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ScienceDirect

Procedia CIRP 140 (2026) 533–538

www.elsevier.com/locate/procedia

33rd CIRP Conference on Life Cycle Engineering (LCE 2026)

Retrofit as a Module Driver: Enabling Circular and Service-Oriented Vehicle Architectures

Bastian Nolte[a,*], Pascal Inselmann[b], Umut Volkan Kizgin[a], Sven Wehrend[b], Jana Wendt[c], Katharina Zumach[b], Dirk Clasen[c], Michael Thomas[d,e], Dieter Krause[b], Thomas Vietor[a]

[a]*Technische Universität Braunschweig, Institute for Engineering Design, Hermann-Blenk-Str. 42, 38108 Brunswick, Germany*
[b]*Hamburg University of Technology, Institute of Product Development and Mechanical Engineering Design, Denickestraße 17, 21073 Hamburg, Germany*
[c]*Volkswagen AG, Volkswagen Commercial Vehicles, Berliner Ring 2, 38440 Wolfsburg, Germany*
[d]*Fraunhofer Center Circular Economy for Mobility CCEM, Hermann-Münch-Str. 2, 38440 Wolfsburg, Germany*
[e]*Technische Universität Braunschweig, Institute for Surface Technology, Riedenkamp 2, 38108 Brunswick, Germany*

* Corresponding author. Tel.: +49-152-520-36501 ; *E-mail address:* b.nolte@tu-braunschweig.de

Abstract

The climate emergency has prompted the European Green Deal, triggering far-reaching circular-economy legislation for road vehicles. Emerging directives – most notably the draft End-of-Life Vehicle Regulation – tighten material-recovery quotas and favor business models in which manufacturers retain ownership of their fleets. As a result, the Mobility as a Service (MaaS) business model is becoming increasingly important for the automotive industry, significantly impacting vehicle design and modularization strategies. Unlike the conventional paradigm, which prioritizes personalization and initial purchase decisions, MaaS vehicles experience intensified usage patterns, leading to accelerated aesthetic and haptic degradation of user-facing components. Consequently, product architectures must increasingly take into account simplified maintenance and refurbishment strategies to maintain high perceived quality over prolonged operational lifespans. Current modularization methods, however, do not explicitly address these requirements. To bridge this gap, this paper introduces Retrofit as a dedicated module driver, extending the established catalogue guiding early-stage modular product structuring. Retrofit refers to the systematic capability of exchanging or renewing modules within a vehicle, particularly focusing on swift renewal of interior surfaces and components that rapidly deteriorate under high utilization, thereby safeguarding perceived quality and residual value. To illustrate this concept, the paper presents a case study of an automotive seat module. Seats represent a critical interface for user comfort and vehicle perception, making them ideal for demonstrating retrofit-driven modularization. Using this example, the study shows how Retrofit facilitates rapid, cost-effective replacements and refurbishments of wear-prone interior modules, contributing to improved fleet operability and sustainability. The findings underline Retrofit's strategic role in future automotive product architectures, emphasizing the need for automotive manufacturers to adapt modularization strategies accordingly. Integrating Retrofit as a module driver aligns automotive products with the evolving economic, environmental, and operational objectives of MaaS business models.

Keywords: Retrofit; module drivers; modularization; Circular Economy; Mobility-as-a-Service; Sustainable Product Development

1. Introduction

The climate crisis is acting as a key driver of stricter environmental regulation. Climate change and environmental degradation have been identified by the European Union as existential threats, to which the European Green Deal serves as a central response [1]. This comprehensive policy package not only targets climate neutrality but explicitly aims to promote

10.1016/j.procir.2026.05.090

resource conservation and circular economy principles [2]. In this context, regulatory requirements for circularity in the automotive sector have been significantly tightened. For example, in 2023, the European Commission proposed a new End-of-Life Vehicles (ELV) Regulation, which mandates that at least 25% of the plastic used in new vehicles must originate from recycled sources – of which one quarter must come directly from end-of-life vehicles [3, 4].

Such regulations significantly increase the demand for recyclable materials recovered from end-of-life vehicles. The revised legal framework is specifically intended to create both greater supply and stronger demand for high-quality recyclates in the automotive industry [4, 5]. Analyses within the legislative impact assessment also flag potential supply-demand constraints and feasibility considerations for meeting recycled-content targets [6]. To meet this material demand while retaining value within the product cycle, new business models are gaining relevance. One approach involves not selling vehicles at the end of their first life cycle, but instead keeping them in OEM ownership and continuing to operate them – e.g., through mobility services such as carsharing or Mobility as a Service (MaaS), in which the OEM acts as operator [6, 7]. This allows manufacturers to take back vehicles after use and reintegrate their material content internally.

This paradigm shift introduces new requirements for vehicle durability and adaptability to enable sustainable and economically viable long-term use. Long-lasting components – ideally usable beyond a single vehicle life cycle – become a key success factor, which presupposes a modular design approach. Only through modularity can components and assemblies be efficiently replaced, upgraded, or repaired when needed. Retrofit measures and planned product updates become drivers of modular product architectures, as only a modular system enables efficient adjustments and updates throughout the life cycle [8–10]. This design-for-circularity approach allows vehicles to be configured for extended service life and continuously adapted to evolving requirements – such as technological advancements or new functions – without requiring premature replacement [8, 10]. Moreover, by enabling periodic functional upgrades and planned aesthetic refreshes (e.g., retrofit of visible modules with new functional surfaces), it preserves value and customer acceptance; product appearance is a proven driver of consumer preference and competitive differentiation, and design refreshes can stimulate sales – thereby creating a sustained competitive advantage [11–14].

To clarify the scope of this work, quantitative assessments such as monetary savings, CO_2 reduction potential, or redesign costs are not included. These analyses are beyond the scope of this conceptual and exploratory study, as the objective here is to establish the architectural implications of retrofit rather than to evaluate downstream environmental or economic effects. The present study therefore concentrates on how retrofit acts as a design driver and influences interfaces, structural constraints, and overall product architecture.

2. State of the art

2.1. Retrofit definition

According to the Cambridge dictionary, the term retrofit describes an occasion when a machine is provided with a part that the machine did not have when it was built [15]. It is an approach in mechanical engineering for updating existing equipment, for example machine tools, and making it future-proof, efficient, and sustainable without having to replace it completely [16]. In contrast, the term facelift describes an improvement made to a product in order to increase its customer appeal [17]. It hereby describes design and technical updates during the series production period.

In the field of mobility, retrofitting is particularly common in aviation. This is because, during the typically long service life of an aircraft, the requirements for the aircraft cabin change, which means that the cabin must be redesigned accordingly to meet the new requirements [18]. Aircraft cabins are therefore modernized at regular intervals. This updating or retrofitting of existing aircraft can include, for example, a change in the cabin layout, the replacement of cabin systems or other cabin interior equipment, or the upgrading of the cabin surface [19]. Knowledge and documentation of the current condition of the aircraft is therefore of great importance for planning the retrofit [20].

2.2. Modularization

A modular design offers distinct advantages for retrofitting, as modules can be replaced more cost-effectively. The literature contains a variety of approaches to the design of modular products. The fundamental procedure is consistent across most of them and can be outlined as three core steps: "product decomposition," "analysis and modification of components," and "reintegration into modules" [21]. Depending on how analysis and reintegration are carried out, three approaches can be distinguished: technical-functional, organizational-processual, and product-strategic approaches [22].

One approach that allows both technical-functional and product-strategic aspects to be taken into account is the integrated PKT approach for the development of modular product families. This approach includes various tools to support both the core steps of decomposition and analysis of the product and reintegration into modules. Decomposition and analysis of the components are supported, among other things, by the so-called Module Interface Graph (MIG) [23]. This graph provides a visual representation of the components of a product and their interaction. Reintegration into modules is carried out within the framework of life cycle modularization. In this case, modules are formed based on the concept of module drivers from the MFD [24]. However, specific modularizations are created for each life cycle phase. Once the technical and functional aspects have been addressed, they can be integrated into the module drivers during the product development process. These different modularizations can then be displayed in the MIG and thus easily compared.

2.3. Retrofit approaches in the automotive industry

In the context of research and development on retrofit in the automotive sector, a range of approaches can be identified that pursue both technical and sustainability objectives. Table 1 provides a comprehensive overview of the projects. The projects are differentiated according to their objectives, methodological approach, and the components involved.

The concepts demonstrate the broad spectrum of possibilities for sustainable and safety-oriented retrofitting of existing vehicles.

While Ehsan et al. (2005) [25] investigated the thermally optimized integration of catalytic converters for the purpose of emission reduction, Mazumder (2015) [26] demonstrated a method to achieve structurally stable electrification through the targeted placement of batteries. Lucci et al. (2024) [27] concentrate on assistance systems in the domain of heavy commercial vehicles to enhance road safety.

The concept of "ecofitting" views retrofitting as a holistic, circular economic model that takes into account not only ecological but also social and aesthetic aspects. [28]

Collectively, these works demonstrate that retrofitting solutions offer a forward-looking potential for a sustainable mobility transition [28]. The four works under consideration adopt a retrofitting perspective from the standpoint of private vehicles. The transition to novel mobility applications, such as MaaS, is giving rise to novel requirements that are being integrated into product architecture.

Table 1. Retrofit methods in the automotive industry

Source	Objective	Method	Affected component
Ehsan et al., 2005 [25]	Reducing emissions by retrofitting a catalytic converter	Performing a temperature profile analysis along the exhaust pipe to determine the optimal installation position	Catalyst
Mazumder, 2015 [26]	Conversion of a combustion engine vehicle to electric drive	Driving dynamics simulation, crash tests, thermal analysis and layout optimization.	Battery, electric motor, control unit
Lucci et al., 2024 [27]	Increasing traffic safety by retrofitting of driver assistance systems	Experimental method: sensors are mounted on heavy commercial vehicles and tested.	Cameras, screens, data loggers
Mausbach et al., 2020 [28]	Development of a circular business model for vehicle conversion	Research into design, analysis of the market and integration of culture and aesthetics	Electric drive, interior upgrades, control systems

In the context of Mobility as a Service (MaaS), the requirements for vehicle architectures are undergoing a fundamental shift. OEMs, who increasingly act not only as developers but also as operators of their vehicle fleets, face the challenge of ensuring long-term, economically viable operation while maintaining a consistently high-quality user experience.

2.4. Approaches from other as-a-service domains

Retrofit is also a key element of lifecycle strategy in other sectors characterized by intensive use of as-a-Service products, even if not explicitly labeled as such (Table 2). In micromobility, providers like Swapfiets and Bolt implement systematic maintenance strategies aimed at preserving visual and tactile product quality: frequently used surfaces such as grips, saddles, rims, or plastic covers are regularly replaced, functional components are reused, and hardware is deliberately designed in a modular fashion to enable fast part replacement [29–31]. Similar approaches can be found in the furniture-as-a-service sector. Pei et al. (2022) [33] demonstrate that providers enable multiple reuse cycles through durable materials, modular product architectures, and structured maintenance and return processes. The ability to exchange individual components not only preserves functionality but also helps maintain visual and haptic product quality, a key factor in usage-intensive rental models. In the field of household appliances-as-a-service, studies such as Stiksma (2023) [32] examine circular strategies for extending product lifespans and demonstrate how modular, data-driven approaches, such as digital product passports and assessment systems, can specifically support retrofitting processes. The B2B printing and IT sector also relies on visual and functional refurbishment as part of service-centric business models.

Table 2. Approaches from other as-a-Service Domains

Industry (as-a-Service)	Product	Typical retrofit measures: replacement of	Source
Micromobility	E-scooter, bicycle	Tires, battery pack, controller, lighting, frame components	[29–31]
Household appliances	Washing machine, dryer, dishwasher	Drum, electronics, gaskets, bearings	[32]
Furniture	Sofas, beds	Surfaces/covers, upholstery, screws, casters	[33]
Office equipment (Print as a Service)	Printers, copiers	Toner unit, rollers, firmware, control boards	[34]
IT hardware (B2B) (Device as a Service)	Laptop, tablet, smartphone	Battery, display, memory, fan replacement	[35]

Companies like Canon, Ricoh, and Xerox operate leasing and remanufacturing systems, in which returned devices are both mechanically and visually refurbished before being re-deployed [34]. In the area of IT hardware, Hidalgo-

Crespo et al. (2024) [35] emphasize the importance of circular design principles – particularly modularity, easy disassembly, and standardized interfaces – as enablers for refurbishment and remanufacturing within service-based models such as Device-as-a-Service.

Although these practices are not always explicitly described as "retrofit," they pursue the same objective: maintaining both the functional and aesthetic-tactile value of products under heavy usage within circular, ownership-decoupled business models.

3. Retrofit as a modul driver

This gives rise to a previously underrepresented but strategically relevant module driver: retrofit for aesthetic and haptic value preservation.

In contrast to technology-driven upgrades that introduce new functions or performance features, the retrofit module driver exclusively addresses the renewal and refreshing of user-facing components to maintain the vehicle's visual and tactile quality throughout its service life. This is particularly critical in MaaS operations, where frequent user turnover makes interior perception a key determinant of customer satisfaction.

The following components are particularly relevant within the scope of this retrofit module driver:

- Interior trims: modular structures enabling easy removal and replacement in case of wear, soiling, or damage.
- Seat covers and padding: exchangeable elements for heavy-duty use or brand-specific design updates (e.g. seasonal or service-tier dependent).
- Control and grip components: standardized interfaces allowing fast replacement of worn contact surfaces.
- Floor and footwell areas: modular mats or insert systems to enable cost-efficient maintenance.

Retrofit in this context does not aim at functional upgrades but serves as a strategy for aesthetic maintenance**.** Systematically integrating this module driver into vehicle architecture allows for maintaining a near-new condition throughout operation – both functionally and perceptually. In doing so, retrofit directly supports customer satisfaction, brand perception, and the economic extension of vehicle service life within MaaS business models.

4. Module Interface Graph of an automotive seat

Figure 1 presents the Module Interface Graph (MIG) of a product family of automotive seats. The visualization reveals that the internal frame of the seats is largely standardized, whereas the covers are predominantly variant. In several cases, these variant components are connected via non-destructively separable interfaces, which leads to additional efforts and costs during retrofit. Within the context of Mobility-as-a-Service (MaaS), considering retrofit as a module driver is therefore of strategic relevance, as it enables the evaluation of standardization potential for customer-facing components as well as the separability of interfaces in the modularization process.

Retrofit plays a pivotal role in the transition towards a circular economy, as it extends the operational lifespan of products. Consequently, incorporating retrofit considerations into modularization processes is instrumental in developing product architectures that facilitate long-lasting products.

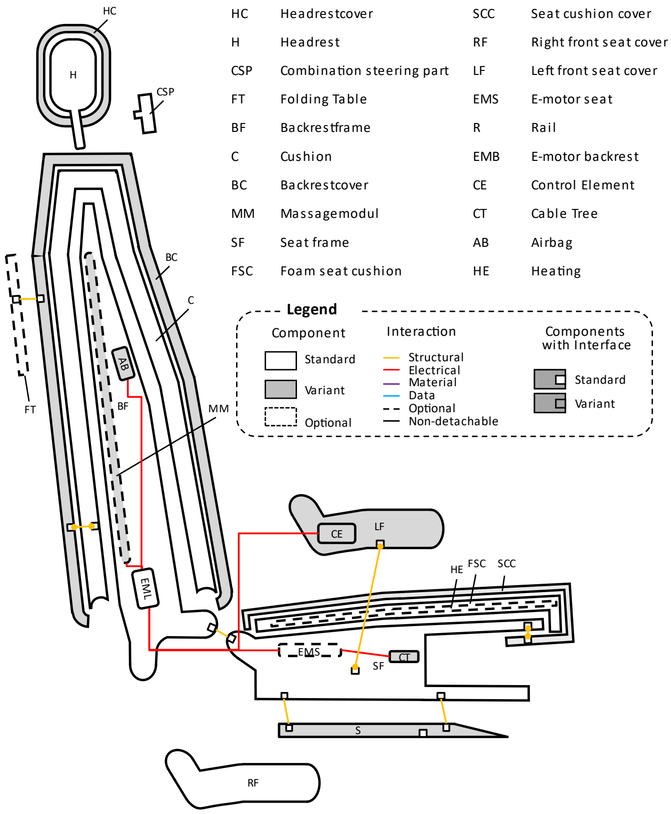

Fig. 1. Module Interface Graph of a product family of car seats.

5. Discussion

5.1. Discussion from a methodical perspective

This work positions retrofit for aesthetic and haptic value preservation as a distinct module driver within lifecycle-oriented product architecture. Methodically, this driver can be operationalized alongside established drivers by introducing perceived-quality (PQ) preservation as an explicit design criterion in early architecture decisions.

Methodologically, this reframes early architecture work around three linked decisions:

- interface and cut-line strategy that enforces a layered module stack – a user-interface layer cleanly decoupled from functional and safety layers;
- standardization of recurrent user-facing modules to enable rapid, repeatable replacement with minimal risk to adjacent systems;
- and evaluation across replacement cycles, extending beyond static BOM or mass considerations to life-cycle cost and life-cycle assessment with multi-criteria decision

analysis that trades refurbishment time/downtime, spare-parts inventory, PQ uplift, and CO_2 equivalent per refresh.

Governance and data feedback are integral: digital product passports and service records support threshold policies and close the loop from field use to architecture updates.

5.2. Discussion from an industry perspective

The use of retrofit as a module driver leads to a fundamental change in the previous approach to vehicle seats. Instead of replacing the entire seat as a single module, the seat is divided into individual, clearly defined modules. The modules to be considered in this context include, for example, the headrest, seat cushion, seat cover, and other components. Replacement therefore no longer takes place at the seat level, but at the component level.

The functionality of this concept requires adequate design of the individual components and their surfaces. In this context, materials that are haptic or optical and that come into direct contact with customers in MaaS vehicles are particularly relevant. The method aims to support the development of standardized interfaces within the seat architecture to enable modular replacement.

The focus is on materials that can be easily replaced after a certain period of use without changing the basic properties and functionalities of the seat. However, challenges arise when integrating new functions into existing structures. Legal requirements that may have changed since the vehicle was originally registered must be taken into account. In certain cases, this may mean that a vehicle with a redesigned interior must be retested. This represents an additional expense that must be carefully evaluated in industrial practice.

5.3 Practical Challenges and Boundary Conditions for Retrofit-Oriented Architectures

Beyond the methodological and industry-specific considerations discussed above, the implementation of retrofit as a module driver is shaped by several overarching practical constraints that frame its feasibility in real-world vehicle systems. A first set of limitations arises from technical integration requirements. Safety-relevant subsystems, such as airbags, sensor units, wiring harnesses, and anchorage structures, follow rigid design rules and functional dependencies that restrict how cleanly a seat can be divided into exchangeable modules. These constraints define non-negotiable boundaries for module separability and interface placement.

A second boundary condition concerns platform and generational compatibility. Vehicle seats vary widely across model years, trim levels, and interior architectures. Differences in geometries, electronics, and fastening strategies reduce the degree to which replacement modules can be standardized or shared across different vehicle variants. Without a certain level of architectural standardization, retrofit solutions risk remaining isolated applications.

Regulatory requirements constitute an additional framework condition. Seats and interior modules must comply with stringent rules on crashworthiness, fire safety, and occupant protection. Retrofit-driven modifications may therefore require additional testing or certification, depending on which visible or functional elements are renewed during the service life.

System-level considerations further influence the overall viability of retrofit. Modular replacement requires refurbishment processes, reverse-logistics capabilities, inspection routines, and suitable inventory strategies. These structures entail organisational and economic implications, as they shape the effort, resources, and coordination needed to implement retrofit concepts at scale. Taken together, these boundary conditions highlight that retrofit as a module driver not only influences product architecture but also interacts with technical, regulatory, economic, and organisational constraints that shape its industrial implementation potential.

6. Conclusion and Outlook

This paper has examined retrofit as a module driver in the context of increasingly stringent circular-economy regulation and the shift towards Mobility-as-a-Service business models. While regulatory pressure – such as the proposed ELV Regulation – requires higher recycled content and longer vehicle lifespans, service-based operation models intensify the need for adaptable and durable product architectures.

The review of existing approaches shows that retrofit is already well established in other domains such as aviation, micromobility, furniture, and IT hardware, where modular architectures and systematic refurbishment strategies ensure long service lives under intensive use. Translating these principles to the automotive sector highlights retrofit not only as a means of functional updating but also as a strategic driver for preserving aesthetic and haptic quality.

The analysis of a Module Interface Graph for automotive seats demonstrated how retrofit-oriented modularization can reveal standardization and separability potential for user-facing components. Embedding retrofit into modularization methods thus provides a systematic way to balance durability, customer perception, and lifecycle sustainability.

The discussion emphasized two complementary perspectives. From a methodological view, retrofit requires formalizing perceived quality over time as a design criterion, integrating replacement cycles into LCC and LCA, and validating interfaces for repeated use. From an industrial view, wear- and design-related retrofits can be operationalized to sustain service quality, while hardware-based upgrades to meet new legal requirements remain a challenge when applied to legacy structures.

Future work should focus on

- metrics and accelerated tests for perceived-quality degradation,
- decision models capturing both economic and ecological effects of retrofit cycles,
- robust interface design rules to manage modularity without compromising safety, and

- strategies for scaling retrofit across fleets and product generations.
- integration of new surface functionalities to enable more user-friendly and smart interaction, increase durability, or facilitate easier cleaning.

Extending retrofit from aesthetic refreshes towards functional hardware upgrades represents an open research field with significant potential to align competitiveness, customer acceptance, and regulatory compliance in future mobility ecosystems.

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