required to apply the tool, which assesses the time it takes to apply the tool and obtain the results. Amount of product life cycle data required, which assess the amount of data from the product life cycle (e.g., manufacturing processes, materials, use, distribution, and end of life) necessary to use the tool. Results accuracy, which assesses the reliability and accuracy of the results obtained after applying the tool. Possibility to integrate with existing design methods/tools of the company, which assesses the possibility of the tool to be integrated with existing design methods, processes, and tools, to facilitate their use. Possibility to outsource the tool, which assesses the possibility to outsource the tool, when there is no internal expertise to use it, or budget to purchase it. Possibility to upgrade (evolve), which assesses the possibility of the tool to be upgraded so it can evolve (over time) and not become out of date and useless. Requires user personal judgement to use it, which assesses the amount of personal judgement needed to use it.

Table 2. Assessment of eco-design tools.

Acronyms							
EDG	Eco-design Guidelines (Generic, Regulations/directives)						
EDG-CH	Eco-design Guidelines-Checklists						
SM	Sustainable Minds (LCA software-based tool)						
SP	Simapro (LCA software-based tool)						
ADF	Assessment of Design Features						
LDS	LED Driver Selector						
SS	Solidworks-Simulation						
Tools							
	EDG	**EDG-CH**	**SM**	**SP**	**ADF**	**LDS**	**SS**
Criteria							
Learning time	*none*	*none*	*medium*	*high*	*high*	*low*	*high*
Cost	*none*	*none*	*high*	*high*	*none*	*none*	*high*
Usability	*high*	*high*	*medium*	*low*	*low*	*high*	*low*
Environmental science knowledge required	*low*	*low*	*medium*	*high*	*medium*	*none*	*none*
Time required to apply the tool	*low*	*low*	*medium*	*high*	*medium*	*low*	*high*
Amount of product life cycle data required	*none*	*none*	*high*	*high*	*medium*	*none*	*none*
Results accuracy	*low*	*low*	*medium*	*high*	*medium*	*high*	*high*
Possibility to integrate with existing design methods/tools of the company	*high*	*high*	*low*	*low*	*medium*	*high*	*high*
Possibility to outsource the tool	*high*	*high*	*high*	*high*	*high*	*high*	*high*
Possibility to upgrade (evolve)	*high*	*high*	*high*	*high*	*high*	*high*	*high*
Requires user personal judgement to use it	*medium*	*medium*	*high*	*high*	*high*	*low*	*low*

The use of 'high' qualifiers in the following criteria: 'learning time', 'cost', 'environmental science knowledge required', 'time required to apply the tool', 'amount of product life cycle data required', and 'requires user to personal judgement to use it' could be potential barriers to increase the implementation of such tools. On the other hand, the use of 'high' qualifiers in the following criteria: 'usability', 'results accuracy', 'possibility to integrate with existing design methods/tools of the company', 'possibility to outsource the tool', and 'possibility to upgrade (evolve)' might facilitate the adoption of such tools.

4.3. Limitations of the Study

Since the findings of this paper area based on a single case study, the insights may not be generalizable, so these should be validated with additional case studies with different characteristics: (1) company size, (2) company expertise in eco-design implementation, (3) product designers (e.g., in-house, external, different eco-design experience), to validate the initial findings presented in this paper.

5. Conclusions

This paper has described and examined a design and development process to design a LED-based lighting product based on a real-world case study with a lighting manufacturer. The description and examination of the process followed, has contributed to increase the understanding about the application of eco-design and development processes, and the tools used during these. In particular, it has provided new insights about what issues could be hampering the wider implementation of the existing methods and tools used to eco-design lighting products:

- The eco-design method followed required the application of additional tools, not used in the previous existing design process used by the company, which made the eco-design process more time-consuming and costly, particularly when the new tool had to be purchased, and designers/engineers had never used them before, and had to learn how to use them, which was the case with the LCA-based software Simapro tool.
- Different tools applied presented different issues which may make their implementation difficult, but, in general, the key technical barriers found were: Long learning time required to use them, high cost, high previous environmental science knowledge required by the product designer to be able to use it, long time required to apply it, high amount of product life cycle data required, low results accuracy, low possibility to integrate with existing methods and tools of the company, low possibility to outsource the tool when there is not in-house expertise to use it, or when tools (e.g., software) are not available, low possibility to upgrade (evolve) the tool, low possibility to use the tool without expertise in eco-design (i.e., tools which can provide results without product designer personal judgement).
- Some tools used during the eco-design process such as tests, certifications, LED driver selector, solidworks-simulation, and consumer studies are tools which are also used in non-eco-design processes, so their integration in eco-design processes is easier. These tools, although they do not assist product designers in assessing the environmental impact of their design decisions, can contribute indirectly to reduce the environmental impact of lighting products by: (1) increasing the durability (quality) of the lighting product, and hence its lifespan, in the case of tests and certifications, (2) optimizing the amount of material used via simulation and optimization, in the case of solidworks-simulations tools, or optimizing the amount of energy used by the lighting product in the case of the LED driver selector, and (3) ensuring that eco-design features of the lighting product are accepted by consumers to ensure the marketability of the product.
- Eco-design guidelines and Eco-design guidelines checklists were easy to use and flexible enough to address different eco-design issues (e.g., materials, recyclability), particularly in the early stages of the eco-design process. However, the guidelines utilized during this study did not incorporate quantifiable metrics and targets which could be evaluated in later stages of the eco-design process, and therefore, were not suitable for evaluation of the environmental improvements of the final product version. One of the problems we found with this type of tools is that they can be quite generic, both in guidance (e.g., use recyclable materials) and the capacity to evaluate (e.g., lack of metrics) the guidance provided.
- LCA software-based tools such as SM and SP are the tools that provided more accurate objective environmental impact assessment results, and the ones that better supported the decision-making processes during the design process. However, their application required high amounts of data quantity/quality (from the product life cycle) to do the assessments, and high expertise to use the tools and interpret the results. In addition, these tools were costly, and were not design-oriented eco-design tools, which is reflected in their user interfaces, and functionality. This means that they were not easy to use and were not adapted to product designers' needs. Although it was found that some tools such as solidworks-sustainability has tried to address these problems, still this tool has not reached the advanced functionality of more conventional LCA software-based tools such as SP, so its environmental impact assessment capabilities are quite basic. Although LCA software-based tools such as SM can be outsourced, the integration of these in design processes via outsourcing is not ideal for design and development processes where a constant design–assessment iteration process is required.
- The ADF tool required the use of a physical prototype and also knowledge about eco-design by the product designer, in order to be effective. This meant that the

effectiveness of the results using this tool were biased by the experience of the product designer in eco-design, so product designers with different knowledge about eco-design will provide different results, and that results provided by users (product designers) with no experience in eco-design will not be reliable. This type of tool was used because other tools used (e.g., SM, SP) cannot assess some eco-design features of the product.

- In general, it was found that all the tools trialed during the study, and particularly the ones that support design-related decision-making processes, did not link the potential environmental impact reduction of each design decision, with the associated economic costs that the company could save at the same time. This should be addressed in future tools to incentivize the adoption of eco-design methods and tools by industry.

All the insights provided in this study can be used to inform the improvement of existing methods and tools, or the development of new improved methods and tools, to reduce the environmental impact of LED lighting products. Although the findings are particularly relevant to LED lighting products, they can also be used to inform the research and development of methods and tools to eco-design other categories of products, since some insights are also applicable to other product categories.

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