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Systematic Design Approach for Functional Integration of Vehicular Wireless Power Transfers Modules

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Abstract: This paper presents a systematic design approach to the development of functionally integrated mechanical-electrical lightweight systems. The development of these systems requires the end-to-end consideration of all product domains involved, aspects of lightweight design and their mutual interdependencies. To manage this complexity, a specialized approach is developed, which extends the V-model of VDI 2206 problem-specific and purpose-oriented. In line with the proposed approach, this work presents the conception and evaluation of three functionally integrated on-board receiver units of automotive wireless power transfer systems for electric vehicles. These concepts provide a significant reduction of the vertical dimensions, which significantly increases the applicability and transferability of wireless power transfer systems.

Keywords: systems engineering; mechanical-electrical systems; functional integration; wireless charging; electric vehicles

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1. Introduction

The electrification of powertrains consistently increases vehicle weights, therefore the construction of necessary technical structures in a consistent lightweight design is inevitable [1,2]. In particular, the functional integration of active and passive electrical or electronic elements into existing mechanical lightweight structures enables a mass and volume reduction by combining several functions into a single component.

The design of these mechanical-electrical lightweight systems (MEL) requires the synergistic interaction of the domains involved, taking into account additional aspects of lightweight design such as design, production and dimensioning. Figure 1 illustrates the interactive engineering of functionally integrated MEL (FIMEL). Thus, the development of MEL requires an end-to-end consideration of multiple interdependencies between activities of the development process and the electrical elements, which functionally upgrade the composite structure. Only mastering of all interfaces within the development process leads to a FIMEL meeting all requirements, whereby the particular challenge is to harmonize different ways of thinking and working practices of the disciplines involved.

Existing design approaches focusing on interdisciplinary and cross-domain development tasks are specified towards the systematic development of product-neutral [3–5], mechatronic [6–8] or lightweight-specific designs [9,10]. Several approaches describe the simultaneous development of individual domains involved [4,5,8,11], whereby none of the existing approaches links the working strategies of all domains involved to enable the simultaneous development of novel FIMEL and its corresponding manufacturing and joining technologies. Therefore, a problem-specific and purpose-oriented approach is required, which supports synergistic interactions of the disciplines involved and considers additional aspects of lightweight design for the development of FIMEL.

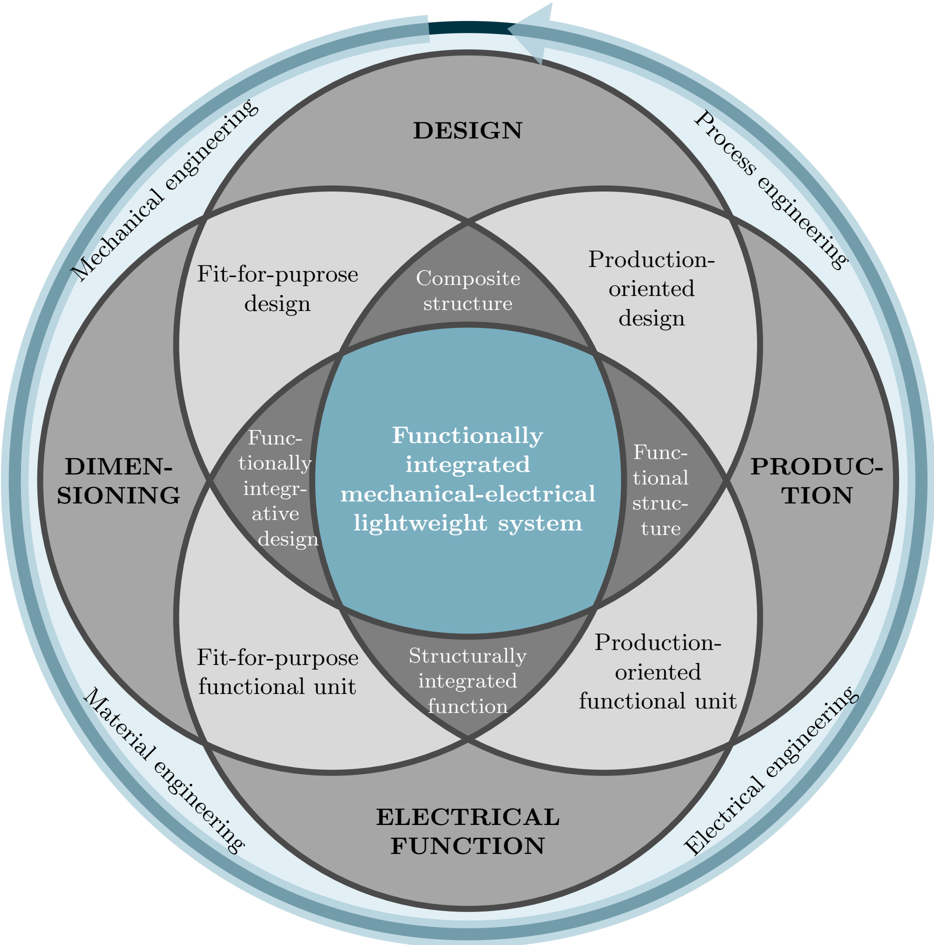

Figure 1. Interactive engineering of functionally integrated mechanical-electrical lightweight systems.

This paper presents a systematic approach to the development of FIMEL, which extends the V-model to an end-to-end cross-domain development process by combining the interactive engineering of MEL and additional aspects of lightweight design. This approach is shown on the example of the development of functionally integrated wireless power transfer systems (WPTS) for electric vehicles (EVs). In particular, the size and the spatial distribution of the coil, ferrites, and shielding to be integrated requires a consistent transdisciplinary synthesis of the domains of mechanics, electrics, material, manufacturing and assembly. Using the proposed design approach enables the development of three different functionally integrated WPTS with a significantly reduced vertical dimension (z-dimension) and high volumetric power density compared to existing designs given in [12]. Due to the reduced z-dimension, the presented concepts improve the vehicular installation possibilities to the entire underbody area, the charging possibilities for users and the interoperability of WPTS for EVs.

The paper is divided into five sections. Based on the state of the art for functional integration of MEL in Section 2, Section 3 shows the specialized V-model. The applicability of the proposed approach is demonstrated on the development of functionally integrated receiver units of WPTS for EVs in Section 4.

2. Functional Integration of Mechanical-Electrical Lightweight Systems

The design of FIMEL aims at upgrading lightweight systems with additional electrical functionalities to achieve higher-level development goals such as cost, weight or space reduction. Therefore, the development of these systems requires an end-to-end cross-domain engineering approach considering additional aspects of lightweight design (see Figure 1). Based on the formulation of challenges and requirements, this section analyzes known approaches and derives recommendations for an adapted design approach to the development of FIMEL.

2.1. Challenges and Requirements

Functional integration is a design process increasing the functional density and/or the degree of space utilization of a given system. The level of integration increases due to the introduction of additional functions, the reduction of the required space or the number of components [9,13]. Thus, it can be systematically increased depending on the functional elements to be integrated and the chosen type of design.

The type of design can be classified between two extrema: differential design and integral design. Differential design strives for maximum functional separation, whereas integral design focuses on the minimization of the number of individual parts. The optimal design for functional integration is an intersection of both extrema: integrated design. It is defined as the expedient limitation of spatial integration using a minimal number of elements required. Thus, a transdisciplinary synthesis of the required elements and their applicability for spatial integration is required to achieve the optimal level of integration [14].

Depending on their size, the electrical elements to be integrated are miniaturized or macro-scaled compared to their carrying structure. Miniaturized elements such as sensors or antennas are typically integrated centralized on carrier plates such as printed circuit boards (PCB) resulting in an integral design [15,16]. The mechanical properties of miniaturized elements are typically neglected, as they affect the structural integrity of the composite structure mainly through their geometry [17,18]. Consequently, the design or layouts of the composite structure is adapted to ensure a sufficient structural integrity [15]. In contrast, macro-scaled elements such as coils or switches are distributed spatially in the composite structure using differential or integrated designs [19]. Due to the decentralization combined with the size of the elements, the mechanical properties of macro-scaled elements significantly affect the mechanical dimensioning of the MEL. Consequently, their mechanical properties are not negligible.

An efficient process to the development of FIMEL supports the functional integration of miniaturized and macro-scaled elements. This requires a systematic design approach meeting the following requirements:

- **Generality**: The approach is independent of the specific application, i.e., solution- and product-independent. Thus, the development process is problem-specific, purpose-oriented, situation-oriented, adaptable and expandable. Consequently, it supports all types of construction (new construction, modification design and variant design).
- **Totality**: The approach structures the development process holistically from requirement analysis to elaboration.
- **Intelligibility**: The approach provides an easy-to-understand idea and consistent methodical support. Regardless of the developer's experience, the procedure is easy to apply.
- **Cross-domain collaboration**: The support of a cross-domain and interdisciplinary way of working is imperative. It is supported by methods throughout the development process. In particular, the easy transition of cross-domain and domain-specific methods is taken into account.
- **Interaction of product and production**: The development of FIMEL requires consistent consideration of the interactions between product and production system. This interdependence is synchronized by appropriate methods.
- **Equality of domains**: The project-specific domains and their established way of working is treated on an equal footing and, if necessary, synchronized.

- **Support of functional integration**: The development of FIMEL requires the interactive coordination of design, production, dimensioning and electrical functions (see Figure 1). This results in consistent interactions of mechanical, electrical, material and process engineering as wells as assembly. The approach consistently provides methodical support for mastering these interdependencies.
- **Consistent requirements management**: The consistent detailing during the development process requires an end-to-end management of requirements. Consequently, the approach enables transparent analysis and synthesis of requirements and priorities along the entire development process.
- **Modeling and simulation**: The approach supports the implementation of mathematical, numerical and physical models, as well as simulations along the entire development process.
- **Control of progress**: The interdisciplinary development process of FIMEL requires the synchronization of the development results. Consequently, the approach provides stage gates or control points for synchronization as well as possibilities for progression and iteration.

2.2. *State-of-the-Art Design Approaches*

Interdisciplinary and cross-domain development tasks are very complex due to the high number of interfaces and interactions. Thus, systematic approaches are required to solve these types of development tasks efficiently and target-oriented.

For the development of MEL, appropriate approaches can be classified as product-neutral, mechatronic and lightweight-specific depending on their product specification. Product-neutral approaches are typically based on VDI 2221 [3] with the main phases: clarifying and adaptation of the task, elaboration of the solution concept, designing the modules and elaborating the details and verification. Based on this approach, the works of Vielhaber and Stoffels [4] Roos et al. [5] interactively combine the development of product and production system. Furthermore, the work of Stoffels [11] enables the simultaneous consideration of the material system. Moreover, the approach of Grunwald [20] supports the synthesis of product and assembly system. However, none of these approaches address the development of mechanical-electrical products.

In the context of mechatronic product development, the well-known V-model [6] for the development of mechatronic products provides a generic approach, which supports cross-domain development tasks by merging discipline-specific guidelines. For this reason, it serves as a framework for many authors to develop task-specific and purpose-oriented strategies in the context of interdisciplinary developments. In this respect, several authors use the V-model to specify the synthesis of mechatronic product development with additional aspects such as quality assurance of embedded software [21] or reliability engineering [22,23]. Furthermore, several authors developed adapted design approaches for the development of mechantronic products [24,25], lightweight mechatronic products [26], adaptronic products [7] and cybertronic products [27]. All mentioned approaches based on the V-model focus on cross-domain system design and system integration, whereas the detailing of the product is carried out domain-specific. This can result in communication issues between the departments involved, as each department develops a discipline-specific optimum [28]. However, the global optimum does not necessarily result from a straightforward combination of the local optima. Therefore, the approach of Watty [29] for the product development of microsystems technology proposes an end-to-end cross domain development process. However, no specific guidance is given on how to implement the cross-domain design in practice.

Irrespective of the V-model, the approach of Kallenbach et al. [30] for development of mechatronic products focuses on the interaction between function and design based on the product-neutral design approach of VDI 2221 [6]. However, methods or guidelines are not recommended. Interactions between the product and the production system are also not taken into account. Especially for the development of highly complex mechatronic systems, the design approach of Brudniok [31] enables the management of complexity due to the interdependencies between the variety of spatial and functional integrated individual elements. However, the approach focuses on the domain of mechanical engineering and its methods, while the other domains of mechatronics are considered only in an accompanying way. Consequently, the impact of cross-domain interactions on the development of FIMEL is not sufficiently taken into account. An integrated approach for the transdisciplinary planning and synchronization of mechatronic product development processes based on partial models is presented in [28]. In particular, this approach focuses the management of interdependencies between the domain-specific departments involved. However, an existing product architecture is required for the conception of the production system. Especially in the development of innovative FIMEL, this is not effective due to the influence of the manufacturing process on the product properties. Moreover, an integrative development process has been established for the design of mechanical-electronic products, which takes into account the numerous interactions from the product and production system at an early stage [8,32]. On this basis, an adapted design approach for development of molded interconnect devices (MID) is presented in [33], which considers the interactive development of product and production system as well as the interdisciplinary interactions with the other domains such as electronics or assembly. However, the specific approach is limited to the production process of laser direct structuring. As a result, this production-driven product development requires a high degree of maturity and a comprehensive understanding of the corresponding production system. Based on the work of Kaiser [33], a design approach for the optimization of the exisiting MID and their corresponding manufacturing process is presented in [34]. Analogous to Kaiser [33], this approach requires a manufacturing process with a high degree of maturity. In particular, these conditions are not yet met in the development of innovative products manufactured and joined with novel technologies.

The development of complex lightweight products requires an interactive engineering approach, taking into account the different dependencies between selected lightweight design, materials and manufacturing technologies [9,10]. In this respect, the authors of [35,36] extended the product-neutral design approach of VDI Verein Deutscher Ingenieure [6] to lightweight-specific strategies regarding conception, dimensioning, material and manufacturing. However, this requires a high expertise of the engineer in terms of lightweight designs. To handle this complexity, the approaches of Helms [10] and Modler et al. [9] include the continuous synthesis of lightweight design and manufacturing systems as well as an end-to-end management of requirement. Based on this approach, Weck [37] recommended the development of the electrical or electronic elements to be integrated according to the serial method of product-neutral approaches given in [3,38]. The synthesis of the functional module and the integration into the lightweight system is carried out interactively considering construction, dimensioning and production. This approach is particularly suitable for FIMEL with miniaturized elements and a small amount of interdependencies between the elements. In addition, the approach requires an extensive knowledge about the interaction of the individual elements and their effect to the mechanical properties of the lightweight system.

2.3. Needs for Action

Based on the proposed requirements, the state-of-the-art engineering approaches for the development of lightweight and mechatronic or mechanical-electrical products are evaluated with regard to their suitability for the development of FIMEL. Table 1 gives an overview of the evaluation, which serves as a basis for deriving needs for action.

In the overall analysis, none of the approaches examined meet all defined requirements for the development of FIMEL. The main deficiencies are:

- There is an insufficient linkage between the working strategies of the domains.
- The methodical support for an efficient and purpose-oriented development of functionally integrated products is insufficient.

- There is no guideline for the simultaneous development of novel FIMEL and its corresponding manufacturing and joining technologies.

Table 1. Analysis of product-neutral, mechatronic and lightweight-specific approaches based on selected requirements for the development of functionally integrated mechanical-electrical lightweight systems.

	Generality	Totality	Intelligibility	Cross-Domain Collaboration	Interaction of Product and Production	Equality of Domains	Support of Functional Integration	Consistent Requirements Management	Modeling and Simulation	Control of Progress
Product-Neutral Approaches										
GRUNWALD [20]	●	●	●	●	◑	●	○	◑	○	◑
MIP [5]	●	◑	●	◑	●	●	○	●	●	◕
PAHL/BEITZ [38]	●	●	●	○	○	○	○	●	○	◕
STOFFELS [11]	●	●	●	●	●	●	○	◑	◑	◕
VDI 2221 [3]	●	●	●	○	○	○	○	●	○	◕
VIELHABER [4]	●	●	●	◑	●	◑	○	●	○	●
Mechatronic approaches										
3-LEVEL-MODEL [21]	●	●	●	◑	○	●	◑	◑	◑	◑
2V-MODEL [23]	◑	●	◑	○	○	○	○	◔	○	○
BRUDNIOK [31]	◑	●	◑	◑	○	◑	◕	◑	●	◕
HELLENBRAND [28]	●	◑	◕	●	●	◑	○	○	●	◑
KALLENBACH [30]	●	●	●	○	○	●	○	○	○	◑
KAISER [33]	●	◕	●	●	◕	●	●	◑	◑	◕
PEITZ [34]	◑	◑	●	◑	◑	●	◑	◑	◑	◑
VDI 2206 [6]	●	●	◕	◕	◑	●	○	◔	●	○
VIRES [8]	●	◕	●	●	●	●	◕	◑	◑	◕
INERELA [24]	●	●	●	●	◕	●	◕	◑	●	◕
LÜDECKE [26]	●	●	●	◑	○	◑	◕	◑	●	●
ISERMANN [25]	●	●	●	◕	○	●	○	◑	◑	◑
NATTERMANN [7]	◑	●	●	●	○	●	◑	●	●	●
Lightweight-specific approaches										
ELLENRIEDER [35]	◕	◑	●	○	○	○	◑	○	○	○
HELMS [10]	●	◑	◕	◑	●	●	◕	●	○	◑
KLEIN [36]	●	●	●	○	○	○	○	●	○	○
MODLER [9]	●	●	●	○	○	○	○	●	○	○
WECK [37]	●	●	●	◕	●	●	●	○	○	○

○ not addressed; ◔ hardly fulfilled; ◑ rudimentary fulfilled; ◕ partly fulfilled; ● completely fulfilled.

Due to these reasons, an end-to-end cross-domain systematic design approach is required, which combines the interactive engineering of MEL with additional aspects of functionally integrated lightweight design and takes into account the various interdependencies of mechanical, electrical, material and process engineering.

3. V-Model to the Development of Mechanical-Electrical Lightweight Systems

On the basis of the proposed requirements and the analyzed deficiencies of the state-of-the-art design approaches, an adapted systematic design approach to the development of FIMEL was developed. Figure 2 illustrates the proposed approach, which addresses the identified needs for action through a problem-specific synthesis and adaptation of the established approaches. The abbrevations used in the approach are given in Table 2. The authors already published the basic idea of the proposed approach in [39]. However, the presented work extends this basic idea to a specific framework for the development of FIMEL.

According to Ponn and Lindemann [40], the proposed approach is divided into two spaces of concretization: the product-property space (PPS) and product-solution space (PSS). The PSS is categorized in the system level, module level and component level. At each hierarchical level, the PSS includes all requirements, functions, active principles and components. The consideration of their mutual interdependencies leads to a progressive detailing of the PSS by analyzing, varying and detailing. As part of the PSS, it contains all modules and property-inducing domains of the development process, which results in a three-dimensional V-model. In particular, consistent property-based analysis and synchronization of the domains involved, as described in [41], restrict and detail the product step by step. This enables the development of MEL to an optimum in the sense of systemic lightweight design, which does not necessarily result from a straightforward merging of optimal subsystems or modules.

The PPS is divided into macro and micro phases, which are terminated with macro-control points (MACP) or micro-control points (MICP). While the macro phases include all hierarchical levels of the PSS, the micro phases are limited to a specific hierarchical level. According to Lüdeke [26], the control points are used for analysis and synchronization of the cross-domain product properties. Consequently, the control points are the starting point of progression and iteration.

Derived from Nattermann and Anderl [7], the requirement analysis is part of the development process to ensure a cross-domain understanding of the development task. According to Mattmann [41], the requirements and boundary conditions are formulated as quantified target values to ensure property-based analysis and synthesis across all product domains throughout the entire development process. Finally, all requirements are captured, documented and assigned to the product domains.

According to Lüdeke [26], the conception is based on the procedure of the well-known V-model. However, the top-down principle is intended as decomposition strategy based on the concept of Shishko and Cassingham [42]. Thus, the system is decomposed to the component level being a reasonable limitation for MEL. On this basis, the concepts are progressively developed from the specification of functions to components. Contrary to the concept of the V-model, a domain-specific partitioning of individual functions, modules and components is pointless due to the mutual interdependencies between the domains of MEL. The conception results in at least one principle design, which is developed and evaluated across domains based on the requirements known at this stage of development. Moreover, the manufacturing and joining technologies, including tooling concepts and materials, are assigned to the principle designs.

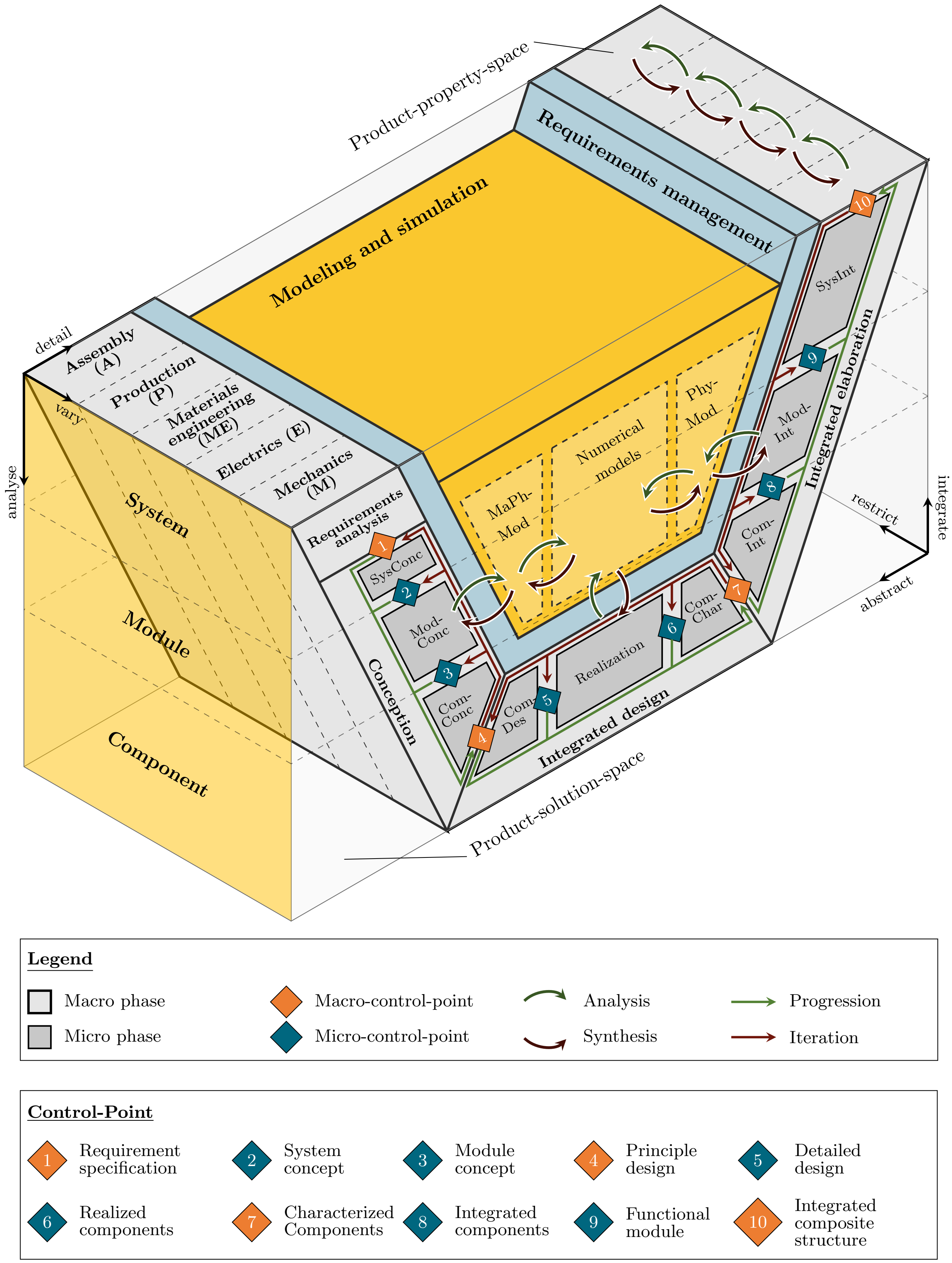

Figure 2. Systematic design approach to the development of functionally integrated mechanical-electrical lightweight systems.

Table 2. Description of the abbreviations used in the proposed approach.

Acronym	Description
ComChar	Component characterization
ComConc	Component conception
ComInt	Component integration
ModConc	Module conception
ModInt	Module integration
MaPhMod	Mathematical-physical models
PhyMod	Physical models
SysConc	System conception
SysDes	System design
SysInt	System integration

Based on the principle designs, the integrated design is used for detailing, implementation and characterization at component level. Incompatibilities by integrating the individual components to modules are examined using modeling and simulation up to system level according to Nattermann and Anderl [7]. The integrated design differs depending on the architecture of the principle designs. In the case of differential designs, the components are mainly detailed domain-specific. In contrast, integral designs require consistent cross-domain interactions to evaluate functionalities and to manage implications of design changes. Finally, all components are defined and characterized numerically and experimentally across domains. Furthermore, the processes and tools for production and assembly are implemented and tested.

The integrated elaboration describes the gradual integration of characterized components for successive optimization of FIMEL. Similar to the previous macro phase, the procedure differs depending on the architecture of the principle design. Integral designs require a component-by-component validation of functionally integrated electrical elements from component level to system level. Contrary, differential designs can be integrated directly at the module level. Parallel to the integration of the product components, the process modules are integrated for an efficient production and assembly. Consequently, a validated FIMEL as integrated composite structure with corresponding production and assembly technologies is available at the end of this macro phase.

The end-to-end requirements management links the property-inducing domains with modeling and simulation throughout the entire development process. This avoids time-consuming iterations and increases transparency between domain-specific departments [43]. The administration of the requirements can be executed document-based or computer-aided.

Managing the complexity to develop FIMEL requires continuous support by computer-aided tools such as qualitative and quantitative models. Qualitative models describe requirements, functional, collaborative or logical structures and basically support the development of product architectures. As product concretization increases, domain-specific or cross-domain quantitative models in the form of mathematical-physical (MaPhMod) or numerical modeling enable simulative validation of product properties. Alternatively, the design of physical prototypes (PhyMod) can progressively support the development at an early stage [44]. Accordingly, the methodical chain of modeling from mathematical-physical models to physical prototypes can be adapted on demand. Thus, the development process for modification design or variant design can be shortened under the condition of a comprehensive knowledge of the collaborative interactions of the individual product components and high quality models.

4. Functionally Integrated Lightweight Designs of Vehicular Wireless Power Transfer Modules

This paper shows the applicability of the proposed systematic design approach on the example of the development of functionally integrated lightweight designs of vehicular WPTS. This includes the development of a highly integrated car pad module (CPM) of

WPTS for EVs with a transfer power of more than 3.6 kW. The development target is to combine the structural function of underbody covers (UBCs) and the electrical functionality of CPMs aimed at significantly reducing the z-dimension compared to existing designs. As a result, the vehicular installation possibilities are extended to the entire underbody area. Figure 3 shows the components of conventional CPMs and respective power electronics, which can be installed internally or externally in a separate housing. Figure 4 illustrates the development target.

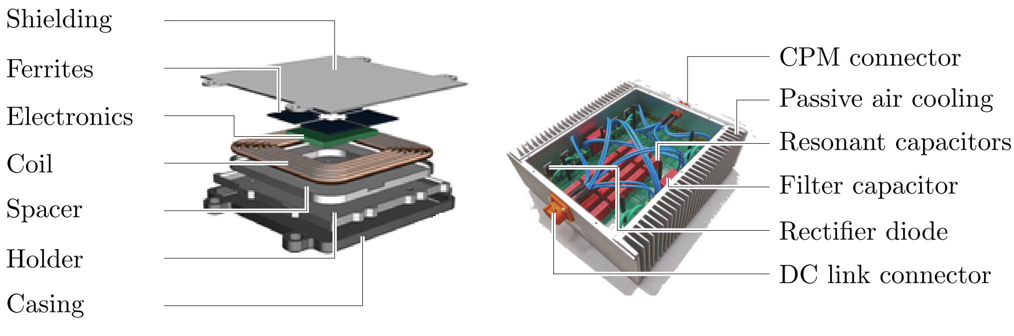

Figure 3. Components of conventional CPMs: (**a**) CPM; and (**b**) external power electronics.

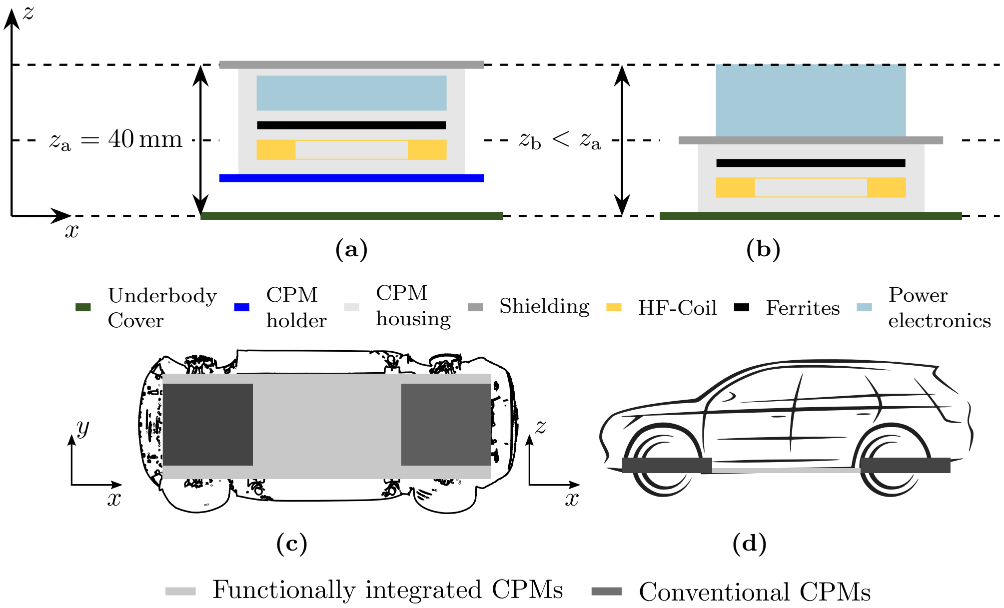

Figure 4. Qualitative comparison of the z-dimension of: (**a**) conventional designs of CPMs with a maximum transmission power of 3.6 kW given in [12]; (**b**) the functionally integrated CPM to be developed with a transmission power of more than 3.6 kW; and (**c**,**d**) possible installation space of CPM designs in (**c**) xy-plane and (**d**) xz-plane.

4.1. Requirements Analysis

According to the development task, the requirements of the FIMEL to be developed result from the combination of the system specifications and the boundary conditions of the UBC and the CPM. An efficient approach for capturing requirements arising from the integration of both systems is the partitioning of boundary conditions and technical specifications to the product domains. Table 3 summarizes and assigns the system specifications and boundary conditions of the FIMEL to be developed to the product domains. In addition to these requirements, underfloor impact scenarios must be taken into consideration due to the specific installation position of CPMs on the underbodies of EVs. These requirements are given in [12].

Table 3. System specifications and boundary conditions for the development of functionally integrated CPMs.

Domain	Parameter	Variable	Range of Values	Unit
E, M	Air gap	s	100–210	mm
E, M, P, A	Area of CPM coil (x,y)	$A_{\mathrm{CPM,max}}$	300 × 300	mm^2
E, M, P, A	Area of UBC (x,y)	$A_{\mathrm{UBC,max}}$	916 × 593	mm^2
E	Battery voltage	V_{batt}	300–470	V
E, M, ME	Cooling flow rate	$v_{\mathrm{c,air}}$	2.5	$\mathrm{m\,s^{-1}}$
E, M	Efficiency	η	>80	%
E	Input power	P_2	3.6–11	kW
E	Input voltage	V_1	0–540	V
E	Magnetic field strength at periphery of EVs	H_{per}	<21.5	$\mathrm{A\,m^{-1}}$
E, M, ME	Maximum ambient temperature	$T_{\mathrm{amb,max}}$	80	°C
E, M, ME	Minimum ambient temperature	$T_{\mathrm{amb,min}}$	−40	°C
E, M, ME	Misalignment longitudinal	$\triangle x$	±75	mm
E, M, ME	Misalignment transversal	$\triangle y$	±150	mm
M, P, A	Lot size	N	<10	
E, M, ME	Operating temperature	T_{oper}	<110	°C
E	Output voltage	V_2	300–470	V
E	Transmission frequency	f_0	81.38–90	kHz

M, mechanics; E, electrics; ME, material engineering; P, production; A, assembly.

4.2. Conception

The conception aims at deriving principle designs, which are synchronized across all product domains. For that reason, the progress of the product domains is analyzed and synchronized at specific micro-control-points from system level to component level. Regarding to CPMs, various integration levels are conceivable on system level considering components of the magnetic circuit and the power electronics. Table 4 summarizes five potential integration levels. Assuming an integral design, the system boundary is gradually shifted to a minimum integration of coil and ferrites, as the local proximity of these components is absolutely necessary to ensure sufficient magnetic and thermal coupling. The shielding can be integrated or applied independent of the product architecture.

Considering various criteria, a cross-domain evaluation of the integration levels was executed according to Table 5. On this basis, Levels 1 and 5 were assessed as most promising with regard to the development goals. Level 1 inherently leads to the lowest total volume and weight, since additional interfaces and assembly points are eliminated. Thus, assembly and production costs as well as the use of materials are reduced. However, the integral system architecture results in a high complexity due to the high amount of interactions between the domains. Level 5 enables the highest reduction of z-dimension. The spatial integration of the magnetic active components results in a partial decoupling of the magnetic and electronic domain. This reduces the complexity on component level. However, the distribution of the voltage compensation between two spatially separated assemblies is challenging and requires special effort in assembly and insulation.

Table 4. Potential integration levels of functionally integrated CPMs.

Components \ Integration Level	1	2	3	4	5
Coil	UBC	UBC	UBC	UBC	UBC
Ferrites	UBC	UBC	UBC	UBC	UBC
Compensation capacitors	UBC	UBC	UBC	UBC	Box
Rectifier and cooling	UBC	UBC	UBC	Box	Box
Filter	UBC	UBC	Box	Box	Box
Measuring electronics and communication	UBC	Box	Box	Box	Box
Shielding	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid

Table 5. Cross-domain evaluation of the integration levels.

Domains	Criteria	Integration Level 1	2	3	4	5
M, E, ME, P, A	Weight	●	◑	◑	◑	◔
E, ME	Insulation	●	◑	◑	◑	◔
E, ME, P, A	Contacting	●	◕	◕	◕	◔
M, E, ME, P, A	Recycling	○	○	○	◑	◕
E, ME	Shielding	●	◕	◔	◔	◔
M, ME	Structural integrity	◕	◕	○	○	●
M, E, P, A	Maintenance	○	◔	◑	◕	●
E, ME	Efficiency	●	◕	○	◑	◔
M, E, ME, P, A	z-dimension	○	◑	◑	◑	●

○ very bad; ◔ poor; ◑ acceptable; ◕ good; ● very good. M, mechanics; E, electrics; ME, material engineering; P, production; A, assembly.

The conception progresses across hierarchies at the module and component level due to the functional architecture of CPMs. According to the preferred integration levels, the system is decomposed into the respective components listed in Figure 5. On this basis, their characteristics are specified using a morphological box, which supports the interactive conception of FIMEL by taking into account the mutual dependencies of the product domains. As the power electronics is specified as integrated or externally applied, a proper consideration of this component is disregarded.

The combination of the characteristics is based on the preferred integration levels. This results in a sandwich concept (red path), a space-frame concept (green path) and a shell concept (blue path), whereby the concept names are derived from the characteristic of the underbody cover. These serve as basis for the development of detailed principle designs. Figure 6 illustrates the resulting designs of the proposed concepts.

The sandwich concept is based on a sandwich core, which serves as a milled carrier element for the electrical and electronic components. The core element is bonded to a stiff top and bottom layer. The top layer is made of GMTex and the bottom layer carried out as aluminum sheet utilized as shielding. Thus, this type of composite structure is characterized by a high bending stiffness combined with a low z-dimension.

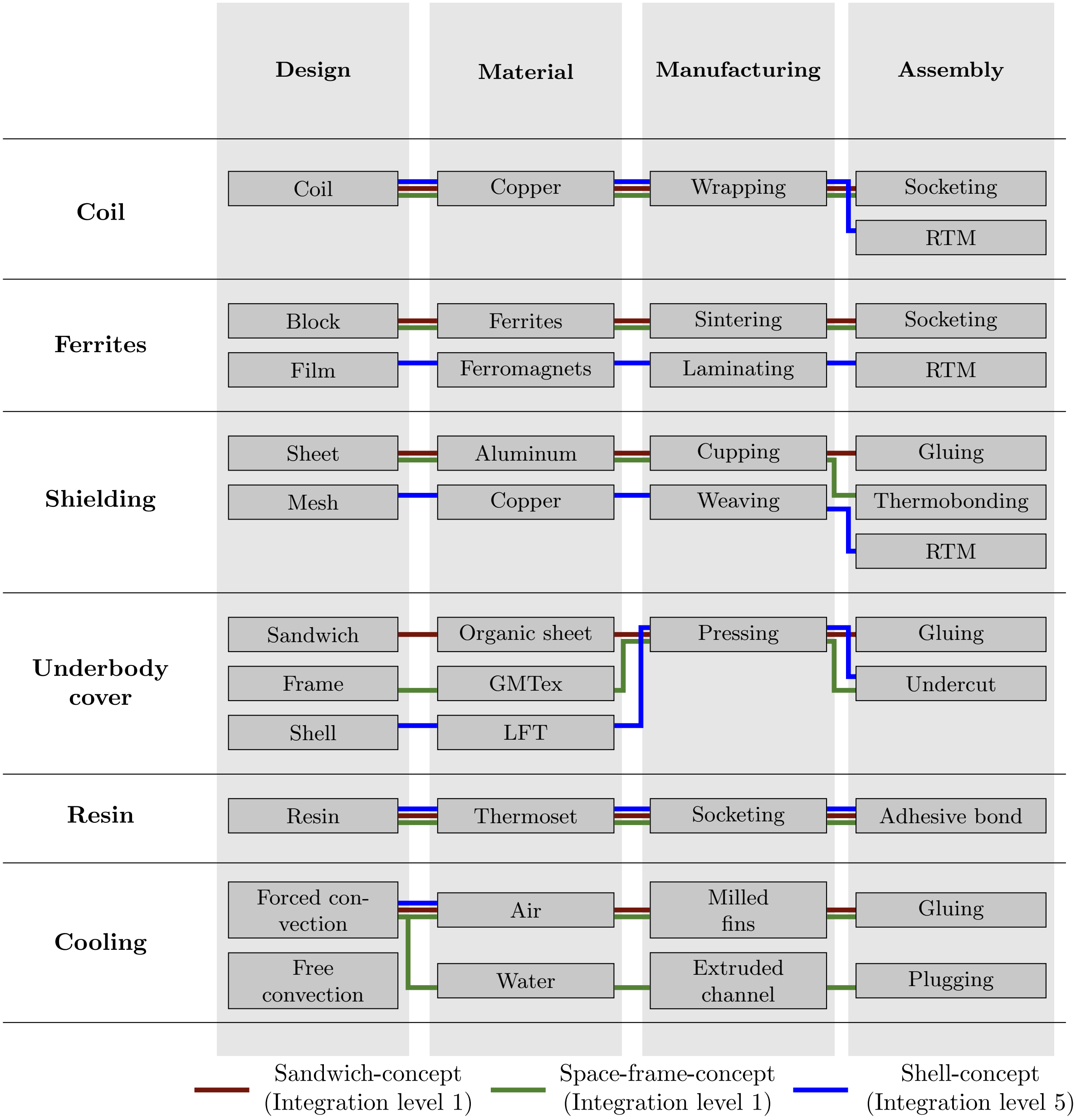

Figure 5. Proposed morphological box to the conception of functionally integrated CPMs.

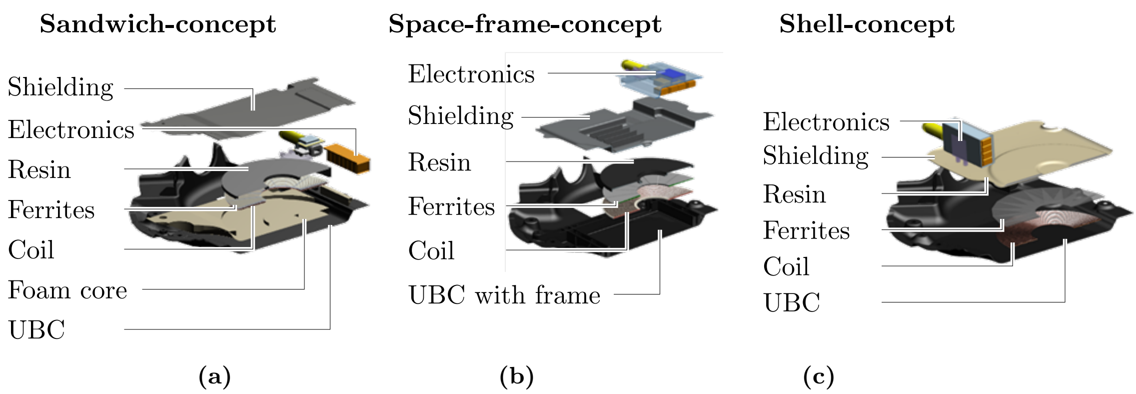

Figure 6. Proposed concepts of functionally integrated CPMs: (**a**) sandwich concept; (**b**) space-frame concept; and (**c**) shell concept.

In contrast to the sandwich concept, the space-frame concept provides stiffness by local ribs added to the UBC. Thus, this concept enables the use of endless fiber reinforced materials to protect the integrated components. The aluminum shielding is thermally bonded to the local ribs. Thus, the power electronics is located on top of the shielding.

According to integration Level 5, the shell concept is designed for the functional and spatial integration of the coil, the ferrites and the shielding by using a thermoset resin with a high thermal conductivity to ensure adequate thermal coupling. Contrary to the previous concepts, this design is intended to allow deflection within safe limits. Consequently, the integrated components must have sufficient elongations at break, while ensuring the structural integrity of the composite structure. For that reason, the use of conventional ferrites is not feasible due to their brittle fracture behavior. Besides, the use of aluminum shielding in form of sheets is challenging, as this significantly reduces the mechanical properties of the composite. Instead, ferromagnetic sheets and textile metal meshes are intended. However, the development of this functionally integrated CPM is very challenging to the current state of the art. Therefore, it is gradually detailed within the integrated design.

4.3. Integrated Design

The first step of the integrated design is to detail the components of the principle designs in terms of shape, material and tolerances. Modeling and simulation is used to evaluate incompatibilities between the components up to system level, taking into account all product domains. In this respect, specialized electromagnetic, thermal and structural models were developed, which are partly given in [45]. This results in a detailed magnetic circuit to be integrated combined with an adequate power electronics depending on the architecture of the respective concepts. Figure 7 shows the magnetic circuit components of the proposed concepts.

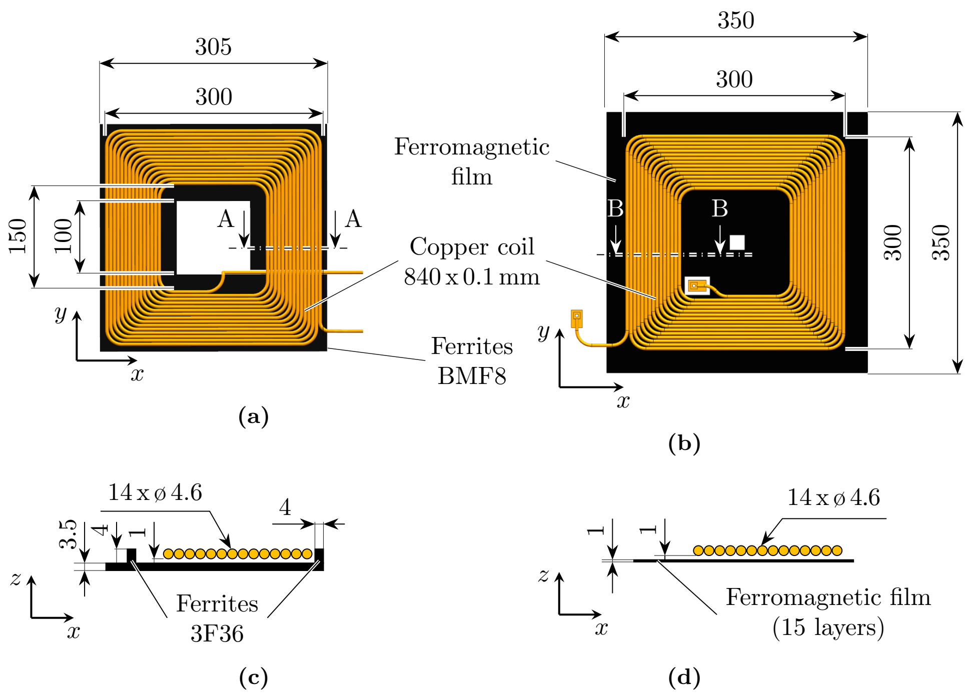

Figure 7. Dimensions of the CPM components (unit: mm): (**a**) sandwich concept and space-frame concept; (**b**) shell concept; (**c**) section A-A; (**d**) section B-B.

Based on the detailed designs, the components are physically realized with appropriate processes and tools. At this stage, the domain-specific realizations are not fully parallelizable, as suitable elements must be available for the production of product components. The following component characterization describes the experimental and simulative evaluation of the components according to their specifications. This micro phase is of decisive importance, as it enables verifying and validating the basic simulation models of FIMEL within the development process for the first time. Consequently, the degree of concretization can only be increased with incremental iterations and progressions. To ensure an efficient knowledge gain, the experimental studies of the CPM components were parallelized using electrical, thermal and mechanical as well as cross-domain testing. The authors intend to publish the results in upcoming papers, therefore only a brief description is given herein.

4.4. Integrated Elaboration

Based on the characterized components, the structural integrity is studied. This is executed component-by-component in the case of the shell concept, whereas the differential designs of the sandwich and space-frame concepts enable direct integration at module level. Incompatibilities are progressively eliminated by iterations. For that reason, generic prototypes were used to evaluate the overall performance, where the z-dimension depends on the respective concept. The prototypes of the sandwich and space-frame concepts were already published [45], therefore only the demonstrator of the shell concept shown in Figure 8 is described herein.

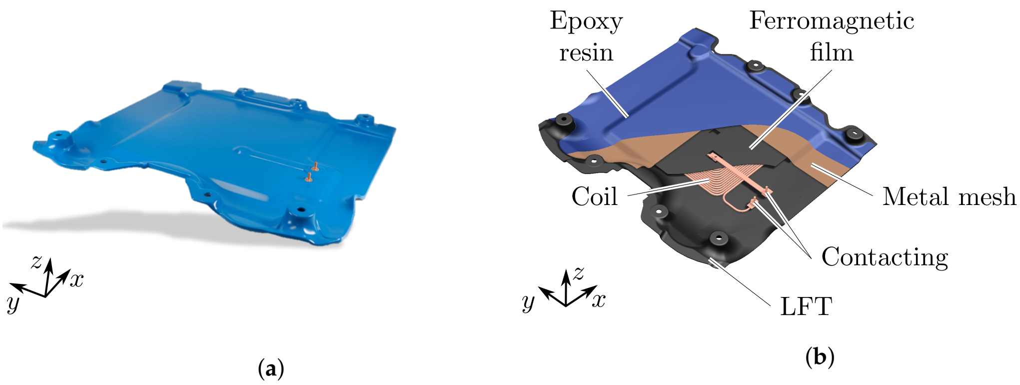

Figure 8. Generic prototype of the proposed shell concept: (**a**) photograph; and (**b**) exploded view.

The functionally integrated design of the shell concept is based on epoxy resin Aradur® HY 2966 [46] providing a sufficient structural connection and thermal coupling between the lossy integrated components. Flexible ferromagnetic films substitute the conventional ferrites and metallic wire mesh is used as shielding. Utilizing available tools, the manufacturing process is divided into three stages. First, the components to be integrated and the UBC are manufactured by long fiber reinforced thermoplastic (LFT) production processes. Secondly, coil, ferromagnetic film and epoxy resin are combined to a plastic-integrated functional unit using resin transfer molding (RTM). Thirdly, the functional unit, the metal mesh and the UBC are combined by epoxy resin using vacuum-assisted resin infusion (VARI). This procedure can be reduced to a two-step process if an RTM tool of adequate size is available for the production of the CPM. The demonstrator is scaled to the dimensions of 600 mm × 600 mm with a z-dimension of 15 mm and a weight of 8.1 kg.

Based on generic demonstrators, the electromagnetic and thermal performance of the proposed concepts were evaluated using a hardware-in-the-loop (HiL) test bench at TU Dresden. Additionally, structural testing was executed based on load cases given in [12]. In total, this enabled a cross-domain evaluation, which is summarized in Table 6.

Table 6. Cross-domain evaluation of the integration levels.

Domains	Criteria	Sandwich-Concept	Space-Frame-Concept	Shell-Concept
M	Mechanical robustness	●	●	◑
M, E, ME, P, A	Efficiency	◑	◕	◑
M, E, ME, P	Thermal management	◔	●	◕
M, E, ME, P, A	z-dimension	◑	○	●
M, E, ME, P, A	Volumetric power density	○	◑	●
M, E, ME, P, A	Gravimetric power density	◑	◑	●
E, ME	Insulation	●	◕	◔
E, ME, P, A	Contacting	●	◕	◑
M, E, A	Maintenance	○	◕	◕
M, E, ME, P, A	Recycling	○	◕	◕

○ very bad; ◔ poor; ◑ acceptable; ◕ good; ● very good. M, mechanics; E, electrics; ME, material engineering; P, production; A, assembly.

With regard to the development goals, the shell concept is the most favorable, as it enables the lowest z-dimension combined with the highest volumetric power density. According to the standardized testing scenarios given in [47], efficiency measurements of the proposed concepts were conducted. The efficiency measurements were performed "DC-to-DC", i.e., from the DC link voltage of the power electronics on the transmitting side to the battery voltage on the receiving side. Consequently, the input rectifier or the power factor correction of the primary power electronics was not accounted for. The range of the measured efficiency was defined by the best- and worst-case scenarios of misalignment as well as the power levels given in Table 3. Accordingly, the shell concept enables an efficiency range of 81.4–93.1%, which is slightly reduced compared to the other proposed concepts (sandwich concept: 88.7–91.7%; space-frame concept: 87.9–90.1%). This is explained with the high spatial coupling of the active components and additional power losses caused by the novel ferromagnetic films and the metal mesh. Assuming active air cooling, the shell concept is limited to a transmission power of 7.2 kW, whereas the differential sandwich concept and the space-frame concept enable a transmission power of 11 kW.

However, the proposed concepts are significantly reduced in terms of z-dimensions compared to existing designs, which ensures a high volumetric power density. In particular, the methodical support and the end-to-end cross-domain development of the proposed system engineering approach enables the realization of the ultra-thin shell concept using ferromagnetic films as alternative for ferrites and metal mesh as shielding for the first time.

5. Conclusions

The development of functionally integrated mechanical-electrical lightweight systems requires a specialized systematic design approach due to the various mutual interdependencies of the product domains involved. This work introduces a novel design approach providing an end-to-end consideration of the interdependencies of integrated elements and domains. The approach is based on the existing V-model, which is adapted to a problem-specific and purpose-oriented model through the synthesis of works given in the literature. The applicability of the proposed approach is demonstrated by the development of functionally integrated receiver units of WPTS for EVs. To increase the applicability and transferability of WPTS, the development goal is the reduction of the vertical dimension compared to existing designs (40 mm). In line with the proposed design approach, the conception process utilizes an extended morphological box considering the characteristics of components, production process, materials and assembly. This leads to three different concepts: sandwich concept, space-frame concept and shell concept. Whereas the sandwich concept and the space-frame concept are differential designs using conventional ferrites and shielding, the shell concept provides an integral design with novel ferromagnetic films as alternative for ferrites and metal mesh as shielding. In the context of automotive wireless power transfer systems, these materials are used for the first time. In particular, the spatial and functional integration of coil, ferromagnetic films and metal meshes into an automotive underbody cover using thermal conductive resin results in a significant reduction of the vertical dimension measured to 15 mm. Due to the high spatial coupling of the integrated elements, the average transmission efficiency of 85% is slightly reduced compared to the sandwich concept with 90% and space-frame concept with 89%. However, the differential design increases the vertical dimensions of the sandwich concept (28 mm) and the space-frame concept (35 mm). Therefore, the shell concept is evaluated as most promising with respect to the development goal, although the transmission power is still limited to 7.2 kW due to a lower efficiency. However, this can be improved in future works as optimization potential has been identified.

As a consequence, this paper demonstrates the applicability of the proposed design approach by elaborating the shell concept to proof-of-concept level. However, the applicability needs to be demonstrated in the context of further interdisciplinary development tasks. It is assumed that the approach is very effective in the development of functionally integrated mechanical-electrical lightweight systems with a small number of individual elements to be integrated, since the consistent interaction of the domains involved enables a development by a small number of iterations. With increasing complexity due to a high number of different individual elements to be integrated and corresponding interdependencies, a consistent synthesis of the domains involved can be very challenging. In this context, splitting into cross-domain and domain-specific development activities with defined synchronization points might be more effective. However, the proposed approach shows a very systematic method and rigid basis for the development of FIMEL and can be efficiently adapted to this requirement, which is planned for future work.

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Abbreviations

The following abbreviations are used in this manuscript:

CPM	Car pad module
ComChar	Component characterization
ComConc	Component conception
ComInt	Component integration
DC	Direct current
EVs	Electric vehicles
FIMEL	Functionally integrated mechanical-electrical lightweight systems
GMTex	Glass mat reinforced thermoplastic
HiL	Hardware-in-the-Loop
LFT	Long fiber reinforced thermoplastic
MACP	Macro-control-point
MEL	Mechanical-electrical systems
MICP	Micro-control-point
MID	Molded interconnect devices
ModConc	Module conception
ModInt	Module integration
MaPhMod	Mathematical-physical models

PCB	Printed circuit board
PhyMod	Physical models
PPS	Product-property-space
PSS	Product-solution-space
RTM	Resin transfer molding
SysConc	System conception
SysDes	System design
SysInt	System integration
UBC	Underbody cover
VARI	Vacuum-assisted resin infusion
WPTS	Wireless power transfer systems

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