



HAL
open science

Leading LCA result interpretation towards efficient ecodesign strategies for Power Electronics: the case of DC-DC buck converters

Li Fang, Ernesto Quisbert-Trujillo, Pierre Lefranc, Maud Rio

► To cite this version:

Li Fang, Ernesto Quisbert-Trujillo, Pierre Lefranc, Maud Rio. Leading LCA result interpretation towards efficient ecodesign strategies for Power Electronics: the case of DC-DC buck converters. 31st CIRP Conference on Life Cycle Engineering (LCE 2024), Jun 2024, Turin, Italy. pp.731-736, 10.1016/j.procir.2024.01.102 . hal-04626742

HAL Id: hal-04626742

<https://hal.science/hal-04626742>

Submitted on 27 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Leading LCA result interpretation towards efficient ecodesign strategies for Power Electronics: the case of DC-DC buck converters

Li Fang^{a,b,*}, Ernesto Quisbert-Trujillo^a, Pierre Lefranc^b, Maud Rio^a +^aUniv. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 38000 Grenoble, France^bUniv. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, F-38000 Grenoble, France* Corresponding author. Tel.: +336-0189-5428; E-mail address: li.fang@grenoble-inp.fr

Abstract

Power Electronics (PE) endorse a critical role for ensuring energy transitions targeting carbon neutrality in 2050. Design strategies based on Life Cycle Assessment (LCA) have recently been introduced into the PE field to ecodesign Power Electronics Converters (PEC). LCA is a multi-criteria approach aimed at assessing environmental impacts at various stages of the product lifecycle, and its use is widely spread among scientific and ecodesign communities. Nevertheless, interpreting LCA results for PECs is challenging because of the complexity of PE (as systems with multiple subsystems and components) and multicriteria aspects of LCA. Previous research suggests a functional-analysis-based perspective to simplify the lifecycle modeling of electronics and integrate comprehensively LCA outcomes with the Product Development Process (PDP) and ecodesign. Inspired by this original proposition, this study derives a novel framework that dissects and guides the interpretation of LCA results of PECs in order to identify environmental hot spots and establish operational ecodesign strategies. The proposed framework helps to reveal the cause-and-effect relationships between the technical characteristics of hardware solutions and the prospective environmental consequences that may arise to PE designers. A case study of a DC-DC buck converter is presented to debate the effectiveness of this proposed framework in PEC with designers.

© 2024 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the scientific committee of the 31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Keywords: Design for environment, Power Electronics, Eco Design, Life Cycle Assessment, Product Development Process

1. Introduction

Power Electronics (PE) technologies endorse multiple roles in energy transition [1], such as supporting renewable energy system integration, or enabling efficient intermittent energy usage [2]. Life Cycle environmental impact Assessment (LCA) conducted on PE systems shows their significant contributions for their manufacturing and the end-of-life treatment they require once broken [3]. Despite the efforts conducted by the micro-electronic industry, the processes involved to produce high-tech electronic components, such as electronic chips used in PE, are highly energy and resource intensive [4]. In addition, the effect of landfill and incineration processes of discarded PE products release a significant amount of toxic contaminants into

the environment [3]. Thus, PE product's lifecycle environmental impacts should be systematically minimized and their design should support repair, maintenance, remanufacturing and intensive recovery resource recycling [5]. Despite the latest publications about PE systems LCA [6], interpreting LCA results for a PE designer remains challenging [7]. In manufacturing companies, product designers are often unable to address environmental issues by themselves (without being helped with a LCA or ecodesign expert) due to knowledge gaps and lack of resources [8]. They usually need support from a lifecycle engineer who performs LCA and provides them with specific guidelines. Still, product designers would not be familiar with LCA calculation, or modeling methods, or terminologies [8]. The environmental indicators

need to be “translated” into common engineering language to provide specific design guidelines. For example, reducing mass or lowering power make sense to PE designers, who feel comfortable to make changes in that scope [7]. However, in the PE industry, this “translation process” presents a significant challenge for lifecycle engineers with no expertise in PE products. Such a process is indeed much more complex than reducing mass or change a “hotspot” component to another. PE system comprises multiple subsystems and numerous components lifecycles. In addition, modeling the use phase and the end-of-life treatments operating on a territory are challenging.

Quisbert-Trujillo, E. et al. (2020) [9], argued that every electronic component contributes to both the Functional Unit (FU) and the environmental impact of electronic products. Indeed, conducting a functional analysis (FA) to establish links between technical characteristics of electronic components, functions and environmental impacts can facilitate the development of pertinent ecodesign strategies [8]. As the FU is at the core of any LCA, in this paper, a FA-based approach to establish the cause-and-effect link between technical parameters and environmental indicators has been proposed. This approach aims to effectively support lifecycle engineers and PE designers in communicating with the PE product design and develop ecodesign strategies. The following research question guides this paper:

How to facilitate LCA result interpretation for PE designers to develop efficient PE ecodesign strategies during the design process development?

The formulated hypothesis is that functional analysis can be used as a vector of integration of environmental lifecycle constraints into PE design process.

In this paper, building upon the current state of the art in coupling FA with LCA (section 2), a methodology based on the FA to interpret LCA results and develop ecodesign strategies for PE (section 3) has been proposed. The added value of this methodology was criticized to improve the capacity of PE designers to ecodesign a DC-DC buck converter through a real design case study (section 4). The discussion critically outlined the efficiency and limitations of this methodology (section 5). In conclusion, the paper offers a summary and the perspectives for future research (section 6).

2. State-of-the-art research

2.1. Role of Functional Analysis in product ecodesign decision-making

Referring to the value management and analysis standards [9], value is the measurement of stakeholders need satisfaction of a product, project or organization, in regard to the resources required [10]. FA methods [11] are based on the principles of identifying and quantifying “techno-centred” needs of product functionality needs throughout the lifecycle, which are determined by defining the desired functionality in the product lifecycle [12]. Design solutions are then compared given the ratio between the value satisfied and the resource required [13]. The FA approach can be combined with LCA methods as early as possible during the design process. Six propositions are formulated in [14] to allow lifecycle engineers to communicate environmental impacts quantification generated by technical

solution choices. Sharing such environmental information, as precisely as possible, is crucial to influence design solutions decision-making. In particular, functional requirements and lifecycle inventories can be coupled: tracing resources and energy flows input and output in air, water and soils, involved satisfying a function. The originality of the research presented in this article is to join the functional architecture of PEC to environmental impact indicators during the PDP together to support the ecodesign process.

LCA result interpretation in a process of ecodesign supposes to understand the product environmental impact allocation [15] in regard to the technical performance of design alternatives [16] to improve the product’s lifecycle technico-environmental performance [17]. The future potential circular design function failure identification participates to handle the risk of adopting circular design scenarios, such as reuse, repair, remanufacture design strategies for PE systems [18].

2.2 Application of Functional Analysis on LCA Interpretation

Previous research focused on praxis [19] reveals the fundamental role of FA for electronic design. Starting from Voice of Customers (VoC), engineers translate user requirements into primary and secondary functions, which are then analysed from a hardware perspective. This means that FA is coupled with a technical analysis, in which specific capacities of electronic components for fulfilling specific functions are identified. Following [14] recommendations for merging LCA with FA in electronics, Quisbert-Trujillo, E., et al. [8] argues to focus on each electronic component contributing to the FU causing environmental impact hotspots. A pair of interrelated concepts (functions and capacities) linked to electronic components is proposed, to model the lifecycle of electronic systems, and support ecodesign.

3. Proposal for a Functional Analysis-based methodology for PE ecodesign strategies development

Considering the opportunity addressed in the previous section, this research proposes to apply a functional architecture analysis to support LCA result interpretation of PE designer activity, and, eventually, ease PE designers to ecodesign their product. The functional architecture is illustrated in Fig. 1. By discretizing the Functional Unit into functional blocks of primary, secondary (etc.) levels, linked to technical constraints, through a tree-diagram. Each functional block is connected with a component block that translates the required technical constraints into the technical parameters, and from which can be estimated some environmental impacts.

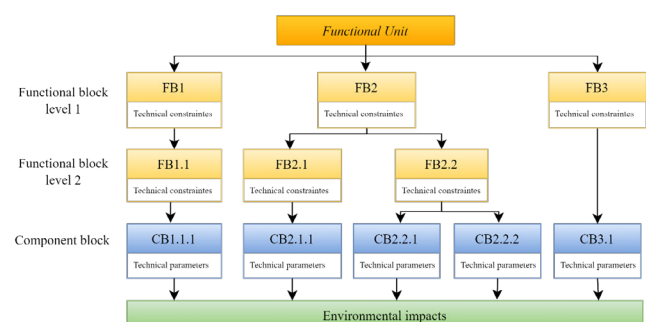


Figure 1 Functional architecture coupled with technical parameters and environmental impact indicators inspired by [18]

Based on this functional architecture coupled with technical parameters and environmental impact indicators, a methodology for PE ecodesign strategies development is established. This methodology comprises four steps: (1) establish functional architecture coupled with environmental indicators, (2) identify the main critical technical parameters, (3) elaborate a design strategy, (4) evaluate qualitatively the technico-environmental performance of the design choices made. This proposition has been experimented through several workshops involving two lifecycle engineers and a PE product designer. Each step of this process is described in the following sections.

3.1 Coupling the functional architecture with environmental indicators

The functional architecture of the system is firstly developed in collaboration between the PE designer and the lifecycle engineer. Using the Functional Analysis System Technique (FAST), the PE designer assists the lifecycle engineer in breaking down the converter system into functional blocks across multiple system levels. Then, the hardware components were associated with the corresponding functional blocks. The PE engineer clarifies the technical constraints imposed by these functional blocks and the technical parameters of the hardware components selected. Subsequently, the lifecycle engineer associates the LCA results with each functional block.

3.2 Critical technical parameters identification

By comparing environmental impacts of the functional blocks in each system level, the critical functional blocks and related hardware component blocks are targeted. This process helps to identify the technical parameters that require reconsideration while still adhering to the technical constraints.

3.3 Strategies elaboration

Ecodesign strategies are developed to optimize the identified technical parameters of the functional blocks through a process of idea divergence and convergence involving workshop participants.

In the phase of idea divergence, participants discuss and elaborate on potential ecodesign strategies for each critical functional block by referencing the R-strategy options: "rethink," "reduce," "repair," "reuse," "repurpose", and "recycle"[20]. The PE-adapted circular ecodesign guidelines are provided to assist participants in anticipating the requirements of each strategy on the design and their potential environmental impacts during the whole lifecycle. These guidelines are divided into three parts: R-scenario description, methods for estimating potential lifecycle environmental impacts, and design constraints.

For instance, if the strategy of "repurposing electronic components in the functional block i is considered, the guideline associated is as below:

(A) Scenario description: electronic components designed for repurposing can be reused in another application after their initial use. This is achieved through a repurposing process involving disassembly, cleaning, diagnostics, transportation,

and reassembly" [16]. Analytical equation for environmental impacts estimation adapted from [21]:

$$B_i = \frac{1+(u_i-1)(1-x_i/100)}{u_i} * (B_{mat_i} + B_{man_i} + B_{rpp_i} + B_{EoL_i}) + B_{use_i}$$

Notations:

- B_{mat_i} , B_{man_i} , B_{EoL_i} , B_{rpp_i} , B_{use_i} , represent the environmental impacts generated by the functional block "i" for each lifecycle stage, per unit of usage. The steps to include for estimating the potential environmental impacts in case of repurposing process are: disassembly, cleaning, diagnostics, transportation, and reassembly.
- u_i represents the maximum amount of usage cycles that components in the functional block "i" can withstand.
- x_i signifies the percentage of the functional block "i" that can be efficiently repurposed within the loop.

(B) Design constraints encompass the following factors:

- u_i - associated with the component(s) usage intensity and Mean Time Between Failure (MTBF) data within the FU.
- x_i - qualitatively linked to the ease of nondestructive disassembly of components. This ease depends on factors such as soldering points, soldering techniques, desoldering tools, etc. [22]. Empirical data from product repair practitioners should be consulted to define this factor.

3.4 Qualitative evaluation

In the last step, participants finalize the ecodesign strategies by converging ideas and excluding non-promising strategies. A quantitative evaluation is conducted by considering four criteria: the environmental aspects (related to each indicator), technical aspects (relative compliance with functional requirements and compatibility between strategies), economic aspects (relative adherence to the economic budget), and time aspects (relative adherence to the time budget).

4. Case study

This methodology was applied to a concrete case study, aiming at ecodesigning a DC-DC buck converter, at the G2ELab electrical engineering laboratory in France. This converter is a prototype designed and manufactured by a PE engineer, and used for educational purpose in an electrical engineering school. The system is used as a demonstrator to illustrate the functionality of a buck converter and the control law design (Fig. 2).

The LCA of this converter was conducted by a lifecycle engineer using the EIME© software, associated with relevant electronic databases (CODDE® 2023-02), to model the

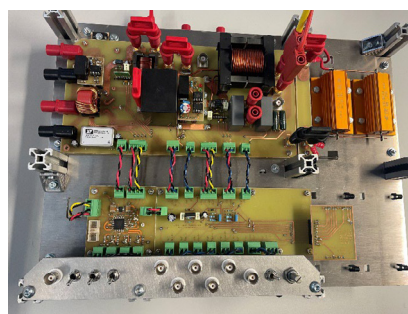


Figure 2 DC-DC buck converter

lifecycle inventory of the buck converter and estimate the potential environmental impacts throughout its lifecycle. This analysis was performed using the midpoint impact indicator set known as "Indicators for PEF EF 3.0." The chosen FU was "to demonstrate the function of the 100 W DC/DC buck converter over 25 school years for 5 pairs of students (equivalent to 16 hours and 12 minutes of usage per year)". The hypothesis made for the maintenance phase is that all active components are estimated to have a 10-year lifetime and will need to be replaced twice during their usage. This use case is totally different from an equivalent buck converter industrial application usage, usually functioning all day long and not designed for being manipulated with students.

The sixteen environmental indicators chosen were normalized using the global normalization factors for the Environmental Footprint as proposed in the technical report of the Joint Research Centre in 2017 [23]. The LCA results (Fig. 3) obtained, show that the resource, minerals and metals (kg SB eq.) use, the ecotoxicity, and the freshwater (CTUe) indicators, are contributing to more than 80% of the normalized impact over the entire lifecycle of the buck converter. A low contribution to the total impact does not necessarily mean that the impact category is not important, because normalized indicators indicate the contribution of the buck converter to a specific impact category (e.g. climate change, eutrophication) in comparison to a reference value. The reference value represents the total global impact for that specific impact category. Ant this total impact can have significant consequences on the environment. A relatively lower contribution to one category compared to others does not necessarily imply a low impact. Therefore, in addition to resource use, minerals and metals (kg SB eq.) and ecotoxicity; freshwater (CTUe), climate change (kg CO₂ eq.) and water use (m³) have been also included as relevant indicators for ecodesign the buck. Such indicators are indeed considered significant for the ecodesign of electronic products (e.g. [4][23][24]).

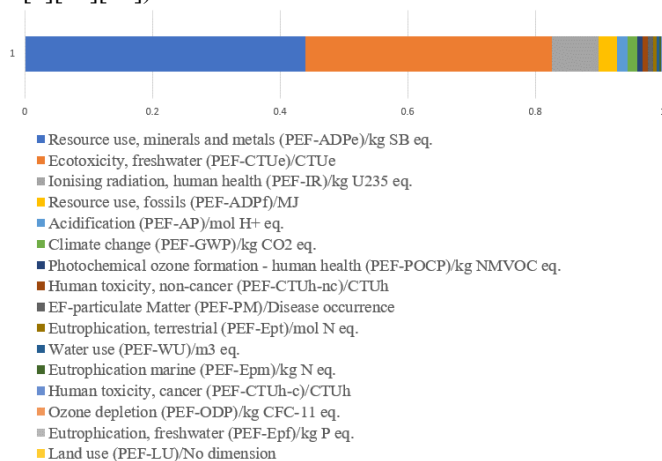


Figure 3 Proportional estimation of normalized environmental impact indicators throughout the entire lifecycle of the DC-DC buck converter

The PE designer and the lifecycle engineers collaborated in this case study to develop ecodesign strategies for improving the environmental performances of this buck-prototype. The objective addressed to the buck designer was to reduce minerals and metals (PEF-ADPe/kg SB eq.) resources use, and minimize the ecotoxicity, the freshwater (PEF-CTUe/CTUe) and water use (PEF-WU/m³), as well as reduce climate change

(PEF-GWP/kg CO₂-eq.) contributions, in priority over the entire lifecycle without causing significant adverse effects on other indicators.

Three workshops, each lasting three hours, were conducted with the PE converter designer (not skilled in ecodesign), and two authors of this paper, who participates as "lifecycle engineers". The primary focus of this study is on the interpretation of LCA results and the elaboration of ecodesign strategies. The implementation of these strategies is outside the scope of this paper, and will be considered in our future work.

4.1 Establish functional architecture coupled with environmental indicators

The lifecycle engineers and the PE designer conducted the Functional Analysis System Technique (FAST) analysis together. At this step the functional blocks at different system levels are identified, thereby establishing the functional architecture of the converter. Subsequently, lifecycle engineers could link environmental indicators to the functional blocks at each system level.

4.2 Critical technical parameters identification

Thanks to the functional architectural impact-model established, the hotspots in the functional architecture are easily identified, by analyzing the contributions of the functional blocks for each environmental impact indicator across various stages of the product's lifecycle. For instance, in the manufacturing stage, the hotspots contributing to climate change/kg CO₂eq and resource use, minerals and metals/kg SB-eq., within the functional architecture are illustrated in Fig. 4 and Fig. 5.

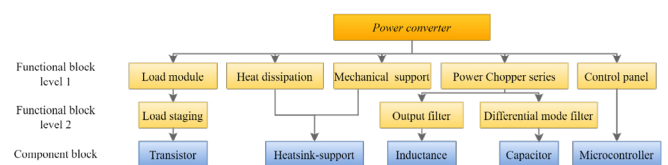


Figure 4 Critical functional architecture that contributes to more than an 80% impact on climate change/kg CO₂-eq established during workshops.

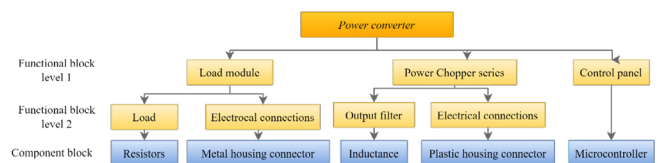


Figure 5 Critical functional architecture that contributes to more than an 80% impact on resource use, minerals and metals/kg Sb-eq established during workshops.

For different environmental indicators, the critical functional blocks and component blocks vary, as can be seen in these two examples. This way of presenting the critical functional architecture provides a diverse perspective across the selected environmental indicators. During a redesign workshop, the PE designer shows his ability to address different functional blocks in order to mitigate the various environmental impacts generated by design choices. Taking the example of a hotspots analysis process for reducing the impact on climate change/kg CO₂-eq.: at the system level, the critical functional blocks of the buck contributing to more than 80%

impact on climate change/kg CO₂-eq were identified quickly. Critical blocks were respectively identified at the subsystem levels, and finally the impactful components were pointed out. The technical parameters of the components that needed to be optimized were then highlighted, along with the technical constraints that must be respected, as illustrated in Fig. 6 on an example of a transistor. This transistor is used in the load module of the buck to perform the function of load staging. This example shows the cause-effect chain in which electrical constraints drive the sizing of technical parameters, which in turn determine hardware selection. Specific technical parameters that require optimization are emphasized, such as voltage breakdown and average current ratings. Additionally, this illustrates the environmental impacts generated by packaging technology choices, associated origins, and the mass of the selected hardware. Mathematical expressions that elucidate the influential factors determining environmental impacts are provided for each lifecycle stage, as follows:

Notations:

- Bxx_{i,j} is the environmental impact (per category) of component j in functional block i in each lifecycle stage.
- LC_{ixx,i,j} is the corresponding intermediary flow in the lifecycle database.
- Mass_{i,j} is the mass of component j in Functional Blocks i.
- EoL_i is the corresponding end-of-life process in the lifecycle database.
- MF is the maintenance frequency.

Mathematical expression:

- (1) Manufacturing: Bman_{i,j}=f(LC_{iman,i,j}, Mass_{i,j})
- (2) Transportation : Btrans_{i,j}=f(Trans_{i,j}, Mass_{i,j})
- (3) Use: Buse_{i,j}=f(Power/W,worktime/h)
- (4) Maintenance: Bmain_{i,j}= MF x f(Btrans_{i,j}, Bman_{i,j},Bmain_{i,j})
- (5) End of life: Beol_{i,j}=f(Eol_i, Mass_{i,j})

This example focuses on a hotspot analysis process aimed at reducing the impact on climate change (in kg CO₂eq.), but the other four additional hotspot indicators associated with this component have also been analyzed. The buck designers and the lifecycle engineers need this multi-criteria vision to identify the potential environmental transfers that could appear during the redesign, by highlighting the contributions of this component to specific lifecycle stages across different impact categories.

4.3 Strategies elaboration

All participants used the PE ecodesign strategy development template to discuss potential ecodesign strategies for each targeted functional block. For example, in the functional block of “load staging” in the “load module”, it was determined that the component “MOSFET transistor” (Reference IXFN180N20 - Packaging SOT227) is the largest contributor. After considering each of the R-scenarios suggested in the template, the PE designer selected three R-scenarios that seemed most convincing and proposed the following potential design scenarios:

- (a) Reduce: resize the MOSFET transistor. The current of the MOSFET transistor is oversized. It should be changed into an optimized component of packaging that has a more favorable environmental profile. To do so, the following technical parameters of the MOSFET need to be reconsidered to ensure that they still fulfil functional requirements of load staging.
- (b) Repurpose: the recovered MOSFET from the laboratory's stock instead of using new ones. In this case, the MOSFET will not be subject to intensive use, so a repurposed one can fulfil the estimated lifetime of the converter.
- (c) Rethink: replace the MOSFET with a relay, which serves the same switching function. The operating characteristics required for the relay are switching frequency (given in Hz), and maximum switched load (given in Ohm).

4.4 Qualitative evaluation & strategy convergence

A qualitative evaluation of these draught strategies was conducted by all participants, considering four aspects: technical, environmental, economic, and time consumption. As a result, scenario (c) was excluded because it was estimated to have a negative impact on switching performance and could potentially cause loads to move in a rebounding manner, ultimately failing to meet functional requirements of “charge staging” in “charge module” block. The other two strategies passed the qualitative evaluation, and their compatibility was confirmed by the PE designer, achieving convergence. Additional ecodesign strategies are still pending and will be explored with the PE designer in collaboration with the lifecycle engineers.

5. Discussion

Overall, the proposed LCA result interpretation process supported by functional architecture to develop PE ecodesign strategies was successful.

In the case study, three advantages of the proposed methodologies were identified. First, formalizing the functional architecture efficiently helped the PE designer to gain a comprehensive system overview. Simultaneously, it provided the flexibility to delve into specific details. Secondly, representing functional blocks associated with environmental indicators enabled the lifecycle engineers to effectively highlight the hotspots. The environmental indicators (e.g. kg CO₂-eq.) could then be “translated” into technical characteristics (e.g. packaging technology and mass of MOSFET) that the PE designer is familiar with. This enables the PE designer to adjust the electrical parameters with specific

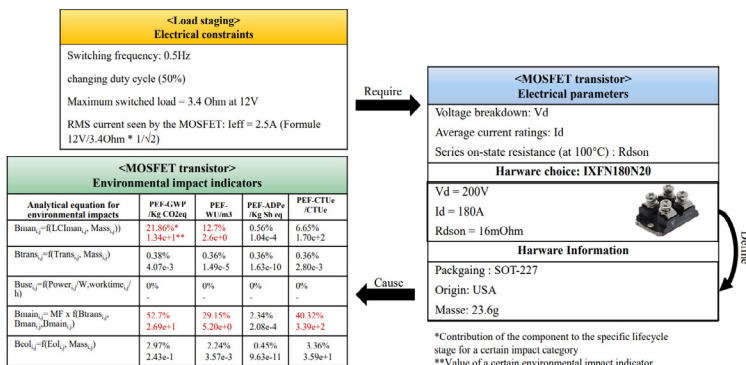


Figure 6 Cause-effect chains for the MOSFET transistor performing load staging in load modules

objectives. Third, the ecodesign strategy template was useful in diverging ideas and integrating R-scenario considerations into the elaboration of ecodesign strategies.

However, the case study revealed several issues. Firstly, the results provided by the resource use, minerals, and metal indicator (PEF-ADPe/kg SB-eq.) have been criticized for not considering material dissipation in the industrial processes, particularly during recycling. Therefore, a resource dissipation indicator should be adopted to better account for the impact on raw material depletion [26]. The second aspect concerned the abundance of ecodesign concepts that can be addressed more deeply. Essentially, many other stakeholders are involved in PE product design, requiring a greater diversity in workshops' participants to address the divergences, such as a mechanical engineer, repair engineer, purchasing engineers, etc. Furthermore, participants have difficulties in estimating the amount of usage cycles (u_i) and the percentage of the component repair/reuse/repurposing (x_i), despite the given guidelines. The quantitative and qualitative methods should be developed to define these parameters for both PE functional blocks and electronic components. This entails identifying influential factors, such as usage intensity, Mean Time Between Failure (MTBF), component reliability, and then establishing their relationship with u_i and x_i .

6. Conclusion and ongoing research

This paper proposes a methodology based on functional analysis for interpreting LCA results and developing ecodesign strategies for PE in a collaborative manner. The case study showed that this method can be adapted to support PE ecodesign strategy development by following a series of workshops with the help of lifecycle engineer. The methodology consists of 4 steps (1) functional architecture coupling with environmental indicators definition, (2) critical technical parameters identification (3) strategy elaboration (4) qualitative evaluation. In the case study of the DC-DC buck converter, the entire PE ecodesign strategy development process was carried out, including conducting a LCA of the buck under development. The result shows clear, organized, and comprehensive functional architecture diagram describing the complexity of PE system design. This diagram was effective in displaying the technical characteristics and environmental footprint of each block in the system-level definition (including sub-and under-levels). Based on that, PE designers' choices to satisfy functional specification therefore took into consideration both technical and environmental impact performances. Several ecodesign strategies were developed and qualified during the workshops.

Ongoing research is currently testing this methodology in an industrial product, and extended format (more complex design, iterative steps, multiple experts). The methodology is thus under a second evaluation for quantifying its effectiveness. in eco-innovative PE design strategy development.

Acknowledgements

This research was funded in whole or in part by the Agence Nationale de la Recherche (ANR) under the project ANR-21-CE10-0010-01.

References

- [1] Blaabjerg, Y. Yang, K. Ma, and Wang X., Power Electronics – The Key Technology for Renewable Energy System Integration, ICRERA 2015, doi: 0.1109/ICRERA.2015.7418680.
- [2] Popović-Gerber J. et al., Power electronics enabling efficient energy usage: Energy savings potential and technological challenges, IEEE transactions on power electronics, 2011.
- [3] Hurtado Albir and Carrasco Hernández, Environmental Aspects of Manufacturing and Disposal of Power Electronics Equipment, EPE Journal, Sep. 2011, doi: 10.1080/09398368.2011.11463798.
- [4] Pirson T., Delhaye T. P., Pip A. G., Le Brun G., Raskin J.-P., and Bol D., The Environmental Footprint of IC Production: Review, Analysis, and Lessons From Historical Trends, IEEE Transactions on Semiconductor Manufacturing, Feb. 2023, doi: 10.1109/TSM.2022.3228311
- [5] S. Kara, C. Herrmann, and M. Hauschild, "Operationalization of life cycle engineering," *Resources, Conservation and Recycling*, vol. 190, p. 106836, Mar. 2023, doi: 10.1016/j.resconrec.2022.106836.
- [6] Musil F., How Life Cycle Analyses are Influencing Power Electronics Converter Design. 2023. <https://doi.org/10.30420/566091368>
- [7] Fang L., Lefranc P., and Rio M., Barriers for eco-designing circular Power Electronics Converters, *Procedia CIRP*, vol. 116, pp. 287–292, 2023, doi: 10.1016/j.procir.2023.02.049.
- [8] Brambila-Macias S. A. and Sakao T., Effective ecodesign implementation with the support of a lifecycle engineer, *Journal of Cleaner Production*, 2021, doi: 10.1016/j.jclepro.2020.123520.
- [9] Quisbert-Trujillo E., Ernst T., Samuel K. E., Cor E., and Monnier E., "Lifecycle modeling for the eco design of the Internet of Things," *Procedia CIRP*, 2020, doi: 10.1016/j.procir.2020.02.120.
- [10] Europäische Kommission, Ed., Value management handbook. Office for Official Publications of the Europ. Communities, 1995.
- [11] Fernandes M., "VALUE ANALYSIS: Going into a further dimension," *Engineering, Technology and Applied Science Research*, vol. 5, pp. 781–789, Jan. 2015, doi: 10.5281/zenodo.16988.
- [12] Yannou B., "Analyse Fonctionnelle et Analyse de la Valeur," 1998
- [13] "NF X50-100," Afnor EDITIONS.
- [14] Moreno P. R., Rohmer S., and Ma H.-W., "Analysis of Potential Relationships between Functional Analysis and Life Cycle Assessment," *Procedia CIRP*, Jan. 2015, doi: 10.1016/j.procir.2015.02.035.
- [15] Ijassi W., Ben Rejeb H., and Zwolinski P., "Environmental impact evaluation of co-products: decision-aid tool for allocation in LCA," *Int J Life Cycle Assess*, Nov. 2021, doi: 10.1007/s11367-021-01984-0.
- [16] Bauer T., Mandil G., Monnier É., and Zwolinski P., "Design for cascading applications reuse – understandings of an emerging end-of-use strategy and propositions for its implementation," *Journal of Engineering Design*, Mar. 2021, doi: 10.1080/09544828.2020.1871470.
- [17] de Freitas Lima G., Rahmani B., Rio M., Lembeye Y., and Crebier J.-C., "Eco-Dimensioning Approach for Planar Transformer in a Dual Active Bridge (DAB) Application," *Eng. vol. 2, no. 4*, pp. 544–561, Dec. 2021, doi: 10.3390/eng2040035.
- [18] Rahmani B., Lembeye Y., Rio M., and Crebier J.-C., "Analysis of Passive Power Components Reuse," in *PCIM*, May 2021. Available: <https://hal.archives-ouvertes.fr/hal-03347175>
- [19] Quisbert-Trujillo E., Design methodology for sustainable IoT systems, 2022.
- [20] Potting J., Hekkert M. P., Worrell E., and Hanemaaijer E., "Circular economy: measuring innovation in the product chain," *Planbureau voor de Leefomgeving*, no. 2544, 2017.
- [21] Gehin A., Zwolinski P., and Brissaud D., "Integrated design of product lifecycles—The fridge case study," *CIRP Journal of Manufacturing Science and Technology*, 2009, doi: 10.1016/j.cirpj.2009.05.002.
- [22] Romano T. T. et al., "Evaluation de la démontabilité des convertisseurs électroniques de puissance pour une circularité améliorée".
- [23] Sala S., Crenna E., Secchi M., and Pant M., "Global normalisation factors for the Environmental Footprint and Life Cycle Assessment," *JRC Publications Repository*, 2017.
- [24] Bonvoisin J., Lelah A., Mathieux F., and Brissaud D., "An Integrated Method for Environmental Assessment and Ecodesign of ICT-based Optimization Services," *Journal of Cleaner Production*, 2014, doi: 10.1016/j.jclepro.2014.01.003.
- [24] Javier Hurtado Albir F. and Antonio Carrasco Hernández J., "Environmental Aspects of Manufacturing and Disposal of Power Electronics Equipment," *EPE Journal*, 2011, doi: 10.1080/09398368.2011.11463798.
- [25] Charpentier Poncelet A. et al., "Losses and lifetimes of metals in the economy," *Nature Sustainability*, 2022, doi: 10.1038/s41893-022-00895-8.