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Addressing Circularity to Product Designers: Application to a Multi-Cell Power Electronics Converter

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Abstract

Design for enhancing a 4th industrial revolution thinking questions the sustainability of a massive use of IT devices. The communication between people and objects (IoT) inside and outside industries are supported by an increasing diversity of electronics using electric power. This causes irreversible damages on the ecosystems guarantying the livability of our planet. This paper therefore proposes a three stage method for product designers to design multiple-usage life cycle electronic products. The originality of the proposition stands in modeling the multiple-usage life cycle scenario to support the reparability of the electronic device based on a modular design of power converters. The method is applied on a power converter for photovoltaic panels. The paper concludes on the opportunity to merge technological innovations with a circular thinking in the early design stage of electronic based products. The multi-impact analysis and systemic vision as a basis of circular thinking and are a major challenge addressed to product designers in today's 4.0 industries.

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC)—the UN body for assessing the climate change science—reports the alarming trends of our industrial societies to cross our planet boundaries in terms of CO₂ emissions [1]. In addition, the phosphorous and nitrogens cycles, material and ecological footprints, land-use change and blue water cycles are getting irreversibly damaged [2]. Behind this global industrial rise the massive use of electronic products is worldwide, and crossing any spheres from public to private ones. The current service electronics are providing daily is unfortunately not founded on a circular thinking of material and energy flows required to ensure the electronic devices sustainability in a medium perspective. Rare earth elements are used for current electronic applications, such as magnets, batteries, supraconductors, Aluminum alloys, or electric motorisation. 95% of rare earths are produced in China [3] and today EU importations are coming from China (40%), US (34%) and Russia (25%). Their substitution indice is

low in EU. Their recycling rate in EU (old material recycled/its demand) fluctuates between 3 to 8%. Similar high dependency and low recyclability rates are given to the majority of electronics' elementary flows. Improving the electronics capacity of being reused on a given territory will become an important issue for a product designer.

An electronic wastes could be kept minimum by designing modular electronic components and sub-components in a reuse chain. This research focuses on power electronic converters components used in a majority of common electronic products. They are low price and not designed to be repaired. If some spare parts are not provided, and if no maintenance service is offered the broken electronic device containing the converter will be entirely discarded. Electronic components could circulate as long as they were kept functional if they were designed in a multiple-usage life cycles perspective.

This paper objective is therefore to set-up a local circular lifecycle approach for the electronic industry based on a modular design of power converter. A three stage method is proposed to electronic product designers. Section 2 investigates the Wastes of Electric and Electronic Equipements (WEEE) treatments and reuse chains in Europe, addressing the necessity to propose a design method adapted for electronic designers to design for multiple-usage life cycles. A design method is proposed in section 3 to support electronic product design-

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ers design for circularity. The proposed method is applied on a case study in section 4. The application of the first steps of the method addresses recommendations to product designers for multiple-usage life cycle design in electronic using power converters. The last stage of the method is addressed in the conclusion of the paper.

2. Research Context

2.1. From WEEE recycling to reuse chains

This research stands on the definition of [5] of a recycling chain. The economic stability of an industrial system is the condition to its existence. Inputs of WEEE recycling chains concerns million of tons per year. For instance during the year 2016 up to 44.7 million tons of e-wastes were generated globally on the planet [4]. Electronics are discarded despite they are still operative or easily reusable if fixed. The incentives for reusing before recycle and dispose are still weak [6]. More than 70000 tons of EEE were reported by the 28 EU state members to Eurostat for 2012 as having been re-used or prepared for it. This is about 2% of the WEEE collected. Furthermore investigations to better support EEE re-use are reported by the EU in 2015 for seven countries [7]. The diverse organisation forms taken by the EEE re-use in the EU makes its potential assessment difficult to establish globally. However locally the obstacles for reuse directly concern the product manufacturers resistance to re-use, the EEE products' design, and availability of the related spare parts. The expertise required a Design for Re-use approach, as well as the consumer perception toward re-use are key issues. Whereas the main drivers are opening a dialogue between manufacturers and re-use organisations. Encouraging the local authorities commitment towards re-use with local policies and incentives are necessary [7]. Therefore addressing reuse EEE for manufacturer and product designers requires a local investigation.

Ecosystem reports an extraction of 10 to 15 categories of different fraction materials depending on the mode of treatment used for every type of waste. Screens for instance are recycled at 84.5%, comprising 18% of recycled plastic, 6% of nonferrous metals and 49% of glass cathode ray tubes. From the WEEE stream only 77.1 % of small appliances are recycled. The improvement potential is still high for designing products adapted to end-of-life treatments after being discarded. Once the EEE is in the container to be dismantled and recycled its reuse is no more an option. Several components are however usually still functional. The main issue in this research is therefore to support designers in improving the lifecycle chain organisation upstream before the equipment being considered as a waste.

2.2. Requiring a design for product circularity method addressed to electronic designers

This research refers to the ISO standard 14006:2011 assisting organisations in managing their ecodesign practice on a continually improving environmental management system. The

ecodesign approach stands on a systematic integration of the environmental aspects from the early design stages to the end of life stages of the product under development, to globally minimize the negative environmental impacts generated during the whole lifecycle, for a given service provided. The product circularity stands on the capacity of its lifecycle system (actors, processes, etc.) to reduce its service obsolescence. Design for X approaches can be combined together: design for an extended lifespan [9]: components lifespans are aligned to the product lifespan to avoid premature failures; design for remanufacturing [10]; design for upgrade [12]; design for repurposing [13]. Those approaches rely on the design for reliability, maintenance, reparability and adaptability of the product system components [11]. Design for multiple-usage life cycles combines multiple strategies that can be addressed to the product, its components, as well as its material flows: extending the "functional" lifespan, guarantying the technical properties robustness, the components adaptability and flexibility for being reused, upgraded, remanufactured. Medium to long term perspectives of the nexts product lifecycle generations addresses new challenges to product designers. The contextual uncertainty of the value chain depends on the (re-)manufacturing, (re-)usage, logistics, (etc.) in place in the 4.0 future industrial system[14]. The evolution of the society and policies in regard to the product and service consumption and their renewal rate in general around the world should be considered together to drive electronics multiple-usage life sustainable. The highest challenge is to stay within the planetary boundaries [2].

This paper therefore aims to support the reparability of the electronic device during their multiple-usage life cycles. A method for product designers to design a multi-cell power electronic device used for multiple-lives' usage is addressed in the following section.

3. Proposition

The method proposes to model several multiple-use life cycle scenario to help product designers integrate the reparability of the electronic device at the early stage of the design process. This reparability is enabled by the modularity of the electronic device using power converters. The design method proposes three stages.

Stage one: during the need clarification and the benchmark activity. What: elaboration of multiple-use life cycle scenario based on the service provided by the electronic device under development. Integrate the cradle to cradle constrains. How: set the service needed (to provide). Translate this need by the evolutive technical performance of the electronic component integrated in the appliance life cycles used successively, eg.: converting 100 Watt in a system adapted to photovoltaic panels during 5 years, then extract and remanufacture the converter for a 80 Watt power conversion in another system for 3 years etc. Integrate the design for multiple usage guidelines: design the multiple-use product life cycle scenario for an extended lifespan, remanufacturing, upgrade, repurposing, reliability, maintenance, reparability and adaptability. Deliverable: specification

of the perimeter under study, the included activities, to elaborate the lifecycle assessment.

Stage two: at the early design stage of the product design development. What: ecodesign the power converter based on the elaborated life cycle scenarios. How: apply a Life Cycle Assessment (LCA), consider environmental constraints while designing the modular device. Deliverable: specification of a modular power converter electronic device adapted for multiple lifecycle loops perspectives.

Stage three: during embodiment design. What: validate the modular product performances. How: run a technical failure and reliability analysis of the product design for ensuring the multiple-use life cycle scenario associated service. Adapt the risk to the life cycle usage designed. Deliverable: a predictive risk analysis of the service performance proposed during the multiple-use life cycle proposed.

4. Case study

The proposed method aims to assist electronic designers in developing a modular power converter adapted to multiple-use life cycle scenario. This design method has been applied in the *G2ELab* research laboratory in Grenoble. This paper only focuses on stages one and two of the method. The technical failure and reliability analysis of the product design performance is currently under study at the laboratory scale.

4.1. Stage one: the need clarification

This case study considers “converting power” as an elementary need to ensure any electronic product’s functionality. A converter is the most common component of power electronics used in daily life products: television sets, computers, solar panels, household appliances. At this stage the electronic designers describe the potential multiple-use life cycle scenario of an electronic product, as shown in Fig. 1.

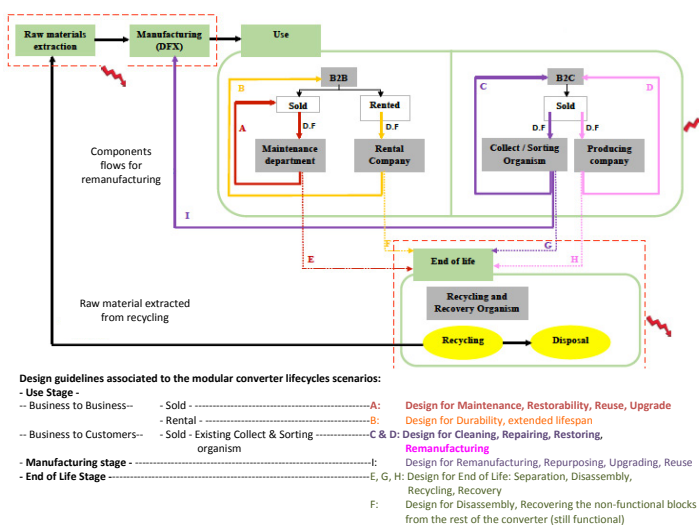


Fig. 1: A modular converter lifecycle scenarios

The contained converter is chosen to be designed in a modular way to provide an adapted power conversion for different

product usage in a design for circularity approach. The product life cycles presented in Fig. 1 follow the extraction of raw materials, manufacturing, use, and the end-of-life stages. Each A to F life cycle scenarios has different transportation stages with a dedicated logistic organism providing a specific transport mode, and a load capacity. A particular focus is made on the use stage scenarios to explore the converter design potentiality to support multiple usage cycles, in an extended lifespan consideration. Two business models are distinguished at the use stage to ensure the electronic product functionality: the Business to Business (B2B) model and Business to Customer (B2C) one.

In the B2B the company in charge of selling or renting the machines with the converter(s), deals with another company using the converter in an electronic product. In a case of converter sold to another business, assuming that the converter no longer meets the requested specifications after a given duration, the after sale service would be in charge of changing the product, extracting the damaged component and reinserting a new one. The broken conversion cell blocks are removed, trashed in dumpsters to be recovered as a WEEE (cycles E, F, G, H). The rest of the converter is reused or remanufactured in another system requiring less power (cycle A). In cycle B the rental company would ensure *in-situ* a repair of the broken converter, or its collection and its replacement. The damaged cells removal and their replacement by spare parts may require a process of mechanization that needs therefore to be designed for an in-situ context. In a B2C scheme the customer buys a system containing a modular converter. Two propositions are envisaged if the converter breaks down. In the first proposition a collecting organism is in charge of cleaning, repairing and remanufacturing the electronic product. A second-life market for the embodied converter begins (cycle C). In cycle I the collected converter is still functional in a decreased power mode, potentially remanufactured in a new product. In the second proposition (cycle D) the producer takes in charge the discarded products with its clients. A discount on a remanufactured product could be given in return to the discarded one for instance.

The specific logistic can be described for each scenario. Variation in the transport modes, quantities, packaging chosen, will depend on each business situation. A converter based system can also be characterized by the industrial application it is designed for. The electronic specification of the system, its size, its design complexity, *etc.* could be standardized per industrial sector of application (eg. decentralized electric production of a given power range). Each proposed scenario could therefore be declined to a given industrial application.

In cycles E,F,G,H the local conversion cells or higher range blocks would join the local WEEE waste stream. In France for instance, the Ecosystem group offers a non-lucrative service agreed nationally to manage the WEEE recycling chain actors, including the WEEE reuse for households and business sectors. An online practical tool¹ supports any EEE producer or user in finding the legal scheme to deal with his EEE. Depending on their size and the materials they contain, the devices are sorted

¹ Ecosystem online tool available on: <https://www.reylum.com>, accessed on sept. 2019

and collected into four large families: the large non-cold appliances, the large cold appliance, the screens, and the small appliances.

The appliance containing the converter is discarded in a collection point certified by Ecosystem. Its containing converter would then be directed to one of the treatment units specialized in depolluting and recycling of WEEE in France. Sibuet Environment is one of the Ecosystem WEEE provider. In addition Sibuet Environment centralises and manages the treatment of WEEE partners in a several french departments, such as Rhone-Alpes. This company is specialized in the rental of dumpsters as well as sorting, recovering and recycling of waste, and organizes the WEEE collection and treatments of the electronic screen waste stream.

Four main stages of treatment are currently followed for screens in a center near Grenoble. They could be adapted to the modular converter. In this treatment center for instance, the engineer collaborates with researchers to co-develop design for disassembly methodologies, and to improve the real treatment process chains [8]. The stage one scenarios involve several actors playing major roles in the service systems provided: the maintenance service, offering a renting business, producing the product, ensuring the sorting of reusable components, recycling and recovering. An effective communication between them actors includes indicating the specificities of the converter, and the rules that must be respected for remanufacturing or for reusing the product in a security space are required to guide the operators. **1- Pre-treatment and separation:** plastic shells are opened to extract the slabs and the tubes, cleaned and treated separately from the rest of the unit. The operators are manually extracting the electronic boards and capacitors to clean them separately. The still functional converter could be extracted at this stage to follow a specific treatment. **2- Depolluting:** the dangerous substances contained in the screens (RoHS: mercury, lead, etc.) are carefully extracted and stored in secure containers before being neutralized in specialized facilities. **3- Dismantling:** the rest of the components is sent to a specific shredder to be disintegrated and broken into small pieces with rotating chains. **4- Material recovery:** materials such as metals and some plastics are sorted for recycling.

4.2. Stage two: ecodesign the converter to match the multiple-use life scenario

At the early design stage a first version of the converter is prototyped in a design for modularity thinking to match the elaborated life cycle scenario. The converter presented in Fig 2 is structured in layers of individual conversion cells connected together in series or in parallel as a network to meet the functional requirements. The cells are welded separately on each printed circuit board (PCB) assembled with metallic connectors. Each conversion cell is a Dual Active Bridge (DAB) DC/DC converter of about 20 Watt. The power of the whole converter equals to the power of the DAB converter multiplied by the number of cells used. This singular design format is based on a technical innovation taken from the micro-electronic industry declined on a macro format. A conventional converter

is composed of a single conversion block, ensuring a specific application. By contrast, the architecture of the converter developed in this research allows to adjust the number of blocks to multiple usages requirements (top Fig. 2). The blocks can be reconfigured by cutting connectors after a first usage. They could be also used for a lower power conversion capacity in another system application where they would fit in. A technical failure and reliability analysis will be required to validate the product performance of the converter (stage three).

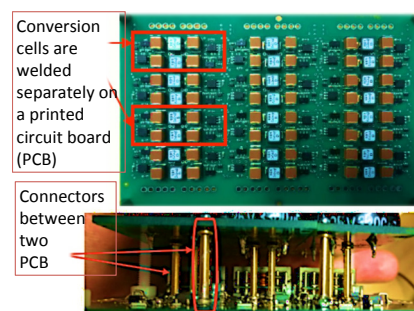


Fig. 2: The converter design: Dual Active Bridge (DAB) conversion cells from G2ELab, approx. size: 10 x 16 x 9 cm

The converter manufacture consist in assembling some electronic components on a PCB to obtain a DAB. The *G2ELab* innovation concerns the DAB structure built as a board superposition. A conversion cells network bridging cells together is therefore designed to meet the given converter requirements. For each component the electronic industry extracts a variety of metals from mines, uses some plastics, and numerous chemicals. The involved processes for raw material extractions (and purifying) requires high quantity of energy and some additional chemicals and water. In addition mines and refineries are implanted all around the world. To produce a circuit board for example, a substantial amount of copper wiring is required. Copper mines use up to 500 gallons of water per second of operation. Raw material and energy flows inventories have therefore been collected during this study using suppliers data and Life-cycle Inventories Databases (Ecoinvent) provided by the Life Cycle Assessment software used to environmentally assess the impact of the converter designs. The conversion cell studied comprises in total 8 connectors 3 pins, 2 of 2 pins, 20 capacitors, 1 transformer, 1 inductor, 2 resistors and 4 schottky diodes. To give some factual numbers, a single connector 3 pins contains about 23mg of Cu, up to 15mg of Nylon, 10mg of Zn, 7mg of Tin, 4mg of glass fibre, 2.37mg of Bromopolystyrene, some traces of Ni, heat stabilizer and gold (0.003mg).

The manufacturing phases go through the classic steps of PCB manufacturing (cf. Fig. 3). Then the components soldering step is a process of reflow soldering based on the surface mount technology, in four stages: preheat, thermal soak, reflow, and cooling. The next step is the verification of each board after soldering to ensure the quality of the links, requiring a camera to compare each electronic card to the specifications. The electronic layers boards are then assembled manually. The final stage of packaging and electrical tests consist in ensuring a protective packaging for an easy handling, and an appropriate

integration into the final electronic equipment. Additional protections from potential damage that may occur during transport and use can be eventually added. Fig. 3 is an illustrative extraction of the qualitative material and energy flow assessment of each operation, conducted in collaboration with research experts in electronics. The color designation varies from green (Low) to red (high). This matrix supports the arguments related to the design for reuse recommendations addressed to the electronic designers.

Step	Description	Energy consumption	Material consumption
Board cutting	The board is cut using a machine in small pieces that are suitable for manufacturing.	Low	Low - Medium
Drilling	connect the laded components and link the copper layers together	Low	Low - Medium
Electroless copper deposition	make connection between top and bottom	Low - Medium	High
Copper plating	Copper is plated up to a thickness for the panel	Low - Medium	High
Image the outer layers	to set a blue light sensitive film which is already has printed circuit diagrams	Low	Low
Image develop	remove the unhardened and unwanted resist from areas that were not polymerized by light	Low	High
Etching	Remove the unwanted copper using a powerful alkaline solution.	Medium - High	High
Automatic optical inspection	Machine accurate inspection of PCBs to ensure the quality is high.	Low	Low
Solder Mask	This solder making is required to protect the cooper surface	Low	Medium - High

Fig. 3: Qualitative environmental assessment matrix applied to the converter: an extraction of the PCB manufacturing process steps inventory

At this early design stage a prospective LCA is necessary to address the environmental impact that would be generated by the proposed scenario. The environmental impact comparison can be envisaged in a case of substitution: a current converter based system is compared to a modular based one used in one of the proposed scenario described in Fig. 1. The comparison can also be envisaged per industrial sector of activity. The modular converter (the product) in a multiple-use scenario (for a given service ensured) is therefore a Product-Service-System (PSS) approach. Eco-designing such PSS is a complex project. This may be envisaged in this research by applying an existing method of PSS integration (eg. [15]). To start any of those environmental assessment scenario the following sub-section presents the first streamlined life cycle assessment comparing a modular to a standard converter based electronic system used in a photovoltaic installation.

4.3. Guidelines for electronic designers from the two first stages of the design method applied in the case study

A streamlined LCA comparison of the modular converter applied as a substitute to an existing converter designed in a photovoltaic panel energy conversion has been conducted at this early design stage. A full ISO Standard 14040:2006 LCA will be completed during the embodiment design process (stage three). In the goal is to provide clear ecodesign recommendations to electronic designers. The scope of this modular converter is defined by its lifecycle scenario. The converter, also called inverter, transforms the electricity produced by a photovoltaic panel, stored in a battery from direct 12V to 48V current

to alternating current form of 220V. Used in small housing solar installations, the converter provides a power of 400W. The power of one conversion cell is 20W, the modular converter is therefore composed of 20 units of conversion cells. The Functional Unit (FU) is to provide a 400W power of a house 24h/24 for 10 years. The perimeter of this study covers the manufacturing plans in Europe, the raw material extractions mines all over the world, the local usage in Grenoble, and the end of life treatments in France.

The inventory analysis has consisted in drawing-up an inventory of input and output material and energy flows, associated with the lifecycle stages of the converter used in the photovoltaic panel. This step required a high investigation from electronic designers. Details about the industrial processes involved at each steps are given. Concerning the foreground data, the modular converter material and energy flow inventory to satisfy the FU is based on direct measurement taken in the electronic laboratory, and on data sheets provided by suppliers. Background data are based on international inventory databases available in the Simapro©software, such as EcoInvent, and in the EcoTransit©online calculation tool². Since the product is not yet commercialized, the transport stages occurring during the life cycles were based on the assumptions presented in Table 1. The distances and transport modes are estimated with EcoTransit©calculation tool.

Table 1: Distribution mode and distance inventory for the modular converter used in the photovoltaic system studied

Cycle	Transport mode	Distance
From Huasheng Electronics Factory to Mawan port	Truck	40km
From Mawan port To Marseille port	Transoceanic freight ship	15000 Km
From Marseille Port To Grenoble	Truck	300 Km
Grenoble B2B	Light Commercial Vehicle	100 Km
Cycle B: maintenance agent to customer	Passager car	100 Km
Cycle C: customer to collection org.	Passager car	100 Km
Cycle C: product redistribution	Lorry 16-32 tons	200 Km
Cycles E, F, G, H (WEEE Collect)	Municipal waste collection Lorry 21t	100 Km

The transport hypotheses for the end-of-life treatment are based on the existing centers' logistic in the Grenoble region. The impact assessment and the interpretation of the proposed scenarios are merging LCA usage and transport gate-to-gate simulations. The complexity of the system (stakeholders, industrial productions, logistic, use contracts) added to the uncertainties in regard to the real scenario that would be effectively followed in the reality, is in favor of rather qualitative prospect analysis. This early stage streamlined analysis is a starting point to address the following elementary guidelines to product designers. The converter is a component of power electronics. To support its multiple reuse this component should therefore be identifiable, accessible and dismountable (eg. with a screw-driver). On the converter itself the cells are kept accessible for

² EcoTransIT World, on: <https://ecotransit.org/>; Accessed: 20.06.2019

maintenance operation. The defective cells are identifiable by an individual electrical test operation. The cells are then disassembled by cutting or desoldering the connector on the PCB. The end-of-life treatment requirement is directly labelled on the cell, similar to label warning from toxic substances. The functional cells can be similarly dismantled from the board, and sorted, to be remanufactured. The cell can also be cut by a PCB cutting machine (e.g. a CNC machine) and then filed again to be reused as an independent cell for other applications.

The step three of the method proposed in Section 3 will be applied during the embodiment design stage to validate the modular product performances. To enable the reuse operation the following recommendations have been formulated. Additional ones will be required to avoid unwanted environmental damage to be generated while improving the functional reliability of the power converter over multiple usage stages.

- No glue on the converter to keep the components connectors accessible.
- In the case of remanufacturing, all cells have to be desoldered for sorting and reuse for another application. A desoldering tool adapted to the shape of the connectors of the conversion cell must be developed, to unsolder the cell at once and not damage any components.
- Design cells independently from each other, detachable manually, inter cells link can be provided by a breadboard for example. This would avoid the use of a specific tool for cells (dis-)assembly. The connection between the boards and the cells have therefore to be tight and effective to ensure the electrical connection.
- Keep cells at a sufficiently distant to enable an access to cut the board without damaging the neighboring cells of the defective component (eg. a conversion cell) to be cut.
- Avoid copper paths between conversion cells so as not to destroy the circuit by cutting it.

This case study the application of the design method proposed only on the two first stages. The technical development requires additional work to be guaranty the functional reliability of the product. This is addressed during the embodiment design stage. A modular converter has a potential to generate less environmental damages than the existing ones, while satisfying the same performance for a longer lifespan. The additional repair and transport steps to follow the multiple-usage life cycle scenario will automatically generate additional environmental damage up to a given reuse cycles and in a given transportation perimeter. Addressing the planetary limits to electronic product designers is part of the ongoing research referring to a resource-based systemic approach defined by [16].

5. Conclusion

This research is based on the constatation that a majority of electronic products are using power converters that are not designed to be reused or repairable. If the converter is no more functional the product is discarded. A three stage de-

sign method has therefore been proposed in this paper to support electronic designers to elaborate multiple-usage scenarios based on a modular design of a power converter. The two first stage of the method has been applied in a case study. A first streamlined environmental impact assessment for the gate-to-gate usage and transportation scenarios has been conducted to address ecodesign recommendations to electronic product designers. The proposed method is easy to use and to integrate during the product design process of any electronic products containing power converters.

The stage three is currently under development at the laboratory scale. This stage includes finding the appropriate method to run the technical failure and reliability analysis of the product under development. In addition a full LCA of the converter multiple-usage scenarios is being conducted to improve its modular architecture in collaboration with electronic designers.

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