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To cite this article: Claudio Favi, Michele Germani, Marco Mandolini & Marco Marconi (2018) Implementation of a software platform to support an eco-design methodology within a manufacturing firm, International Journal of Sustainable Engineering, 11:2, 79-96, DOI: 10.1080/19397038.2018.1439121

To link to this article: <https://doi.org/10.1080/19397038.2018.1439121>



Published online: 19 Feb 2018.



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Implementation of a software platform to support an eco-design methodology within a manufacturing firm

Claudio Favi^a , Michele Germani^b , Marco Mandolini^b  and Marco Marconi^{b1} 

^aDepartment of Engineering and Architecture, Università degli Studi di Parma, Parco Area delle Scienze, Parma, Italy; ^bDepartment of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche, Ancona, Italy

ABSTRACT

The paper aims to explore the implementation of an eco-design methodology and the related software platform (G.EN.ESI – Green ENGINEERING dESIgn) within technical departments of a manufacturing firm. The G.EN.ESI eco-design methodology is based on the life cycle thinking concept and the software platform is conceived as a set of inter-operable software tools able to efficiently exchange data among them and with the traditional design systems (i.e. CAD, PDM and PLM). A multinational company, designing and producing household appliances, adopted the proposed methodology and related software platform for redesigning two cooker hood models with the aim to improve their environmental performances. Design and engineering departments evaluated the methodology and platform impact on the product development process, as well as the platform inter-operability with traditional design tools. The results indicate that methodology and software platform satisfy the requirements of the enterprise in terms of: (i) degree of expertise and training requirement on this subject, (ii) low impact in a consolidated design process and, (iii) good level of inter-operability among heterogeneous tools. However, the testing results highlight the necessity of a further platform optimisations in terms of software integration (single workbench made by integrated software tools with the same graphical user interface).

Abbreviations: BoM: Bill of Material; CAD: Computer-Aided Design; CAE: Computer-Assisted Engineering; CAS: Computer-Aided Software; CBR: Case Base Reasoning; CREER: Cluster Research, Excellence in Ecodesign & Recycling; DB: Database; DfD: Design for Disassembly; DfEE: Design for Energy Efficiency; EDIMS: EcoDesign Integration Method for SMEs; EoL: End of Life; EPD: Environmental Product Declaration; FMEA: Failure Mode and Effect Analysis; G.EN.ESI: Green ENGINEERING dESIgn; GUI: Graphic User Interface; LCA: Life Cycle Assessment; LCC: Life Cycle Costing; LCT: Life Cycle Thinking; LE: Large Enterprises; LED: Light Emission Diode; PDM: Product Data Management; PDP: Product development Process; PLM: Product Life cycle Management; PMMA: Poly Methyl Methacrylate; R&D: Research and Development; REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals; RoHS: Restriction of Hazardous Substances; SME: Small and Medium Enterprises; WEEE: Waste of Electric and Electronic Equipment; XML: Extensible Markup Language

ARTICLE HISTORY

Received 24 January 2017
Accepted 7 February 2018

KEYWORDS

Eco-design methodology;
eco-design software
platform; product
environmental sustainability;
interoperability evaluation

1. Introduction

Currently, eco-design and design for the environment are becoming important strategies for implementation during the PDP for the creation of sustainable business models (de Pauw, Kandachar, and Karana 2015). Companies must deliver products and services that are qualified in terms of environmental sustainability due to both legislative compliance and the pressure of specific markets with highly demanding consumers (Domingo and Aguado 2015). Innovative SMEs are generally more reactive to external stimuli and attempt to realise competitive advantages from environmental and societal challenges. In contrast, traditional companies are more resistant to sustainability or environmental-related pressures and tend to follow the classical design approaches that consider only technical, functional and cost-related requirements (Justina et al. 2016). In both cases, effective support tools are needed to guide designers in ecological design choices.

It is well known that design decisions applied during the conceptual and embodiment phases influence a very large part of the product life cycle performance (both costs and environmental impacts) (Huang 1996; Ulrich and Eppinger 2003; Beitz et al. 2007). Traditional design methods and software tools (e.g. CAD/CAE/CAS) currently support designers only in their functional, structural or aesthetic choices. In recent years, several eco-design methodologies have been proposed and developed, but some choices supply only qualitative results and are too general and not sufficiently specific to be effectively used (e.g. checklists), whereas others require large amounts of data and time for application (e.g. full LCA) (Bovea and Pérez-Belis 2012). Examining the software solutions, the lack of effective integration and inter-operability between eco-design tools and traditional design tools is one of the most critical aspects of the currently available solutions (Rossi, Germani, and Zamagni 2016). Only a few examples are commercially

available as a solution for daily use within design departments (e.g. SolidWorks Sustainability), but essential limitations in terms of boundaries (only the materials and manufacturing phases are considered and the use phase and end-of-life issues are neglected) and quality of results are observed (Morbidoni, Favi, and Germani 2011).

This paper aims to explore the impacts caused by implementation of a structured eco-design methodology and a related software platform (G.EN.ESI-Green ENgineering dESIgn) within the PDP of a multinational corporation. The paper investigates feedback from end users (product designers, engineers and practitioners) relative to the daily use of platform tools and the consequences of this implementation in a consolidated design process (i.e. changes in the traditional design workflow). Most of the existing barriers observed for implementation of eco-design tools in traditional manufacturing firms have been set as company objectives (targets) with the aim of testing the effectiveness and the robustness of the eco-design framework in a real industrial context.

It is worth noting that the G.EN.ESI eco-design framework has been chosen as the most suitable and complete suite for this analysis. First, the methodology is compliant with the life cycle assessment (LCA) principles and encompasses all design aspects related to the product life cycle. Second, the software platform is conceived as a set of inter-operable software tools that are able to efficiently exchange data among each other and with the traditional design systems (i.e. CAD, PDM and PLM) <http://genesi-fp7.eu/>.

The paper is structured as follows: Section 2 presents a critical review of the eco-design methodologies and tools currently used in design departments, highlighting the main barriers to implementation in the traditional context. Section 3 introduces the G.EN.ESI methodology, and Section 4 presents the G.EN.ESI software platform by defining the main features and inter-operability with traditional design tools. Section 5 describes the deployment of the G.EN.ESI methodology and software platform within the design department of a manufacturing company, including feedback analysis from the end users. Section 6 presents and analyses the results in terms of the impact of such a methodology and software platform on the PDP and inter-operability with other design tools. This section also discusses the achieved environmental improvements in the case study (cooker hood) obtained using the G.EN.ESI software platform. Finally, Section 7 summarises the outcomes of this study and presents selected proposals for future work.

2. State of the art

The new challenge of environmental sustainability has pushed industrial firms in the development and use of methods and tools used to assess the environmental impacts of their products (Bovea and Wang 2007). The literature contains many eco-design frameworks and several reviews. Janin (2000) classified eco-design tools into two main categories according to the tool characteristics and the recommendations supplied to the user. Navarro et al. (2005) based the classification on the functional aspects of eco-design tools. Hernandez Pardo et al. (2011) proposed a different classification of eco-tools according to the three properties of complexity, type and main function.

The most recent classification (Rossi, Germani, and Zamagni 2016) includes (i) LCA tools, (ii) CAD-integrated tools and methodologies, (iii) diagram tools, (iv) checklists and guidelines, (v) design for X approaches, (vi) methods for supporting the company's eco-design implementation and generation of eco-innovation, (vii) methods for implementing the entire life cycle and user centred design for sustainability and (viii) methods for integrating different existing tools. As an outcome, the literature highlights a broad and fragmented set of eco-design methods and tools that are developed based on specific needs and requirements.

Despite the large variety of methods and tools available for assessment of environmental performances, their use within the traditional industrial context is still limited (Lindahl 2006, Kuijer and Bakker 2015). Existing barriers have been explored and reported in the literature by several authors. The first barrier is the lack of knowledge of designers and engineers with respect to the environmental sciences. Most of the existing tools and methods were conceived for environmental experts, which is the main reason for their limited diffusion in technical departments (Le Pochat, Bertoluci, and Froelich 2007). Another barrier to the use of eco-design tools is related to management information (i.e. where data are stored and how to use them), which appears to be over-formalised for application in a real PDP (Aschehoug and Boks 2016). Consequently, it is possible to observe a divergence between academic methods and real industrial and designer needs (Blessing 2002; Stempfle and Badke-Schaub 2002). Considering these aspects, the current industrial framework highlights an effective resistance to implementation of eco-design principles and tools. Furthermore, companies should endorse the involvement of academics or environmental scientists within the PDP, but this effort requires time and dedicated investments.

A solution to the above-mentioned problems consists of the development of structured methodologies. The ISO/TR 14062 standard (International Organization For Standardization 2002) was the first initiative aimed at integration of environmental aspects within the design process. This standard covers different topics, including business structure, environmental management and specific design activities, but it is too general and not sufficiently structured for effective and efficient application. Looking outside the regulatory framework, different authors have developed other approaches with the goal of integrating eco-design into the design process. For example, Navarro et al. (2005) defined a structured methodology composed of a series of tasks and activities. This methodology, clearly inspired by the PROMISE-manual and developed by Brezet and van Hemel (1997), has important advantages such as (i) added environmental considerations in the traditional design workflow, (ii) transformation of environmental management issues into defined actions and (iii) introduction of eco-design planning activities in the early design stages, including subsequent evaluation activities during the later design stages. This methodology can be considered as the first structured approach for introduction of eco-design into a traditional design approach. However, this approach is only a general framework in which the implementation phase, the workflows among different actors involved in the design process, and the integration and inter-operability of different expertise in a real design scenario are missing.

Different and more promising approaches aim at the creation of eco-design platforms in which environmental tools are interconnected with traditional design tools that are used daily by designers, such as CAD and PLM. This is the case of the GIPIE project (Theret, Zwolinski, and Mathieux 2011) in which the platform tools are able to perform product life cycle assessment and substance compliance evaluation. In this case, a CAD application collects the environmental data, which is subsequently managed by the environmental analyst, to perform an LCA analysis. Methodologies for CAD-LCA integration were proposed by Gaha, Benamara, and Yannou (2011) and Marosky (2007), and Cappelli, Delogu, and Pierini (2006) illustrated integration among LCA, CAD and eco-design guidelines, converging in an integrated design for environment methodology. Another platform example is Seeds4Green (Teulon and Canaguier 2012). However, most of these tools and platforms aim to simplify the data exchange for environmental assessment (i.e. LCA) of a product under development and do not consider the manner (rules, guidelines, knowledge sharing, etc.) in which these processes can be improved, which is the goal of eco-design activities. Turning to the commercially available CAD-based solutions for eco-design, *Solidworks sustainability* is one of the most well-known tools that allows evaluation of the environmental performance of the product under design. Therefore, it is possible to compare different design solutions with respect to the material and the transformation process selection. This commercial tool appears to be promising in terms of rapidity and usability, but it suffers from certain drawbacks: (i) crucial life cycle phases are not included in the analysis (i.e. use and end-of-life), (ii) the quality and reliability of results compared with LCA tools do not allow a clear statement in the decision-making process and (iii) the tool is not compliant with the LCA framework (e.g. goal and scope, functional unit and system boundaries are not defined) (Morbidoni, Favi, and Germani 2011).

Another important issue in effective implementation of eco-design tools in industry is related to the nature and the structure of SMEs and how they approach the environmental aspects during the design process (Simon et al. 2000; Moss, Lambert, and Rennie 2008). Several studies, surveys and literature analyses have identified and listed the stimuli and barriers that play a role in the success or failure of the various eco-design solutions dedicated to SMEs (van Hemel and Cramer 2002; Johansson 2002; Bey, Hauschild, and McAloone 2013). Le Pochat, Bertoluci, and Froelich (2007) faced this problem by developing a method to facilitate the integration and the collaboration of SMEs in eco-design exercises, namely, the eco-design integration method for SMEs (EDIMS). However, this theoretical framework is not supported by tools that can ensure the success of the eco-design integration within the technical design departments of SMEs. Moreover, no metrics or validation processes have been supplied to effectively evaluate the ease of management and the use of eco-design tools for this type of enterprise.

Table 1 summarises the barriers mentioned in the literature review, including impacts on company organisations/strategies during the project development.

In conclusion, the literature analysis notes that most of the eco-design approaches and tools aimed at integrating the environmental aspects in the design process have significant limitations.

The development of eco-design software tools appears to have a favourable outlook in overcoming these limitations through inter-operable modules, a key aspect for a highly usable eco-design platform (Lofthouse 2006). Indeed, to effectively use an eco-design approach within a typical design workflow, evaluation of the inter-operability between eco-tools and design tools is a crucial aspect (Zhang et al. 2013). This goal can be reached by shifting the general tendency of proposing detailed methods and tools for environmental analysis towards developing simplified, integrated and effective methods and tools that can be included within the traditional design processes. In this manner, three main objectives can be reached:

- Collaboration by designers, engineers, suppliers, etc. with different levels of education, knowledge and expertise in the product development process with consideration of eco-design aspects and life cycle principles;
- Effective inter-operability of eco-design tools with traditional design tools (CAD, PDM, PLM, etc.) for ease of data exchange in the environmental analysis;
- Implementation of eco-design methods and tools in a traditional and standardised design context.

3. The G.EN.ESI methodology

The G.EN.ESI methodology supplies a structured workflow (Figure 1) to support integration of environmental design and management activities within the design and engineering departments. The methodology was conceived by accurately considering the above-mentioned existing barriers that limit the use of eco-design methods and tools (see Table 1). The characteristics and the organisation of real industrial companies (both LEs and SMEs) formed the starting point used to define the methodology and to contextualise it within the PDP (Germani et al. 2013a). The definition of an improved business structure, organisation and systematic design workflow supported by specific inter-operable tools to include the variable 'environment' in the decision-making process potentially limits the gap between academic proposals and industrial needs, thus favouring the implementation of standardised and novel eco-design methods and tools in non-structured companies such as SMEs. This methodology represents the foundation of the software platform described in the following section of this paper. Hereafter, only the essential details are introduced, and an in-depth description of each phase can be found in previous research papers by the same authors (Germani et al. 2013a).

3.1. Initialisation

The first three steps represent initialisation of the eco-design process, when the main objectives (environmental and business) must be clearly defined. Before starting a re-design project, it is essential that the company has formed a good understanding of the business case. The initial requirements originate, for example, from legislation or market pressures. The latter are translated into quantitative target values for the relevant indicators (e.g. environmental impact) to be reached using the following re-design activities (Dufrene, Zwolinski, and Brissaud 2013).

Table 1. Existing barriers to implementation of an eco-design approach in industries and related impacts.

Existing barriers	Impacts	References
(1) – Lack of skill and expertise (environmental experts)	New figure/resources to involve; Training activities required; Long-term investment (time and resources).	Ritzén (2000); Lindahl (2006); Le Pochat, Bertoluci, and Froelich (2007); Rossi, Germani, and Zamagni (2016)
(2) – Data management for environmental analysis (design phase)	Data search and availability (where data are stored); Data quality and accuracy (upgradability); Reliability of results.	Marosky (2007); Morbidoni, Favi, and Germani (2011); Hernandez Pardo et al. (2011); Aschehoug and Boks (2016); Rossi, Germani, and Zamagni (2016)
(3) – Standardised methodology implementation (LCA, etc.)	New business structure; New project organisation; Redefinition of PDP.	Brezet and van Hemel (1997); Navarro et al. (2005); Lindahl (2006); Bovea and Pérez-Belis (2012)
(4) – Isolated software tools/platform	Time-consuming (inefficient data exchange); Interpretation of results (difficulty in transforming environmental issues into design actions); High level of expertise required.	van Hemel and Cramer (2002); Lofthouse (2006); Cappelli, Delogu, and Pierini (2006); Theret, Zwolinski, and Mathieux (2011); Teulon and Canaguier (2012); Germani et al. (2013a); Germani et al. (2013b); Dufrene, Zwolinski, and Brissaud (2013); Germani et al. (2016); Rossi, Germani, and Zamagni (2016)
(5) – Gap between academic methods and industrial needs	Resistance to adoption of proposed methods; Endorsement of academic approaches without testing/proof; Long-term investment (time and resources).	Blessing (2002); Stempfle and Badke-Schaub (2002); Rossi, Germani, and Zamagni (2016)
(6) – SMEs organisation	Low degree of follow-up (difficulty in ensuring the success of the eco-design in technical departments); Collaboration with LE and multinational.	Simon et al. (2000); van Hemel and Cramer (2002); Johansson (2002); Lindahl (2006); Le Pochat, Bertoluci, and Froelich (2007); Moss et al. (2008); Bey, Hauschild, and McAloone (2013)

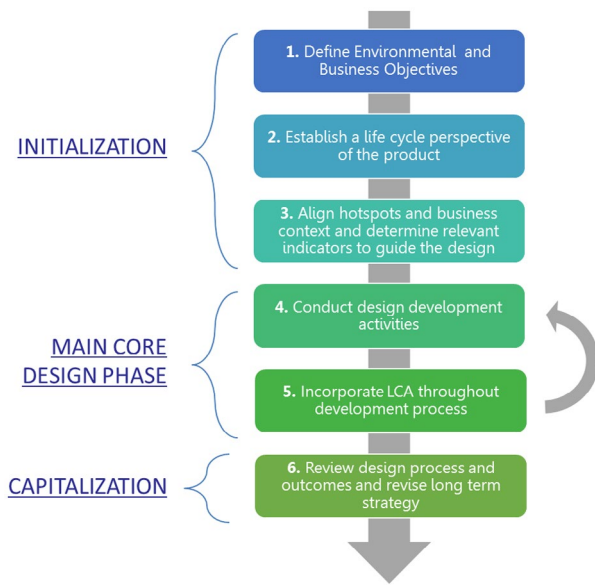


Figure 1. G.EN.ESI methodology steps.

The initialisation phase first consists of determining the project objectives with consideration of all product weaknesses not only related to environmental aspects but also to other drivers (e.g. cost, performance, etc.). To establish these objectives in a clear manner, the project management team can use information from similar projects, European directives, eco-labelling, etc.

Subsequently, an assessment of the product is required to identify the most important ‘hot spots’, considering the entire product life cycle. Qualitative or simplified LCA and LCC analyses must be performed to map all of the potential criticalities. Additionally, other product criteria (e.g. recyclability rate, disassemblability) can be evaluated for a more comprehensive view of the current situation.

Once the environmental hot spots are clearly identified, it is necessary to prioritise efforts for the re-design phase. Based on the project management team experience and supported by an environmental expert in cases for which the internal skills are not sufficient, the strategy is translated into quantitative target values (thresholds) that represent the final objectives for the successive phases.

3.2. Main core design phase

The main core design phase consists of re-designing the initial product configuration and verifying whether the new version satisfies the quantitative target values established in the previous phase.

Step 4 is the core of the re-design phase, and the practical activities involved are the classical ones found in any PDP. Based on the combined evaluation of life cycle aspects and other design constraints (e.g. performance, aesthetic requirements, etc.), the product is optimised to reach the established targets (Germani et al. 2013a). The iterative phases of assessment, advice and action require specific elements, such as tools for supporting the decision-making process through sharing of general eco-design rules, guidelines and specific company knowledge that are opportunely classified and organised.

During Step 5, design solutions are checked to ensure achievement of the environmental objectives and to highlight residual weak points. A life cycle perspective is required to avoid burden shifting (i.e. migration of impacts from one phase to another).

Steps 4 and 5 can be repeated several times before the re-design process is considered complete. Simplified and full LCA and LCC tools, as well as other calculation modules, are generally used in these assessments during the iterative steps and for the final checks. Reports related to the final design choices and assessments constitute the knowledge used to support designers in future projects during the improvement phase (Step 4).

Data availability, knowledge of best practices (both internal and external), inter-operability among all of the needed tools and the possibility of working with a univocal product virtual model are essential aspects to overcoming the most important existing barriers in implementation of an eco-design methodology in real design contexts.

Because the main core design phase is certainly the most data-intensive, impactful and time-consuming phase, the G.EN.ESI platform is primarily focused on supporting the design team during the activities of this key phase.

3.3. Capitalisation

Once the product re-design is completed, the company must review the development process to understand the environmental achievements and the outcomes. This review facilitates establishment of the current environmental position and adjustment of the long-term strategic targets for use in future projects.

4. The G.EN.ESI platform

4.1. Platform description

The G.EN.ESI platform (general architecture shown in Figure 2) is a suite of analyst tools/modules for environmental assessment at different levels. These tools can be used alone for analysis of specific product life cycle phases (i.e. material extraction, manufacturing, transportation, use and end of life) or integrated for concurrent analysis of the entire product life cycle.

All of the G.EN.ESI software tools are interoperable because they can exchange data with each other in a manner transparent to the user via the dedicated *G.EN.ESI XML* file (green arrow in Figure 2). Based on the XML meta-language for achieving a customizable and scalable structure, this schema contains the product BoM and the life cycle-related data (e.g. in-house manufactured products, commercial components, energy-use products). Each tool is able to read/write the *G.EN.ESI XML* file to enrich it with data manually defined by the user or calculated by the tool itself. At the end of the product analysis, the XML file contains all of the life cycle phase-related data for a comprehensive view of the entire product, related components, and life cycle.

One of the G.EN.ESI platform modules (i.e. *GRANTA MI*[™], see description below) is fully integrated with the most common traditional design tools (i.e. CAD, PDM and PLM) and can be directly used as a plug-in. Other modules (i.e. *DfEE*, *LeanDfD* and *CBR*, see description below) are instead able to establish a connection with 3D CAD systems and can directly extract

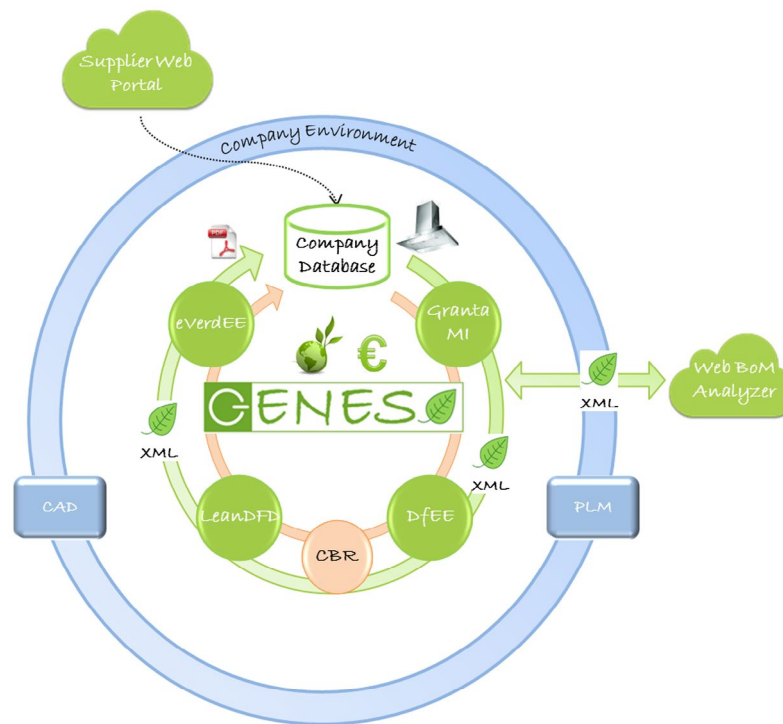


Figure 2. G.EN.ESI platform architecture.

all relevant product-related information (e.g. weight, material, shape, tolerances, manufacturing processes).

Because the main objective of this work is to investigate implementation of the G.EN.ESI methodology and platform in a real industrial context, this section presents only a brief explanation of the functionalities of each tool to clarify how they can be used during design activities. Additional informational details on the G.EN.ESI platform and related tools (i.e. architecture, functionalities, database structure, graphical user interface and algorithms) are available in previous publications (Germani et al. 2013a, 2014a, 2016).

The GRANTA MI™: *Materials Gateway* tool (by Granta Design Ltd) has the main objective of performing a simplified life cycle assessment during the early stages of the design process. The user accesses this module directly in the CAD or PLM environments and can assign materials and a simplified set of manufacturing processes at both the component and assembly levels. The tool assesses the typical product environmental impact in terms of primary energy consumption, carbon dioxide emission, and water consumption and considers selected simplified parameters of the use, transportation and end-of-life phases.

The *Web BoM Analyser* (by Granta Design Ltd) makes available the same functionalities of the GRANTA MI™: *Materials Gateway* tool within a web browser. This module was conceived primarily to guarantee the possibility of using the platform in companies that do not use CAD systems for their design activities. In addition, the G.EN.ESI XML file previously created within the CAD environment can be enriched by adding/removing/modifying components that are not included within the 3D model (e.g. commercial components, screws). Finally, this module can act as a reporting tool (i.e. dashboard) to visualise and plot the results calculated by the other platform tools and stored within the G.EN.ESI XML file.

The DfEE tool (by *Università Politecnica delle Marche*) aims to evaluate the energy consumption, environmental performance and costs relative to the use phase of any energy-using component (e.g. electric motors, lamps, heating elements, etc.), considering the detailed use scenarios (i.e. different working points with different powers and efficiencies for electric motors). Moreover, this module allows comparison of alternatives design solutions, as described in Favi (2013).

With respect to the product end-of-life phase, the *LeanDfD* tool (by *Università Politecnica delle Marche*) allows assessment of the product disassemblability (i.e. disassembly time and cost) of components that should be maintained (e.g. electric motors) or treated at their end of life (e.g. electronic boards). In addition, the tool is able to estimate the product's recyclable mass and identify those criticalities that decrease this value (e.g. material contamination or incompatibilities). Further details on this tool can be found in Favi et al. (2012) and Germani et al. (2014b), where the methodology and preliminary experimental results are presented.

A more detailed assessment of the entire product life cycle is produced by the *eVerDEE* tool (by ENEA: *Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile*). This tool is able to calculate 12 different specific impact categories (e.g. abiotic depletion, ozone layer depletion, etc.) for an advanced environmental analysis by experts and is highly useful in the final phases of the design process (Naldesi et al. 2004).

The *Supplier Web Portal* is an interface aimed towards the supply chain actors and is essentially a web portal dedicated to suppliers to offer updated and reliable data on commercial components used by the platform tools for different analyses (e.g. locations of suppliers for use in calculating the impacts related to transportation, the characteristics of energy-using components to be used by the DfEE tool, etc.).

The CBR (by *Università Politecnica delle Marche*) is a guidance tool developed for the collection and sharing of eco-knowledge. This module supports users in finding the most correct design choices for increased overall product sustainability. As depicted by the red arrow in Figure 2, the CBR tool offers continuous support during all phases of the product design and during the use of other platform tools by making available general and specific eco-design guidelines and lessons learned based on past experiences (Germani et al. 2013b; Rossi et al. 2013).

The above-mentioned tools can be grouped in different categories according to their specific objectives:

- Tools used to support simplified evaluation of product performances (*GRANTA MI™: Materials Gateway and Web BoM Analyzer*), discover the most important hot-spots, and focus the re-design strategy (see Activity A1 in Figure 4 and Section 4.3);
- Tools used to support the detailed investigation of specific product life cycle phases (*DFEE* and *LeanDfD*), verify the previously identified hot-spots, discover additional criticalities, and compare potential alternative solutions (see Activity A2 in Figure 4 and Section 4.3);
- Tools used to perform detailed LCA (*eVerdEE*) by using inventory data stored in the univocal product life cycle model (see Activity A3 in Figure 4 and Section 4.3);
- Tools used to support the implementation of specific re-design suggestions (*CBR*) for improvement of the life cycle performances;
- Tools used to support the collection of data from outside the company boundaries (*Supplier Web Portal*).

4.2. Platform users

The G.EN.ESI platform was conceived with consideration of the stakeholders working along the product development process (PDP) and includes the following:

- *Design Engineer*: Designs the product, creates the 3D models, performs the FMEA, etc.;
- *Product Manager*: Manages the product development projects, participates in design stages and design reviews, and contributes to the company's product strategy;
- *Environmental Manager*: Chooses the relevant indicators to represent the product and explains the performance of these indicators according to environmental legislation (e.g. RoHS) and standards (e.g. ISO 14062). This is a key role, particularly if the company is approaching an eco-design theme for the first time. The Environmental Manager works closely with the Product Manager, especially during decision-making activities. Through this collaboration, the Product Manager learns environmental skills such that environmental responsibilities are shared throughout the design team in the long term.

The creation of new software tools that favour cooperation among the different actors (over-the-wall approach) while addressing the different viewpoints that they hold on the product is another key aspect for implementation of the eco-design approach.

4.3. Platform use: workflow scenarios

The enterprise that owns the G.EN.ESI platform can use all of its tools to configure eco-friendly and cost-effective products and monitor how the product modifications influence these two essential objectives in real time. The G.EN.ESI platform main workflow (Figure 3) consists of three different macro-phases. The first activity (A1) is a preliminary and quick product environmental audit used to understand the hot spots, and the second activity (A2) includes a detailed analysis of the different product life cycle phases and the successive product improvements. Finally, the last activity (A3) is a detailed environmental analysis for verification of the achievement of the expected targets.

Activities A1, A2 and A3 represent the practical implementation of the main core design phase of the G.EN.ESI methodology. In particular, the design tasks included within Step 4 of the methodology are performed during activities A1 and A2, when the product is analysed from different points of view and modified for improved environmental sustainability performances. Step 5, which corresponds to activity A3, verifies that the product configuration meets the targets fixed at the beginning of the re-design process.

As depicted in Figure 3, the main users are the Designers and the Environmental Manager who use the platform tools in a practical manner during the different activities. The Product Manager does not directly use the platform tools but has the important role of managing and steering the project to reach the best feasible solution and supervise the work performed by the design team.

During A1, the Designers perform a first quick product environmental analysis using the Granta MI tool. Because this tool is a plug-in of the CAD system, the data are automatically retrieved from the CAD document, without the need for time-consuming manual inputs by the user. Even if the available information is rough and generic (e.g. tentative materials, non-definitive

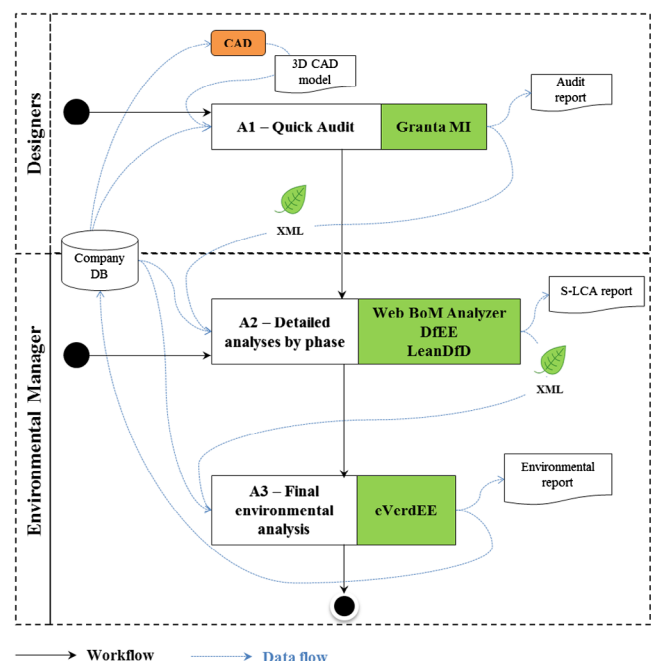


Figure 3. G.EN.ESI platform main workflow.

manufacturing processes, etc.), designers obtain from the Granta MI tool an overview of the product environmental impacts to understand the product major criticalities and arrange possible improvement actions. At the end of activity A1, the tool exports an audit report, and the results are added to the G.EN.ESI XML file, which is stored in the shared company DB (a PDM/PLM or a generic vault).

The objective of Activity A2 (see details in Figure 4) is a detailed analysis of the specific product life cycle phases using the dedicated software platform tools. The Environmental Manager, using the information from suppliers and company buyers (retrieved by means of the supplier web portal), performs the A2 related activities.

If the company has not previously performed Activity A1 within the CAD environment, the platform use begins at this step. Indeed, the product information (e.g. materials, production processes, transportation data, etc.) can be manually input in a new BoM and saved in a new XML file. Instead, if the starting point is an XML file generated during Activity A1, the web-based interface allows modification of an existing BoM, e.g. to add further components that are not modelled within the CAD model.

Because only the material selection, manufacturing and transportation phases have been previously investigated using the Granta MI tool (or the Web BoM Analyzer), the DfEE and LeanDfD tools are used at this stage to respectively detail the use and end-of-life phases. Each tool is able to extract information from the company DB and the XML exchange file with the aim of analysing specific aspects (e.g. energy consumption or carbon footprint of the use phase, recyclability rate, disassemblability of

selected target components, etc.). The Environmental Manager verifies whether the product satisfies the objectives established by the project management team at the beginning of the project. If necessary, an iterative re-design process is applied to improve the product by following the indications for best practices and eco-knowledge supplied by the CBR tool (this phase is not represented in Figure 4).

Once the redesign process reaches the targets, the modifications made in terms of materials, selected commercial components, production processes, transportation and end-of-life strategies are verified through the final environmental analysis (Activity A3 in Figure 3). The eVerDEE tool is used to obtain a final environmental report on the new product version. If the product still has residual shortfall aspects (i.e. not all fixed targets have been reached) not noted during the previous steps, further re-design activities (A1 and/or A3) are launched to reach the final version of the product, which is ready for launch in the market.

5. Case study

5.1. Case study description

A multinational corporation with a headquarters and a design department in Italy (Faber spa) was selected for implementation of the G.EN.ESI eco-design methodology and platform. Due to the introduction of the European Energy Label (Regulation (EU) No 65/2015) for cooker hoods (1 January 2015), Faber was searching for highly efficient and eco-friendly cooker hoods. The use of an eco-design platform was considered as an enabling technology to reach this objective.

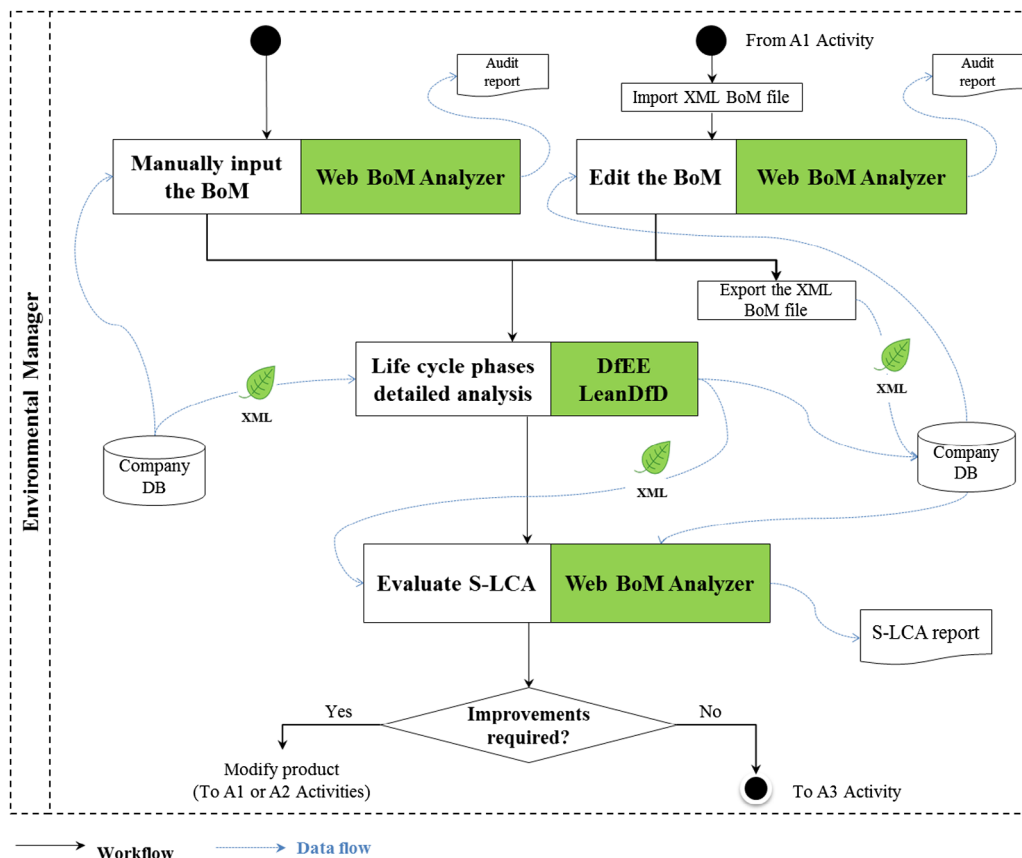


Figure 4. Detailed workflow of the A2 activity.

The testing phase involved different design and engineering departments related to product development, product innovation (research and development, R&D), product manufacturing and assembly. The products analysed in this work are domestic cooker hoods. In particular, the company selected two cooker hoods belonging to the 'T-shape' family, which are generally fixed on the wall and contain both ventilation and filtration functions (Figure 5). The cooker hood is a good example for testing the G.EN.ESI eco-design platform due to its wide variety of components (mechanical, electric and electronic) and sub-assemblies to be improved in terms of sustainability.

The G.EN.ESI eco-design platform was tested by four designers, a product manager and an environmental manager trained on the G.EN.ESI methodology. The designers were selected from a group of dozens with a preference for young engineers less than 30 years of age and with different backgrounds in eco-design. The first criterion was selected to avoid the typical resistances of end users when implementing new IT solutions (e.g. resistance to change to prevent loss of something of value, additional efforts or abilities needed for the job, etc.) and thus to limit the negative influences in the case study.

The engineers first defined the environmental hot spots (initialisation phase); second, they defined the product improvements from an environmental and cost perspective (initialisation phase); third, they re-designed the cooker hoods with the support of the G.EN.ESI platform (main core design phase, Steps A1 and A2), and finally, they conducted LCA and LCC analyses (main core design phase, Step A3). The designers were fully involved in the G.EN.ESI platform use, and the Product and Environmental Managers were only partially involved.

The test began with a one-day workshop in which researchers from Università Politecnica delle Marche, Grenoble INP and University of Bath introduced the eco-design principles and the G.EN.ESI methodology. Subsequently, the same researchers trained the testers for another day on the use of the G.EN.ESI platform and related tools. The participants simulated a complete use scenario following the G.EN.ESI methodology. In the beginning, researchers and testers jointly collaborated in the customisation of the databases for the G.EN.ESI tools, verifying the presence of the cooker hood materials (mainly stainless steels, carbon steels and plastics) and including the commercial energy-use components (lights, motors and electronic boards) for manufacture of a cooker hood.

During the test activity, the researchers supported the testers by giving advice for specific functionalities of the tools during

steps A1 and A2. User manuals and video tutorials aided the engineers during the test. Activity A3 required strong cooperation between the researchers and the Environmental Manager. The software developers were involved during the tests for bug reduction.

The test, lasted 4 months, aimed at redesign of two T-shaped models. Table 2 shows the profiles of the testers engaged.

5.2. Evaluation method

When an enterprise introduces a new design platform, it must evaluate the degree of integration of this platform with the enterprise software solutions (de Moor 2007) and the impact on the internal business processes (Häusler et al. 2009). Software assessment is a process that analyses the subjective and objective data to evaluate a tool (Bandor 2006). First, the test had the scope of evaluating the impact of the G.EN.ESI methodology and the related software platform on the traditional design process of a company. Second, the test focused on evaluation of the interoperability between the G.EN.ESI platform and the design tools as well as the interoperability among the G.EN.ESI tools. The usability validation of each tool is beyond the scope of this paper.

A questionnaire was developed for this evaluation. The questionnaire was conceived based on the existing barriers to implementation of an eco-design approach, as highlighted in the literature review (S2 and Table 1). The characteristic of the company involved in the test did not permit evaluation of barrier 6. *SME organisation* (future work). Barrier 5. *Gap between academic methods and industrial needs* can be evaluated considering the average result obtained from the case study.

The Likert scale (Likert 1932) is the method used in evaluation of the G.EN.ESI methodology and related platform and is common scale used in software evaluation (Mitchell 1992). From the original version of this scale (5 possible answers), the extreme values ('Strongly agree' and 'Strongly disagree') were removed to avoid extremist views (certain people do not accept extreme choices when there are always valid opposing views). Four answers were possible for the users: 'Disagree', 'Neither agree nor disagree', 'Agree' and 'No opinion'. The latter was included to avoid the collection of scores from testers who have not used the G.EN.ESI platform or its software tools. For each item, a 'Note' section was also available to allow users to give suggestions.

The questionnaire was conceived starting with the barriers ((1) Lack of skill and expertise, (2) Data management for environmental analysis, (3) Standardised methodology implementation



Figure 5. T-shaped cooker hoods.

Table 2. Profiles of the testers.

Tester	Education	Background	Involvement
Designer – D1	Master's degree, 25 years old, recruited two years ago as mechanical engineer	Involved in the development of new hoods and cost reduction projects, has basic knowledge in eco-design and environmental related aspects/regulations	Worked mainly with the CAD system and the software tools in the G.EN.ESI platform
Designer – D2	Master's degree, 27 years old, recruited one year ago as designer	Knows the cooker hood product and worked in cooperation with the company designers and laboratory engineers during the entire period; has basic knowledge in eco-design and environmental-related aspects	Used all software tools in the G.EN.ESI platform; actively participated during the cooker hood re-design process following feedback obtained from the G.EN.ESI platform
Designer – D3	Bachelor's degree, 23 years old, internal collaborator at the company for two months	No skills in product design (also including the cooker hood) and limited knowledge of eco-design, environmental issues, and recyclability (scholar level)	Used the G.EN.ESI platform during the thesis period with the focus of activities on LeanDFD
Designer – D4	Master's degree, 25 years old, recruited six months ago as designer	Has basic knowledge of the cooker hood; no background in eco-design and environmental related aspects/regulations	Used all of the software tools of the G.EN.ESI platform; worked in cooperation with the company designers during the entire period
Product Manager – PM	Masters Degree, 48 years old, recruited after receiving degree.	Guides cooker hood designers and is responsible for developing new products for the company; manages the entire product line life, specifies the market requirements for current and future products, and drives a solution set across the development teams; ensures that all products comply with restricted substances legislations; supports the selection and implementation of software systems and tools for reducing the energy and CO ₂ emissions of products	Has not used the G.EN.ESI platform tools but has analysed the reports for driving the PDP
Environmental Manager – EM	Master's degree, 30 years old, recruited after receiving degree	Involved in innovation product projects on blower development, noise reduction systems, and lighting systems; has knowledge of life cycle assessment (LCA), eco-design and environmental related regulations (Reach, RoHS, WEEE) and standard (ISO 14062) from previous work experiences	Continuously participated in cooker hood re-design process; managed feedback obtained from the G.EN.ESI platform

and (4) Isolated software tools/platform), and each one was associated with one or two questionnaire objectives. Each objective was associated with one or two of the evaluation scopes (as reported in Table 3):

- (1) The impact of the G.EN.ESI methodology on the traditional design process of a company;
- (2) The impact of the G.EN.ESI software platform on the traditional design process of a company;
- (3) The interoperability between the G.EN.ESI platform and the design tools;
- (4) The interoperability among the G.EN.ESI tools.

The overall questionnaire consisted of five objectives and 52 items, which represents a good trade-off between the time required for its completion (20 min as the target time) and the possibility of statistical analysis of the results (approximately ten items for each objective). The items were formulated to express both favourable/positive and unfavourable/negative attitudes towards the objective. Table 3 presents an extract of the questionnaire prepared for the users (columns 'Objective', 'Description' and 'Items').

6. Results and discussion

The following sections present the results of the test and the relative analysis related to the following:

- The impact of the G.EN.ESI methodology on the current design workflow and the inter-operability of the G.EN.ESI platform with the company design systems;
- The environmental benefits achieved after a re-design process applied to the cooker hoods using the G.EN.ESI eco-design platform.

6.1. G.EN.ESI methodology and platform evaluation

Ratings given by the users for each item were summarised in a single score to obtain an overall result that considers the different evaluation priorities (objectives) and the different score relevance given by the testers. Such a score can also be useful for future comparisons of alternative solutions.

In this analysis, the company defined a weight for each objective (Ow , from 1 to 3) in accordance with their medium-long term strategies (Table 4). An additional weight (Uw) was considered for differentiating the importance of the scores expressed by the testers. The company placed more importance on the ratings of the Product Manager and Environmental Manager (who better know the internal processes) than those of the young designers. Table 5 presents those weights in a scale from one to three.

The results obtained from the questionnaires were analysed to produce an average score for each user and objective (Equation 1), an average score for each user (Equation 2), an average score for each objective (Equation 3) and an absolute average score (Equation 4).

$$\text{Average score for the } j\text{-th objective and } k\text{-th user} = \frac{\sum_{i=1}^{N_j} R_{i,j,k}}{N_j} \quad (1)$$

$$\text{Average score for the } k\text{-th user} = \frac{\sum_{j=1}^M \left[\left(\sum_{i=1}^{N_j} R_{i,j,k} \right) \cdot Ow_j \right]}{\sum_{j=1}^M (N_j \cdot Ow_j)} \quad (2)$$

$$\text{Average score for the } j\text{-th objective} = \frac{\sum_{k=1}^P \left[\left(\sum_{i=1}^{N_j} R_{i,j,k} \right) \cdot Uw_k \right]}{\sum_{k=1}^P (N_j \cdot Uw_k)} \quad (3)$$

$$\text{Average score} = \frac{\sum_{j=1}^M \frac{\sum_{k=1}^P \left[\left(\sum_{i=1}^{N_j} R_{i,j,k} \right) \cdot Uw_k \right]}{\sum_{k=1}^P (N_j \cdot Uw_k)} \cdot Ow_j}{\sum_{j=1}^M Ow_j} \quad (4)$$

The meaning of each term in the formulas is described below.

- i : counter for the items;
- j : counter for the objectives;
- k : counter for the users;
- $R_{i,j,k}$: score for the i -th item, j -th objective and k -th user;
- N_j : number of items for the j -th objective;
- M : number of objectives (five);
- P : number of users (six);
- Ow_j : weight for the j -th objective;
- Uw_k : weight for the k -th user.

The scores assigned to the responses were the following: 'Disagree' = 2, 'Neither agree nor disagree' = 3, and 'Agree' = 4. For the items with a negative attitude towards the objective, it was necessary to reverse the score assigned to each response to add them to the positive ones.

Before analysing the obtained results, the enterprise identified the following segments for the average score in accordance with the internal procedures for benchmarking of software tools:

- **Average score ≤ 3 :** The platform does not meet the minimal requirements and must be strongly modified and improved. The problematic aspects require important improvements to the platform;
- **$3 < \text{Average score} \leq 3.5$:** The platform meets the minimal requirements, but further improvements might be useful. The users are fairly satisfied, but it is important to implement their recommendations to solve the most important issues;
- **$3.5 < \text{Average score} \leq 4$:** The platform fully satisfies the requirements, and excellent satisfaction is recognised. No important issues have been identified such that the platform and software tools are ready for use within a company.

The above-presented approach was used to evaluate the G.EN.ESI platform as a whole in terms of its integration with the company software tools for an assessment of its degree of maturity. The users involved in the evaluation were the same as those involved in the test of the G.EN.ESI platform presented in the previous section. Questionnaires were submitted to the users after extensive use (more than 8 months) of the platform. Each user gave feedback (Table 6) only for the platform modules used

(4) – Standardised methodology implementation (LCA, etc.)	(4) Impact on the traditional design process	Impact of the proposed methodology and platform on the standard design workflow. This performance can be evaluated in terms of time for design review and design changes required by the company to implement the proposed eco-design methodology and platform. For certain enterprises, a high impact means a great opportunity for improvements, but for others, it means a step too high to be overcome	#1 and #2	The time required during the PDP using the G.EN.ESI platform is acceptable and comparable to the time of a standard design process The additional skills required to use the platform are acceptable and are mainly compatible with existing employee skills The assessment of environmental aspects using the G.EN.ESI platform has been achieved with an acceptable and limited modification relative to the traditional design workflow	Positive
(1) – Lack of skill and expertise (environmental experts)	(5) Training activities	Evaluation of training required before implementing the methodology and use of the platform. This step allows estimation of the initial investment for implementing the proposed eco-design methodology and platform	#1 and #2	The time required for training on all tool functionalities is comparable to the training for other software tools used within the company The training activities are not too specific and can be followed by a wide range of company employees The introduction in eco-design issues methods and tools determine advantages in terms of environmental awareness The language and the support materials used during the training activities are adequate and easily understandable	Positive

and for the objectives for which the individual was in the position to give feedback, which is why certain N/A scores occur. Table 6 contains the average score for each combination of user and objective (Equation 1), the average score for each user (Equation 2), the average score for each objective (Equation 3) and the absolute average score (Equation 4). For each score, the table also contains the standard deviation (round brackets).

From analysis of Tables 6, 7 and 8, the results can be summarised as follows:

- All average scores given by the testers for each objective are greater than 3. According to the previous segments, this means that the platform guarantees the minimal requirements. Users wrote 'Disagree' for approximately 6% of the items, as depicted in Figure 6 (e.g. completeness of supporting materials, necessity for first setting up the database, etc.). Most of the users (57%) wrote 'Agree' with the items.
- The average score (3.53) is within the third segment, i.e. 3.5–4 (Table 6), such that the G.EN.ESI methodology and platform globally satisfy the requirements of the enterprise.
- The analysis of the evaluation scopes (Table 7) highlights that only '3. *The impact of the G.EN.ESI methodology on the traditional design process of a company*' is located outside of the third segment (score 3.44). This item was primarily penalised by the scores obtained for objectives '4. *Personnel to involve*' (3.29) and '3. *Impact on the traditional design process*' (3.44). The lack of internal experts in environmental-related topics requires specific internal training for the engineers involved during the PDP. In the case of a missing internal Environmental Manager, the company must involve an external consultant.
- By analysing the suggestions given by the users (*Note* section of the questionnaire), it was possible to identify an improvement to the G.EN.ESI software platform. The presence of separated but inter-operable tools makes their use somewhat difficult for the users (e.g. different user interfaces).
- The G.EN.ESI methodology and platform obtained good scores (third segment) of 3.56 and 3.70, respectively, for the barriers '4. *Isolated software tools/platform*' and '2. *Data management for environmental analysis*' (Table 8). This result is a direct consequence of the inter-operable architecture of the G.EN.ESI and the *G.ES.ESI XML* file for sharing of data among the software tools. The information smoothly flows among the tools, thus avoiding repeated manual editing. Moreover, the database synchronisation avoids data duplication and possible related errors. The 'integrated and interoperable' approach of the G.EN.ESI platform favours companies in its use because it does not appear as a set of isolated tools. In this manner, the gap between academic methods and industrial needs is mitigated because users can follow the classical design workflow without drastic deviation from the standard practice. This is a clear advantage, especially for SMEs that usually do not have a structured organisation and the necessary availability of resources (both economic and human) to

Table 4. Weights for the objective (*Ow*).

Objective	Weight	Reason
Data integration between traditional design and G.EN.ESI tools	3	The company required that all software systems that elaborate product information must have an interface for integration with CAD and PDM systems
Personnel to involve	3	The company did not foresee the engagement of new employees for management of the product environmental aspects
Inter-operability	3	The company required an high level of data exchange among the software tools to avoid data duplication or misalignments between product information and product revision
Impact on the traditional design process	2	The company has mapped the PDP in terms of activities, actors and documents using a workflow management system. The company is open to acceptance of a low to medium level of impact changes on this process
Training activities	1	The company regularly plans training sessions for technical employees to increase their awareness of environmental and economic aspects

make the changes generally required during the implementation of eco-design approaches.

- The barriers '1. Lack of skill and expertise' and '3. Standardized methodology implementation' both received an average score of 3.44. This result suggests the need for future work related to the G.ES.ESI methodology and platform (presented in the conclusions). However, this score can depend on external issues (not related to G.EN.ESI), such as the eco-design background of human resources and difficulties in re-organising them, lack of multifunctional nature of the staff, lack of cooperation between departments, and scarcity of compulsory requirements.
- The average standard deviation weighted using the users and objective weights is 0.60. Cronbach's Alpha was calculated for each objective for estimation of the test reliability. The values achieved (data integration = 0.0, personnel to involve = 0.2, inter-operability = 0.1, impact 0.8 and training = 0.5) determine the need to increase the number of users (and number of enterprises) to involve to achieve an improved statistical result.

6.2. Environmental benefits achieved for the cooker hoods

During the testing period, the engineers used the G.EN.ESI eco-design platform first to define the environmental hot-spots

and second to re-design the cooker hoods in accordance with the workflow presented in Section 4.3. The platform supported the users during the re-design process of the two cooker hoods. In particular, the platform aided the Designers, Environmental Manager and Product Manager in funding the product criticalities (hot spots) and related eco-design guidelines (activity A1), evaluating design alternatives, and calculating the environmental benefits achieved at the end of the re-design process (activities A2 and A3).

The most important hot spots highlighted were the following:

- High energy consumption of the motor and lamps. The considered models belong to the 'C' class for fluid dynamic efficiency and lighting efficiency. The firm intended to increase the cooker hood class from 'C' to 'A' according to Regulation (EU) No 65/2015. The hot spot was calculated using *GRANTA MI™: Materials Gateway* and *DfEE*.
- Low disassemblability of the electric motor due to non-standardised connections and a high number of threaded liaisons (disassembly time greater than 2 min). The hot spot was calculated using *LeanDfD*.
- No recyclability of the front panel and the cooker hood chassis due to glued parts. The hot spot was calculated using *LeanDfD*.

Table 5. Weights for the users (*Uw*).

Tester	Weight
Designer – D1	2
Designer – D2	2
Designer – D3	1
Designer – D4	1
Product Manager – PM	3
Environmental Manager – EM	3

Table 7. Average scores for the evaluation scopes.

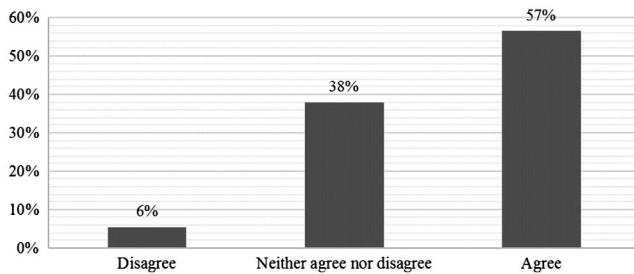
Evaluation scope	Equation	Score
Impact of the G.EN.ESI methodology on the traditional design process of a company	$\frac{\text{Objective 2} + \text{Objective 4} + \text{Objective 5}}{3}$	3.44
Impact of the G.EN.ESI software platform on the traditional design process of a company	$\frac{\text{Objective 1} + \text{Objective 4} + \text{Objective 5}}{3}$	3.53
Interoperability between the G.EN.ESI platform and the design tools	Objective 1	3.56
Interoperability among the G.EN.ESI tools	Objective 3	3.70

Table 6. Results of the G.EN.ESI methodology and platform evaluation: average score and standard deviation (within round brackets).

Objective	D1	D2	D3	D4	EM	PM	Average score and standard deviation for each objective
(1) Data integration between traditional design and G.EN.ESI tools	3.40 (0.89)	3.60 (0.55)	N/A	3.60 (0.55)	3.60 (0.55)	3.60 (0.55)	3.56 (0.61)
(2) Personnel to involve	3.00 (0.71)	3.20 (0.84)	N/A	3.20 (0.84)	3.60 (0.55)	3.20 (0.84)	3.29 (0.74)
(3) Inter-operability	3.75 (0.52)	3.25 (0.55)	N/A	3.50 (0.82)	4.00 (0.41)	3.75 (0.52)	3.70 (0.52)
(4) Impact on the traditional design process	3.40 (0.55)	3.40 (0.55)	N/A	3.80 (0.45)	3.80 (0.45)	3.00 (0.71)	3.44 (0.55)
(5) Training activities	4.00 (0.00)	3.43 (0.53)	3.75 (0.50)	3.75 (0.50)	3.57 (0.53)	3.29 (0.76)	3.58 (0.50)
Average score and standard deviation for each user	3.43 (0.65)	3.34 (0.61)	3.75 (0.50)	3.57 (0.68)	3.70 (0.51)	3.41 (0.66)	3.53 (0.60)

Table 8. Average scores for the barriers in implementation of an eco-design approach.

Barrier	Equation	Score
(1) Lack of skill and expertise (environmental experts)	$\frac{\text{Objective 2} + \text{Objective 5}}{2}$	3.44
(2) Data management for environmental analysis (design phase)	Objective 3	3.70
(4) Standardised methodology implementation (LCA, etc.)	Objective 4	3.44
(5) Isolated software tools/platform	Objective 1	3.56

**Figure 6.** Score breakdown.

The first environmental criticality was solved following the specific guideline supplied by the *CBR tool*: ‘opt for high efficiency component’, which led to the use of a brushless motor in place of an induction motor and LED lamps in place of halogen lamps (Figure 7). Using the *DfEE tool*, the designers and the environmental manager were able to estimate a 55% reduction in energy consumption and CO₂ emission (average value for the cooker hood models).

The second hot spot was solved following the guidelines supplied by the *CBR tool*: ‘minimize component number’, ‘realize a correct selection of fasteners’, ‘use connection elements of similar dimension in order to minimize the number of tools needed for disassembly’, ‘use easily detachable connections’ and ‘ensure easily visible access to connections for disassembly’. These items led to the use of clips for coupling of the two blower components and joining of the four electronic boards into a single unit (a

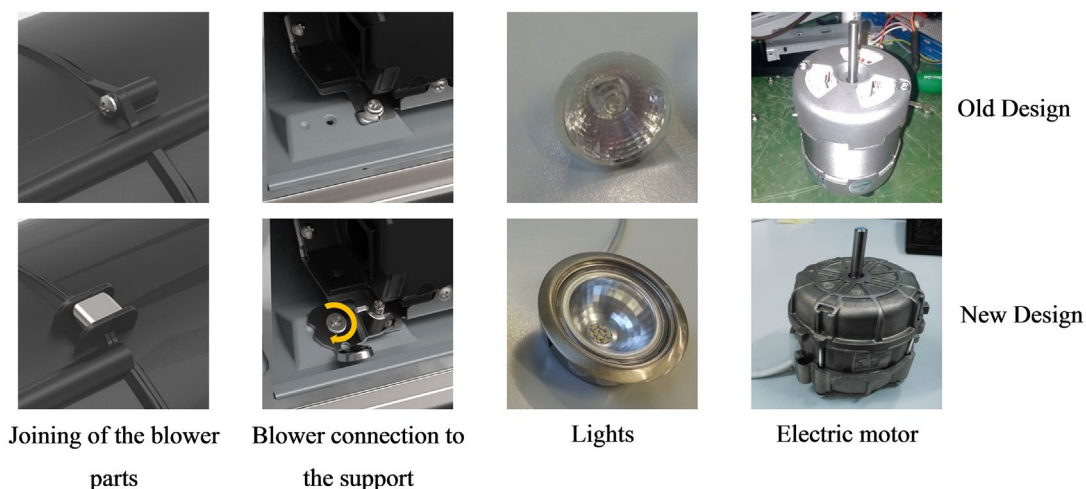
complete re-design of the electronics components was necessary). Using *LeanDfD*, the designers found the best solution in terms of disassemblability. A strong reduction in disassembly time was achieved for the target components (electric motor: -19%, transformer: -27%). Figures 7 and 8 show the re-design solutions adopted for the blower and the overall disassembly advantages for the main components of the cooker hood.

The last hot spot was solved following the guidelines ‘minimize material variety and select the same material for different parts where possible’, ‘select materials with a high level of recyclability’ and ‘avoid the use of adhesive’. The implementation of such guidelines led to the selection of a different material for the frontal panel. Poly-methyl-methacrylate (PMMA) was chosen in place of glass because it can be screwed rather than glued. Moreover, galvanised steel was chosen in place of stainless steel for the internal components (e.g. box of the blower system). *GRANTA MI™: Materials Gateway* supported designers in searching and comparing different materials with consideration of several chemical, physical, economic and environmental parameters. These changes determined an increment of the overall recyclability of 10% (value calculated by *LeanDfD*).

During activity A3, the Environmental Manager used *eVer-dEE* for two LCA analyses (one for each cooker hood model). The average environmental benefits of the re-designed products compared with the original ones were measured using the following indicators: consumption of mineral resources (-20%), consumption of renewable and not-renewable energy (-55%); climate change (-50%), ozone layer depletion (-55%) and acidification (-52%). Further details are available in (Mengarelli et al. 2014).

7. Conclusions

This paper presents the G.EN.ESI eco-design methodology and platform (with inter-operable eco-design software tools) and demonstrates its usefulness in supporting the re-design of a mechatronic product. The proposed case study, which was realised in collaboration with a leading multinational company in the household appliances sector, focused on the improvement of two domestic cooker hood models with the final objective

**Figure 7.** Cooker hood re-design solutions for the blower, lighting system and electric motor compared with the original designs.

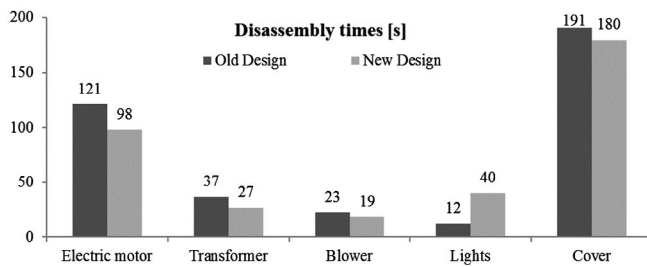


Figure 8. Comparison of the disassembly times between the old and new design for a one-cooker hood model.

of increasing their sustainability in accordance with the related energy label regulation (Regulation EU No 65/2015). A more efficient electric motor (brushless vs. induction) and lighting system (LED vs. halogen) were adopted in both cases. Because the geometry of the blower system is the same for the analysed cooker hood models, the same solution was used in both models. The other solution (PMMA vs. glass frontal panel) was adopted only for the model that adopted this original design solution.

In-depth experimentation was conducted to evaluate the G.EN.ESI methodology and platform in different phases of the product re-design process. At the end of the cooker hood re-design process, a questionnaire was submitted to the involved engineers for evaluation of the platform use. After analysis of the quantitative results and the qualitative feedback, the authors obtained the average and weighted score of 3.53 (Likert scale from 2 to 4). This value, which belongs to the segment 3.5–4, states that the platform satisfies the requirements of the enterprise involved in the test. However, because this value is close to the lower threshold, further optimisations are required to increase the integration and reduce the impact. The low value of Cronbach's Alpha should be investigated by enlarging the number of testers, such as that of the enterprises.

The main limitations, as highlighted by the questionnaire analysis, are first related to the impact of the G.EN.ESI eco-design methodology and platform in terms of required changes to the current PDP (related score = 3.44) and new personnel to involve or to train (related score = 3.29). Second, the presence of separated but inter-operable tools makes their usage somewhat difficult for the users.

The main conclusion of this paper is that the G.EN.ESI software platform allowed implementation of the G.EN.ESI eco-design approach within the design department of a manufacturing company, thus increasing the environmental sustainability of its products (overall environmental impacts, recyclability and energy efficiency). The benefits supplied by the G.EN.ESI platform were confirmed by the questionnaires presented in the previous sections, which evaluated the impact on the internal processes and integration with the enterprise software tools. The results demonstrated the ability to overcome two important barriers (4. *Isolated software tools/platform* and 2. *Data management for environmental analysis*) for the implementation of eco-design tools in design practice.

In the context of an eco-design software platform, the step beyond consists of the development of a univocal graphical user interface (GUI) to integrate the G.EN.ESI platform tools into

a single workbench while maintaining the ability to efficiently exchange data with the standard design tools (e.g. CAD, PDM and PLM systems). This 'hard' integration is expected to positively contribute to overcoming the limits of the 'soft' integration (presented in this paper), thus improving the user experience and creating a more transparent workflow within the platform. Moreover, a single workbench means that the company has to introduce only one system, meaning fewer changes to the PDP and fewer issues in integration with the enterprise software systems. Future work consists of testing G.EN.ESI in SMEs to evaluate its ability to overcome the barrier of 'SMEs organization'.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the European Community's 7th Framework Programme within the G.EN.ESI project [NMP.2011.3.1-1-280371], www.genesi-fp7.eu.

Notes on contributors

Claudio Favi is a research fellow at the Department of Industrial Engineering and Architecture, Università degli Studi di Parma, (Italy). His research topics include eco-design methods and tools, lifecycle methodologies applied to the product design and development and design for X (Assembly, Disassembly, Manufacturing and Cost) methods.

Michele Germani is a full professor of Design tool and Methods for Industrial Engineering at the Department of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche (Italy). He currently focuses his research activities on advanced virtual prototyping systems, design to cost and total cost of ownership, eco-sustainable product design and manufacturing, human-centred design & manufacturing.

Marco Mandolini is a research fellow at the Department of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche (Italy). His area of research includes eco-design, design for X (end-of-life, cost and manufacturing), multi-objective optimization methods and design of biomedical devices.

Marco Marconi is a research fellow at the Department of Economy, Engineering, Society and Business Organization, Università della Tuscia (Italy). His area of research includes lifecycle assessment, eco-design, design for disassembly, tools and methods for end-of-life management and sustainable manufacturing.

ORCID

Claudio Favi  <http://orcid.org/0000-0002-7176-0731>

Michele Germani  <http://orcid.org/0000-0003-1988-8620>

Marco Mandolini  <http://orcid.org/0000-0003-0962-5982>

Marco Marconi  <http://orcid.org/0000-0002-5677-1459>

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