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Driving circularity—An approach to identify potentials for circular design of automotive electronics

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ABSTRACT: The amount of electronic waste worldwide is increasing every year and the often incorrect handling of it has a major impact on the ecosystem. As electronics are also gaining more share in the automotive sector, the industry has to find a suitable way of dealing with them at the vehicle's end-of-life stage. For this reason, this work introduces an approach consisting of the Physical Component Mapping (PCM) for the interface representation of automotive electronics, alongside the Eco-Sensitivity Framework (ESF) as guidance for circular automotive electronics design. A case study shows how the approach accompanies the product development process and supports identifying suitable strategies that are potentially possible or can be made available through design changes. This helps car makers and suppliers of vehicle electronics to accelerate their transition to a circular economy.

KEYWORDS: sustainability, Circular economy, Mechatronics, Automotive PCB, Electronic control unit

1. Introduction and related work

Nowadays, vehicles are transforming into computers on wheels, increasing electronics systems as well as waste. As only 20–30% of the global electronic waste is collected and recycled, improper handling of the majority causes immense environmental impacts due to the release of toxic substances and waste of scarce materials (Bel et al., 2019). The circular economy aims to eliminate waste by keeping materials in use and create economic value by closing loops (Ellen McArthur Foundation, 2024). This involves designing products to support a second life. Based on that, Potting et al. (2017) present the 9R-framework including strategies such as reuse, repair, recycling and their hierarchical categorisation. In automotive industry, the European End-of-Life (EoL) Vehicles directive aims to recover materials through regulations for dismantling, material separation and handling (European Union, 2000). The proposed revision of the directive (European Union, 2023) is tightening regulations, including fixed material quotas and mandatory removal of larger Printed Circuit Boards (PCBs), which will significantly influence future product design.

Since functions like automated driving have to process increasing amounts of data from different sensor systems, implementation in conventional vehicle electrical/electronic architectures (EEAs) is reaching its limits. Therefore, industry is streamlining EEAs by decreasing the number of single Electronic Control Units (ECUs) through merging functions together in centralised units. This reduces cables and computation complexity, and optimises data communication as multiple vehicle functions are controlled on a single device (Wang et al., 2024). ECUs are consolidating into fewer, more powerful High-Performance Computing Units (HPCUs), which, despite higher complexity and cost, offer valuable opportunities for circularity.

In the automotive sector, only around 10% of vehicles scrapped in Germany were recycled in 2022 (Federal Government of Germany, 2022). The rest has been exported to EU or non-EU countries, where the final utilisation and therefore the handling of electrical/electronic (E/E) products often remains unclear. According to Prochatzki et al. (2024), the automotive industry still follows a linear economic model, which generates strong demand for implementation of higher circular strategies in the (automotive) E/E sector to prevent additional environmental damages and the shortage of scarce materials (Richter, 2022). The circular framework for the automotive industry introduced by Esteva et al. (2020) can be a starting point for operational alignment for more sophisticated solutions. While it addresses material, manufacturing, usage and end-of-life, it lacks specific details regarding vehicle electronics, both at the product and component level. However, research emphasises the importance of product development for a functioning circular economy (Rodríguez-González et al., 2022). The assessment of product design circularity proposed by Vimal et al. (2021) helps product developers to improve a design in terms of circularity. Although, according to Potting et al. (2017), recycling is the second least favourable strategy after recovery, it is currently being extensively investigated in automotive research (Fernando et al., 2021; Hagelüken & Goldmann, 2022; Mügge et al., 2023; Cozza et al., 2023). Higher strategies such as repurposing, reuse and reconditioning are investigated with focus on vehicle batteries (Glöser-Chahoud et al., 2021; Kotak et al., 2021; Philippot et al., 2022). Considering vehicle E/E products, dedicated frameworks and standards for the commercial development of EEAs are available, but they do not include specific design considerations of circular strategies (AUTOSAR, 2024; Vector, 2024).

In research, approaches for circular design of EEAs are also limited. A system model to evaluate the reusability of software artifacts during the transition from distributed to centralised EEAs is provided by Phadnis et al. (2024). A virtual simulator for power efficient EEA design is proposed by Chretien et al. (2013), whereas further contributions focus on economic and technical evaluation metrics of EEAs (Kanajan et al., 2006; Popp et al., 2007). On product level, first efforts in automotive research include the integration of disassembly points into ECUs (Chiodo & Ijomah, 2014) and the robot-based disassembly studies of ECUs performed by Li et al. (2018).

As the ease of disassembly is a fundamental product property for circular design (Flipsen et al., 2020), several tools for the graphical mapping of the product structure including the assessment of recycleability and remanufacturability have been published over the last decades. For recycling, introduced methods focus on parameters such as disassembly time, type of fasteners and type of tools (Ishii & Lee, 1996; Kroll & Hanft, 1998; De Fazio et al., 2021). The remanufacturability framework proposed by Fang et al. (2016) assesses both the disassembly and reassembly of products based on design data available in computer-aided design models. Shu & Flowers (1999) and Geda et al. (2019) focus on the choice of joints and fasteners for remanufacturing of products. The presented tools are sophisticated solutions including assessments of multiple factors and often require mature production data. Additionally, they do not categorise products into a fixed structure for certain product groups. Although this makes them flexible to use, it may make their initial application more difficult. Visualizing product disassembly and reassembly, particularly for vehicle electronics, remains a challenge.

2. Research gap and objectives

The simultaneous developments in the fields of industry-wide ecological awareness and technological centralisation in EEAs open up a promising but also complex field for synergies in future product development. Research currently overlooks the combined impact of these parallel processes, risking the loss of potential benefits. While existing frameworks focus on general material and energy flows in the automotive industry, they fail to account for the specific circular flows and design requirements that vary between EEA products, Printed Circuit Board Assembly (PCBA) and component levels. This gap is particularly significant as each level offers different opportunities for circular economy. At the same time, in addition to a theoretical framework, it is important to provide those involved in development of future EEAs with methods to enable them to act and collaborate. For that, a structured breakdown of a product is needed. A physical and functional description has proven to be helpful to understand, analyse and optimise a product design (Pahl et al., 2007), and is therefore a good way for implementation of circular measures. For the realisation of circular design in automotive E/E products, a sophisticated framework for different EEAs and their components and a dedicated system model for the mapping of the EEA's physical product structure is yet missing.

The research objective of this work is to bridge the gap between ecological sustainability goals and technological EEA development through detailed analyses spanning from individual component levels up to complete product systems, providing both practical implementation guidance for product development teams as well as strategic orientation.

This research pursues two complementary goals: first, to create a user-friendly assessment tool that evaluates E/E products' readiness for circular approaches, and second, to develop a framework of possible pathways of circular implementation into current and future vehicle EEAs. Therefore, this paper contributes an approach to tackle the circular design of automotive electronics consisting of the Physical Component Mapping (PCM) for the description of the physical architecture of vehicle E/E products, together with the Eco-Sensitivity Framework (ESF) for identification and of possible circular design strategies.

3. Proposed approach

To improve and accelerate circularity in automotive electronics design, the proposed approach in Fig. 1 includes the PCM for product investigations and the ESF as guidance for circular automotive electronics design. The PCM for interface mapping of automotive electronic products helps to uncover the product's physical structure in three layers (vehicle, housing and E/E components). It is used in the design phase of a product and represents the ease of reassembly. It goes beyond existing disassembly assessment tools like De Fazio et al. (2021) by offering a combination of functions tailored to the automotive electronics sector, namely the physical hierarchy levels of E/E architectures. Crucially, the PCM can be applied across all product states, from early draft designs to fully produced items, empowering designers and engineers to proactively optimize for circularity throughout the product life cycle. As an extension on a higher level, the ESF adapts circular design strategies on economic scale to current and future EEAs with consideration of special automotive conditions. It helps to understand the interdependencies between the individual life phases and shows how different sustainability strategies can be integrated into the early stages of the Product Development Process (PDP) defined by Pahl et al. (2007). It clarifies how the tasks of the individual components are changing and what new possibilities arise. In addition, challenges can be derived from the ESF that need to be solved on the way to a circular automotive future.
In the approach presented in Fig. 1, the PCM and the ESF can be used in an iterative interplay to create a mutual connection between design implementation and strategic planning. Particularly with regard to the nested product hierarchy of electronic products, decision makers and developers can use the results to specify design adjustments and decisions. Special requirements can also be placed on the design across departments at an early stage in order to be able to pursue certain circular strategies.

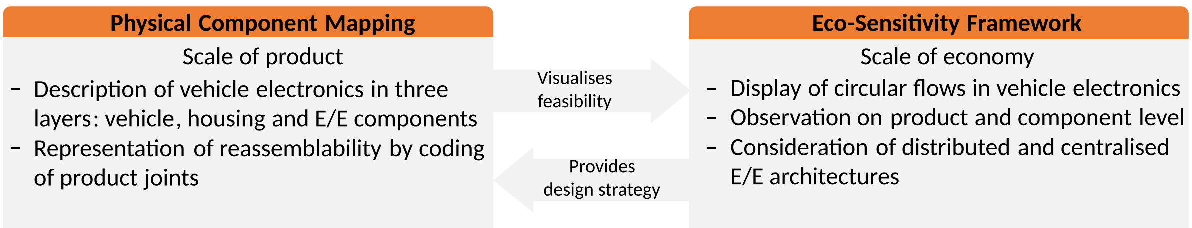


Figure 1. Proposed approach for circular automotive electronics design

3.1. Physical Component Mapping

The research gap states the incomplete consideration of circular design for the various levels of EEA, from whole products to individual valuable components on the PCBA. The PCM adapts the methodology of Phadnis et al. (2024) by providing a structure tailored to automotive EEAs that enable the physical decomposition of an automotive E/E product. This helps to assess component circularity, which depends on adjacent levels. The PCM therefore supports the engineer to uncover weaknesses in product design for circularity and shows room for improvements.
The visualisation of the physical product structure and the product's integration to the vehicle allows evaluation of which circular strategies of the ESF can be applied, or which design adjustments need to be made in order to achieve a specific strategy. The PCM presented in Fig. 2 describes the mechanical integration properties of automotive electronics through different hierarchy levels. It focuses on the consideration of the joining techniques used for the individual elements with regard to disassembly and reassembly. The PCM enables a particular allocation of the product structure and thus introduces a clear annotation for the different components of an automotive electrical product. In collaborative environments, this can simplify communication and understanding.

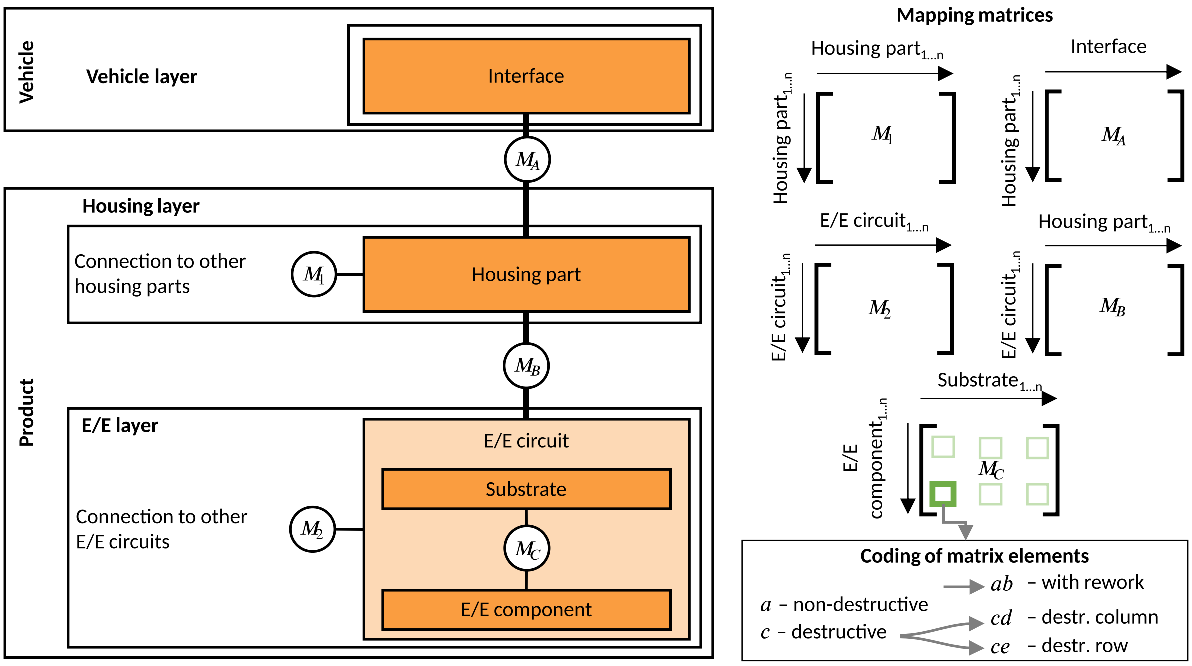


Figure 2. Physical Component Mapping for automotive EEAs (inspired by Phadnis et al. (2024))

The PCM contains three layers: the vehicle layer, the housing layer and the E/E layer. The vehicle layer states the demand for devices within the vehicle's EEA. Depending on the range of functions and the degree of implementation of centralised functions, the number of E/E products differs from vehicle to vehicle. The interfaces are interconnected to allow communication with other devices such as ECUs, actuators or sensors inside the vehicle. Each interface is mapped to an enclosure in the housing layer, which can consist of several more housing parts or even sub-assemblies. The housing layer is mapped to the E/E layer as it holds the E/E components of the device. The E/E layer consists of one or more collections of electrical circuits, which are made up of physical conductive traces embedded in a substrate and E/E components (e.g., transistors, inductors and integrated circuits). In accordance with Phadnis et al. (2024), matrices describe the joining dependencies, where M_A, M_B and M_C consider the vertical integration in between the layers, and M_1 and M_2 map the horizontal connections within the layers. An additional matrix for the connection of individual interfaces in the vehicle layer is not included as this can be seen as a design challenge of in-vehicle communication protocols and data transfer. An element of a mapping matrix defines the physical joint between the objects listed in row and column. The element contains a code that outlines the category of disassembly and reassembly. The former can be divided into non-destructive and destructive and the latter into reassembly with or without rework (Gungor & Gupta, 1998). The composition of the codes is detailed in Fig. 2. Accordingly, two joined components that can be reassembled directly without destruction contain a matrix entry *a*. Detachable connections that require reworking before reassembly are marked with *ab*. For destructive disassembly, a differentiation is made between complete damage to all related parts (*c*), to the part mentioned in the column (*cd*) or the part mentioned in the row (*ce*). The combination of the layers and the basic description of the joining processes used makes the model simple but versatile to map all kinds of vehicle electronics. Based on the mapping matrices, the impacts of design decisions on all existing system levels can be analysed and evaluated in regard of the application of circular strategies, which are discussed in the next section.

3.2. Eco-Sensitivity Framework

The ESF introduced in Fig. 3 comprehensively demonstrates where the strategies to improve circularity can be implemented in EEAs with a focus on ECUs/HPCUs. The methodology of the ESF follows the circularity framework of Esteva et al. (2020) and extends it with a focus on electronics. The PDP is included as independent phase and is then followed by the life cycle stages manufacturing, use phase and EoL. Where the framework of Esteva et al. (2020) introduces material and energy flows, the ESF focuses on physical and digital flows of materials in form of products, components and software. The ten R-strategies (R0-R9) presented by Potting et al. (2017) are considered here from the product level and, if applicable, integrated into the ESF. *Recovery* (R9), *Recycle* (R8) and *Repurpose* (R7) can be applied at

the end of product life. *Remanufacture* (R6), *Refurbish* (R5) and *Repair* (R4) are applicable in the utilisation phase and at the end of life. The highest possible R-strategies *Reduce* (R2), *Rethink* (R1) and *Refuse* (R0) are not included as flows within the ESF but are strategies such as the transformation from distributed to centralised EEAs, which are realised during the design phase in the PDP.
The ESF includes both the distributed and centralized EEAs according to Wang et al. (2024). From this, similarities and differences as well as solutions for hybrid EEAs can be derived. The ESF comprises the PDP, followed by two streams presenting the progression along the life phases and the allocation of different circular strategies. It shows the beneficial impact of circular product development on the individual phases of a vehicle by breaking down how products and components at the PCBA level can be fed back into the life cycle. The ESF not only aims to support the PDP of automotive ECUs but also helps to visualise the product and component flows for guiding decision-making at the governmental and company levels.

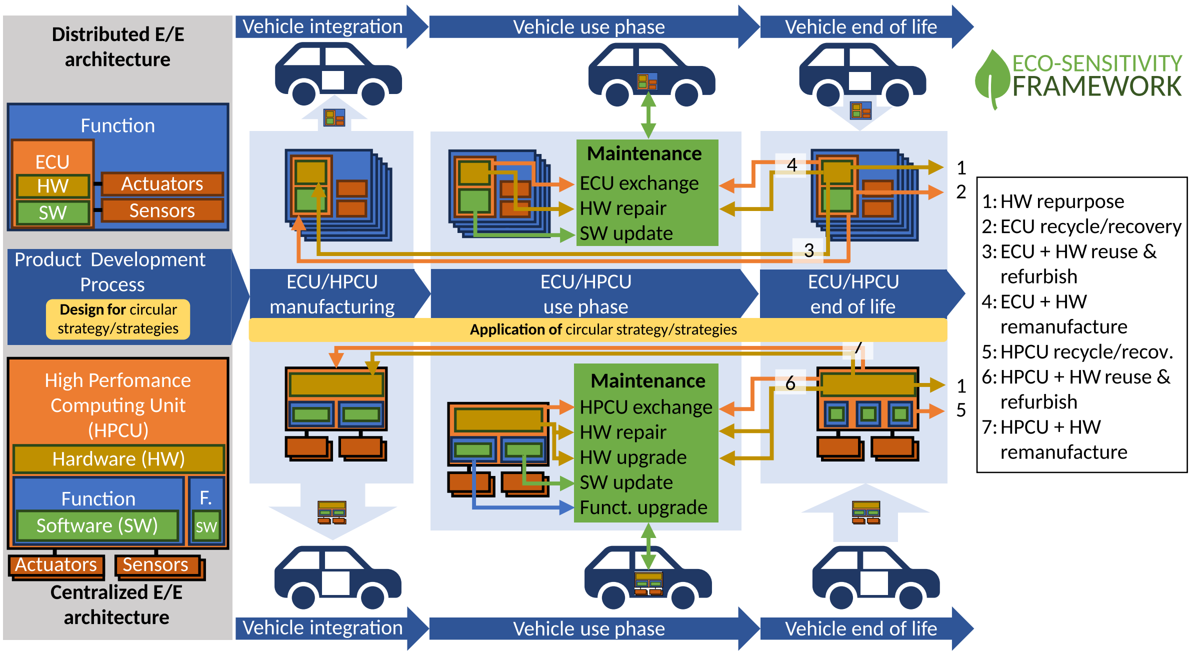


Figure 3. The Eco-Sensitivity Framework applies circular product design strategies onto conventional and future EEAs

The PDP defines all life cycle stages of a product and specifies how the product is designed for one or more circular strategy/strategies. As conflicts of objectives can arise between different strategies, the goal must be set in accordance with economic and ecological feasibility. In the product life cycle, it must be ensured that the necessary infrastructure is available to enable the chosen strategy. The PDP is a continuous operation where valuable information from the manufacturing, use or EoL phase can be retracted back to the design stage. This allows a continuous optimisation in regard to changing requirements and technological opportunities. It is stated that the decisions made during the design phase are responsible for up to 80% of the ecological impacts of a product (Diaz et al., 2021).
Following the route for conventional distributed EEAs, hardware and software components are manufactured tailored to the functions of a single vehicle type. During the manufacturing phase, defective ECUs that have not fulfilled the required quality tests can be put into the rework process to produce a remanufactured unit. These can be added back to vehicle production. Once the vehicle is built and the ECUs are integrated, customising the functional scope, hardware and software of an ECU is very limited because they are adapted for one application and closely interwoven with other ECUs. The integration of an ECU into the overall vehicle system is precisely defined through communication standards and content. Subsequent addition of functions is therefore very cumbersome or even not possible. In case of functional failures, maintenance is done by the dealership. If it is a common fault, the manufacturer can also issue a recall and replace the affected hardware components or install a dedicated software update. There are also repair shops for

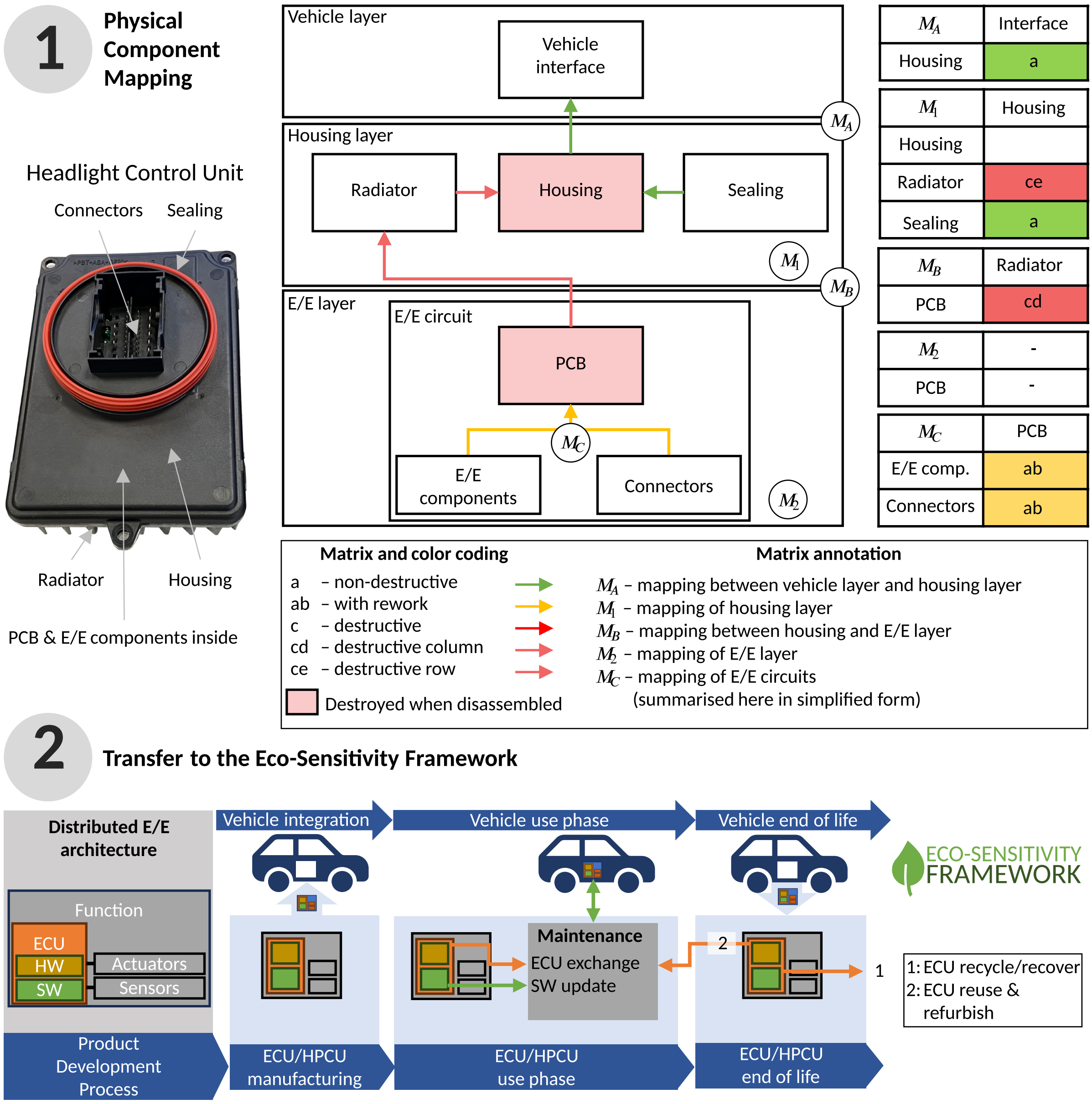
hardware components available (Faurecia Clarion Electronics, 2024; Glaubitz, 2024). As the vehicle reaches the EoL phase, the ECUs can be utilised for remanufacturing, if the given configuration is still used in production. Otherwise, it can be reused/refurbished as spare parts for the aftermarket. Another option is to dismantle the ECU for further reuse of valuable E/E components. Depending on the expected service life and performance, these can either be incorporated as remanufactured components into new ECUs, serve as replacement parts during repair or be used in a cross-industry approach in less demanding use cases. ECUs without further use can be recycled, where dismantleability allows a material sorting beforehand. The least favoured strategy in terms of circularity is thermal recovery.

Centralised EEAs also offer opportunities for circular design strategies. Although the loops of the different strategies are similar to those of conventional EEAs, they offer even more circular potential. The implemented HPCU provides Over-the-Air (OTA)-updateability to expand the range of functions during the use phase. This enables vehicle lifetime extension as the functional expansion allows adaption to future developments. The circular potential can be pushed by making it possible to change not only the software but also the hardware. This can provide recovery of functionalities in case of failure by exchanging components of the same type or even increase the computing power and efficiency of E/E components by upgrading to more sophisticated ones. Thus, the vehicle can be modified more flexibly to future demands of functions such as complex advanced driver assistance systems.

In the EoL stage, a well executed design allows multiple circularity strategies. The reuse of hardware aims to place used E/E components such as integrated circuits, graphical processing units and random access memories from discarded vehicles into HPCUs of active vehicles or even into newly manufactured HPCUs. To ensure viable reuse, thorough quality checks and accurate lifespan estimations are essential. But not only the components on the PCBA level can be reused. With appropriate remanufacturing, used HPCUs can be adopted in the manufacturing of new vehicles or as spare units during the use phase. As the future HPCUs will be more independent in application, a transfer to multiple types of vehicles can be considered (e.g., from high-end to mid-range or entry-level vehicles). EoL treatment of future HPCUs considers the repurposing of hardware in cross-industry applications as the components are maybe no longer powerful enough for automotive applications but can be used in other applications. Similar to the ECUs in distributed EEAs, recycling and recovery of HPCUs can be optimised through a dismountable design, which was covered in the previous section.

4. Case study

The applicability of the proposed approach is illustrated in a case study with a headlight ECU, as shown in Fig. 4. First, the ECU is represented in the PCM and then, the possible circular flows are classified in the ESF. The ECU consists of power electronics and logic components within a housing with a passivecooling radiator mounted with screws directly to the headlight, which represents the vehicle layer. On the housing layer, the outer sealing ring is plugged on. The radiator and the housing are glued together and can only be disassembled by destroying the housing. A reassembly is not possible or only if a new housing component is used. The same applies to the integration of the E/E layer where the PCB is also damaged while it is separated from the radiator. The E/E components such as integrated circuits, transistors and capacitors are mounted to the PCB and can be desoldered depending on whether they are encased in glue or not. Either from the visual or the matrix form in Fig. 4, conclusions in terms of limitation factors or hot spots to focus on in the design stage can be drawn. Using the ESF, possible strategies for circularity can be evaluated. As the product is used inside of a distributed EEA, the range of functions is clearly defined and cannot be modified. The two non-demountable glued joints limit the ECU to be reused or refurbished as a spare part for the same vehicle type or maybe for vehicles with a similar lighting system. In case of maintenance, software updates can be installed or a replacement can be carried out in the event of a fault. The circular flows of components of the E/E layer either as part dispenser for repair or for repurpose are mostly disabled by the product design choices or can be only introduced if solutions are found to open the housing without damaging the electronics. For the EoL scenario, all that remains is material recycling or thermal recovery.



M_A	Interface
Housing	a

M_1	Housing
Housing	
Radiator	ce
Sealing	a

M_B	Radiator
PCB	cd

M_2	-
PCB	-

M_C	PCB
E/E comp.	ab
Connectors	ab

Figure 4. Representing the system structure of an automotive headlight control unit through the PCM and visualising of the capabilities for disassembly/reassembly and circularity through the ESF

5. Discussion and conclusion

This paper addresses the lack of simultaneous consideration of the implementation of circular economy strategies and the technological development of EEAs in the automotive industry. The research objective was twofold: to reconcile ecological awareness with EEA developments through detailed product-tocomponent level analyses, and to provide actionable guidance for product developers as well as decision makers in the product development departments of automotive companies. Specifically, the work aimed to create a framework of possible circular implementation paths for current and future vehicle EEAs and to transfer this theoretical framework into practical application through a user-friendly approach for assessing E/E products' readiness for circular strategies.
To fulfill these objectives, the PCM for the interface mapping of automotive electronics was introduced, accompanied by the ESF, which merges the circular R-strategies from Potting et al. (2017) with the different physical levels of EEAs. The three-layer PCM allows to clearly map components and their relationships, providing a visual aid that breaks down complex automotive electronic products into manageable elements. The PCM's simplified classification of physical joints into destructive and

nondestructive serves as an effective problem identification tool, making product architecture accessible even to stakeholders with non-technical backgrounds. This approach facilitates cross-functional collaboration between engineering, sustainability and business teams, ultimately improving development outcomes.

While the case study analyses an existing product for circular strategies, the approach can also be applied proactively during product development to guide design for circularity. The approach can also have an impact on certain key performance indicators in the automotive industry like reduced carbon footprint and increased material resource efficiency, while simultaneously boosting economic performance indicators through lower material costs and new revenue streams from extended product life cycles. On the product development side, although initial time-to-market might be affected, long-term gains could be expected in product quality, reliability and innovation, ultimately strengthening brand reputation and fostering a more sustainable and resilient automotive industry.

For future research, the approach presented here offers various directions. A transfer of the PCM to a software tool could automate the modeling and visualisation of the product structure, making the approach more accessible to engineers and decision makers. Expanding the ESF to incorporate quantitative environmental impact assessments (including life cycle assessment, circularity metrics and value retention calculations) would enhance its analytical capabilities. Finally, applying the approach in active development projects would provide valuable feedback on its usability while demonstrating its effectiveness in guiding design decisions toward improved circular outcomes in automotive electronics.

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