INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.52

Applying a product modularization approach on the case of a battery pack

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Abstract

When designing battery packs, opposing target-conflicts and design goals arise due to the different disciplines involved in the development process. Looking at the available technologies for battery pack design, different solutions can be found on the market. The development of a battery pack for use in various scenarios therefore presents an interesting use case to evaluate product modularisation approaches. Hence, this paper discusses the application of the Integrated PKT Approach based on a fictious use case of a modular battery pack to derive potential starting points for its improvement.

Keywords: *research methodologies and methods, multi-/cross-/trans-disciplinary approaches, sustainable design*

1. Introduction

As recently updated, six out of nine planetary boundaries, defined within the planetary boundaries framework, set to monitor the stability and resilience of the Earth system are transgressed (Richardson et al., 2023). As a lever to minimize climate change, a shift from fossil fuels to renewable energy is therefore crucial. This encompasses a shift from cars with combustion engines to electrical cars. Looking at the available technologies for battery design, different solutions can be found on the market and the potential for optimization is still high so that no predominant solution can be identified.

When designing battery packs, opposing target-conflicts and design goals arise due to the different disciplines involved in the development process. The need to develop sustainable products also means that the entire life cycle of the product should be taken into account during development. Ideally, the manufacturer does not only think about the first usage of the battery pack in an electrical car but also about a possible second life use scenario. In this case, the battery pack needs to be designed in such a manner that it enables the commonal use of individual modules. The company's design decision while searching for the 'right' degree of modularization should be supported by methodical approaches.

Bearing in mind that this 'right' degree of modularization depends on a company's individual circumstances, the Integrated PKT Approach for the Development of Modular Product Families (Integrated PKT Approach) was developed at the Institute of Product Development and Mechanical Engineering Design (PKT) at Hamburg University of Technology (Krause and Gebhardt, 2023). To continuously improve the approach' s adaptive methodical toolbox, the approach and its tools need to be evaluated against products that face today's challenges. As the target-conflicts and use scenarios lead to a wide list of requirements in the development of battery packs due to the different disciplines involved during development and the various stakeholders within the entire life cycle, those need to be taken into account during the application of the modularization methods. Therefore, based on a fictitious use case of a battery pack manufacturer, the Integrated PKT Approach is applied to the design of modular battery packs. Its suitability for supporting the design of modular battery packs is then discussed in order to derive potential starting points for improvements to the Integrated PKT Approach.

2. Research background

In the following, approaches and methods for developing modular product families are briefly described in order to provide a methodical background. Building on this brief introduction to modularization methods, the Integrated PKT Approach is further described to provide a basis for its later application and evaluation. Lastly, on the basis of general requirements to the development process of a vehicle, target-conflicts in battery pack design are introduced. This highlights the contradicting design goals while developing battery packs and thus sets the frame and boundary conditions under which the Integrated PKT Approach is to be evaluated.

2.1. Methodical support for mechatronic products

In addition to mechanics, the relevance of other development disciplines is increasing in developing new products and product families (Mertens et al., 2023). The rising variety-induced complexity of the emerging mechatronic systems due to new components and increasing digital shares, which require both electronics and software, thus results in new interactions and challenges for product development. To cope with the high variety-related complexity of such systems, the development of modular product families is a possible solution (Simpson et al., 2014; Otto et al., 2016).

Generally, the approaches and methods for developing modular product families can be divided according to technical-functional and product-strategic objectives. For technical-functional structuring, Design Structure Matrix (DSM) is mentioned (Eppinger et al., 2014). One exemplary product-strategic approach is Modular Function Deployment (MFD), using module drivers over diverse life phases for modularization (Erixon, 1998). In addition, there are also approaches in which both objectives are integrated, such as the Product Family Master Plan (Simpson et al., 2014) or the Integrated PKT Approach (Krause and Gebhardt, 2023).

2.2. Integrated PKT Approach for the development of modular product families

The Integrated PKT Approach enables a technical-functional and product-strategic view of the underlying product architecture (Krause and Gebhardt, 2023). This enables a more holistic view with the objective to reduce internal variety, both in components as well as processes, through a modular product structure strategy. The approach follows the concept of an adaptive methodical toolbox that entails different method units as well as their tools (Krause and Gebhardt, 2023). Its core methods are the Design for Variety (DfV) method and Life Phases Modularization (LPM). Figure 1 shows the process of the Integrated PKT Approach. Steps 2 through 5 aim at reducing the internal variety through DfV, while steps 7 through 8 are conducted during LPM. As can be seen in the visualization, the DfV serves as preceding the LPM, but the LPM can also be applied independently.

The method DfV aims at reducing and optimizing the dependencies of internal component variety on relevant product properties (Kipp et al., 2010). Its central tool is the Variety Allocation Model (VAM). The VAM depicts the causal relationships between the customer relevant product properties (external variety) and the components (internal variety). With its help, the product structure can be optimized, for example through the separation of components so that each component is dependent only on one customer relevant property (one-to-one mapping criterion) (Krause and Gebhardt, 2023). Thereby the mapping of external variety by the customer relevant product requirements (R) and the internal variety by functions (F), logics (L) and physical components (P) is somewhat similar to the classification from Systems Engineering (RFLP-Approach (Eigner et al., 2014)), but in DfV the focus is on the variety of elements.

LPM harmonizes module cuts across all life phases involved so that the most uniform module cut possible can be mapped along the product life cycle. In the process, various life phase-specific module drivers are applied to the product architecture. The subsequent harmonization results then in synergies in purchasing, maintenance, production and other life phases (Krause and Gebhardt, 2023). To visualize

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the product family's internal variety and the decomposition of modules, the Module Interface Graph (MIG) is used.

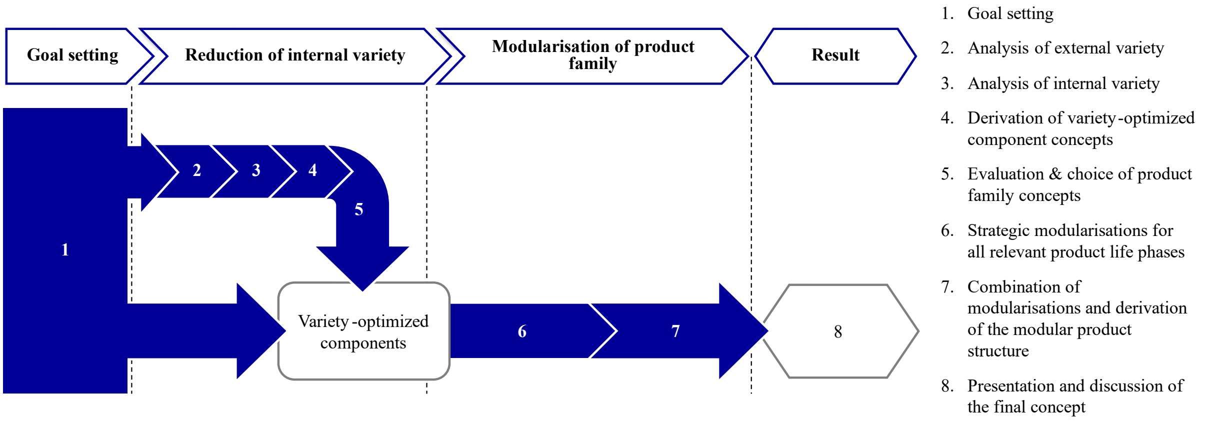

Figure 1. Process of the Integrated PKT Approach (Kipp et al., 2010)

2.3. Target-conflicts in battery pack design

In the overall vehicle development process the engineers can choose out of various vehicle structure types. In the automotive industry, the body-in-white (BIW) is usually derived from the design, package layouts and ergonomic aspects. The most important legal and market requirements are also taken into account (Brown et al., 2002). The body structure holds the complete vehicle together, maintains the shape of the vehicle and supports the various loads placed on it and this with as little mass as possible (Fang, 2023; Brown et al., 2002). The strength and stiffness of the body structure affect the performance of the vehicle and directly influence its handling and vibrational behaviour (Brown et al., 2002). These structures describe the comfort and safety of the vehicle (Gusig and Kruse, 2010). While the battery pack is often regarded as a stand-alone module of the propulsion system, it can also contribute to the strength, stiffness and mass distribution of the car. As part of the body structure, it therefore must fulfil the general requirements set for the car. Additionally, target-conflicts in the design of the battery pack itself arise due to contradicting design goals, as demonstrated in the following:

High power vs. high energy (Rothgang et al., 2015) – high power needs thicker conducting cross sections and better cooling for the occurring losses, hence using more space and weight. In a given design space this reduces maximum energy storage capability, hence range.

Isolation vs. conductivity – in many electrically power transmitting structures a high electrical insulation against other parts is needed but a low thermal conductivity to the environment is needed for good thermal cooling properties of losses in the power transmission (Jossen and Weydanz, 2021). Often, high thermal insulation is linked to high electrical insulation (like in cable insulation) as well as high thermal conductivity can be found in materials with high electrical conductivity (like copper leads). On the other hand, high thermal resistance is needed between separate cells to minimize thermal runaway propagation between cells while a high thermal conductivity from the cells to the environment reduces thermal damages to the cell (Warner, 2015; Golubkov et al., 2014; Christen et al., 2017; Xu et al., 2021).

Mechanical fixation vs. mechanical yield to volumetric changes – The active material volume of a cell changes over age, over temperature as well as over state-of-charge (SOC). Battery packs therefore need to accommodate for this by yield volumes in the fixation like foams at the end of a battery stack. If not, structural stresses may damage the cell when pressure increases due to volume increase in a stiff surrounding structure. On the other hand, mechanical deformations at cell connections (electrical power, data and thermal) may cause failures and need to be securely fastened due to high dynamic loads acting upon the battery pack in mobility applications (Jossen and Weydanz, 2021; Warner, 2015).

Differential vs. integral – Clustering the cells to modules within the battery pack reduces the loads on the cells but leads to an increase in weight and volume due to additional wiring and fixation. Compared to the integral design, the differential design requires higher weight and volume at the same energy. A detailed analysis of the drawbacks and advantages of integral and differential approaches in battery pack design can be found in Heinzen et al. (2023) and Plaumann (2022), the effect of mechanical loading on cells is studied in Zhu et al. (2020).

Reparability vs. efficiency – some chemistries like LiFePo have a significantly prolonged life cycle where high integral density (i.e. by gluing the pack together) may be more efficient on an overall scale outweighing potential benefits of replaceability of low state-of-health (SOH) modules which needs more internal interfaces (Warner, 2015).

3. Application of the Integrated PKT Approach

The described target conflicts lead to multidisciplinary requirements for the development of battery packs. In the following we present the application of the Integrated PKT Approach to a fictitious use case to later evaluate how well the Integrated PKT Approach, especially DfV and the tools MIG and VAM, supports the design of multidisciplinary products such as battery packs. A modular battery pack shall be designed by a fictitious company that offers battery packs to a wide variety of customers. Thereby, the battery pack shall be integrable into cars, different types of commercial vehicles, e-scooters and stationary application. The company itself does not manufacture any part of the battery pack. It buys the components and assembles them. To improve sustainability, the company also wants to offer not only direct sales, but also leasing models so that the battery can be exchanged at the customer's premises and overhauled internally when a SOH threshold is reached. This means that individual modules can be replaced, if necessary, thereby improving the average service life of all modules.

Therefore, the company aims at providing individual solutions for its customers with as little internal variety as possible. The main goal is to design cell modules that suit the different products with varying volumetric design space. In the following we use the expression "cell stack" instead of the widely used term "cell module" in order to avoid misunderstandings concerning the modules which we define later on. Figure 2 shows one possible arrangement of components installed within a battery pack. The illustration is based on the presentation in the MIG.

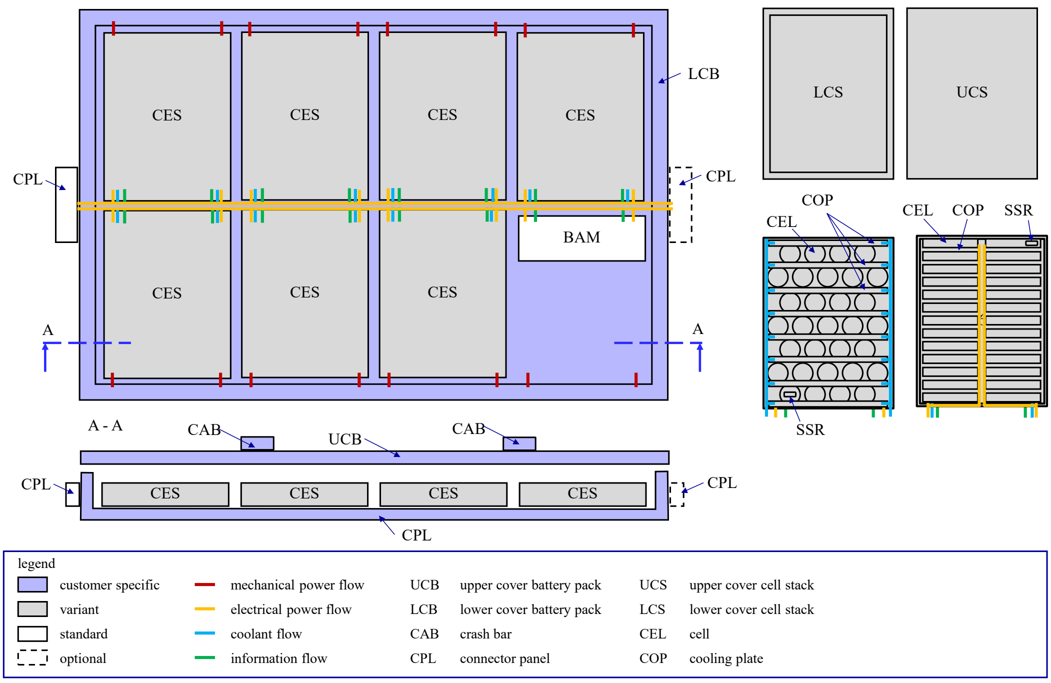

Figure 2. Module Interphase Graph (MIG) of a battery pack

3.1. Identification of the solution space

In the first step, we identify the solution space for the modular battery pack design. On the one hand, we collect information concerning available technologies and the main components of battery packs (based on the MIG in Figure 2) via market research. On the other hand, we identify the requirements

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from the customers' products, such as the volumetric design space for the battery pack. The information is collected in a morphological box, which thus provides an overview of the market research (see blue table in Figure 3 for the morphological box). Each row of the morphological box is dedicated to a design aspect of the battery pack (see first column Figure 3). The possible solutions available at the market are represented in the columns for each respective design aspect (Figure 3). It is to note that the columns itself do not represent viable concepts, because solutions for each design aspect should first be generated without restrictions. In the following step, the different solutions can be combined to possible concepts.

3.2. Verification of the solution space considering technical constraints

As mentioned above, we analyse the combinability of technologies and components considering technical constraints in a second step. After the identification of possible combinations, we redraw the morphological box (see Figure 3).
Only the round cell can have an integrated foam for the so-called cell swelling and thus can have a rigid mechanical fixation. The prismatic and the pouch need an elastic mechanical fixation in the form of a foam (see yellow line between rows 3 and 4 in Figure 3). Air-cooling is excluded from the solution space as it provides insufficient cooling power for most of the applications (see red cross in Figure 3). The direct integration of cells into the battery pack instead of building pre-mountable cell stacks is also excluded concerning the company's strategy.
All other solutions can be combined with each other without further restrictions. For example, NMC cells can be procured either as round cells or as prismatic cells or as pouches.

design aspect	list 1 of possible solutions	list 2 of possible solutions	list 3 of possible solutions
cell chemistry	NMC (nickel manganese cobalt) lithium-ions	LiFePo (lithium iron phosphate) lithium-ions	
cell geometry	round	prismatic	pouch
mechanical fixation	rigid	elastically	
space for cell breathing	foam integrated in cell	foam integrated in cell stack	
cooling circuit	~~air-cooled~~	bottom liquid-cooled: plate	lateral liquid-cooled: partition wall
integration level of cells	~~cell2battery pack~~	cell2stack	
cell connector	aluminium, high flexibility	steel, high flexibility	copper, low flexibility
bus bars	aluminium, lower current small diameter	steel, lower current small diameter	copper, high current big diameter
crash absorber	aluminium	steel	
reinforcement of the housing	inside	inside with integrated thermal components	outside

Figure 3. Reviewed morphological box

Now that the solution space as well as technical constraints are identified, we continue with the variety-oriented battery pack design and use the reviewed morphological box as basis for the following steps.
Therefore, we focus on the car which represents the most difficult product concerning the available design space, because of its densely packed components and the influence of the battery pack on driving dynamics and crash safety. The battery pack is much easier to integrate into vehicles such as e-scooters or trucks that offer more design space.

3.3. Variety-oriented battery pack design

In order to derive a modular battery pack that consists of as few variant components as possible while providing the demanded variety at the market, we use the so-called VAM from the DfV method (Krause and Gebhardt, 2023).
At first, we define the product variety that the company wants to offer and list identified variant properties in the first row of the VAM. After that, we extract all components from the first column of the morphological box and map them to the properties they contribute to (see Figures 3 and 4). For example, the electric driving range is provided by the cells. The cells can vary in their geometry including chemistry and the amount (according to the morphological box), whereby the amount is

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limited by the volumetric design space. Therefore, we add the information regarding the varying technical characteristics in the second row. The crash design for example can be realized with a cross bar in the battery pack or on-top of the battery pack's upper cover (UPB). The upper and lower cover as well as the cross bar are components that are individually designed for each customer order. Components like cell connector, bus bar, cooling partition wall, cooling plate and so forth are usually considered as electrical or coolant flows in the variety-oriented product design and thus neglected in the VAM. In this case study of a mechatronic product, it is fundamentally important to consider them as components in the VAM. The cell connector and the bus bar affect one of the most important properties of the vehicle: the charging and drive power. The cooling circuit realised in the form of the plate varies with the size of the cell stack (concerning width and length). Compared to that, the partition wall varies according to the cell stack's width and height and in addition with the shape of the cell (round, prismatic/ pouch). Furthermore, the cooling plate does not provide sufficient cooling power in all application cases and requires an additional cooling partition wall (optional). The variance of the other components is depicted in Figure 4.

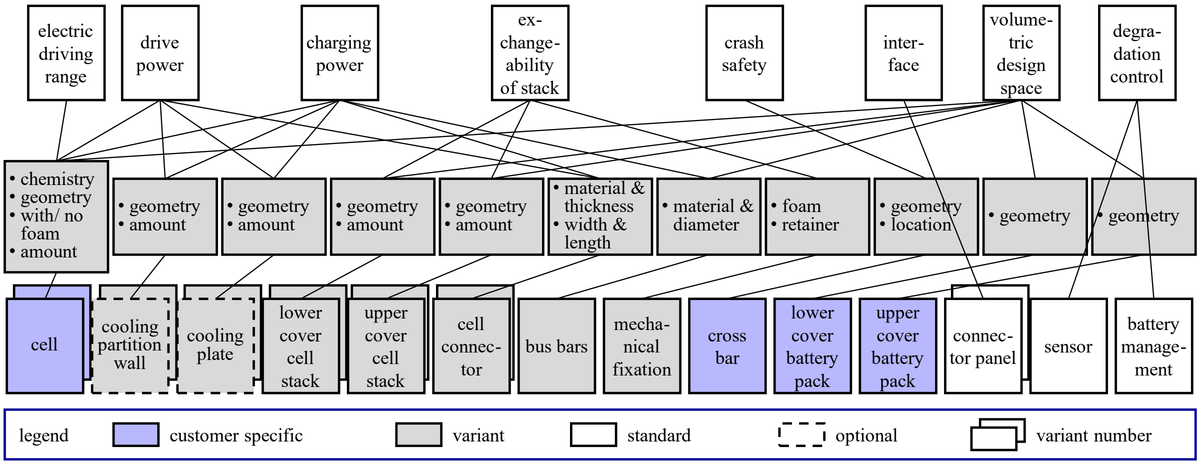

Figure 4. First draft of the VAM of the battery pack

In the next step we examine the one-to-one mapping criterion (see chapter 2.2). Although many customer-relevant properties are realized through more than one component, the product structure cannot be improved further due to physical constraints. After that, we study each variant component and try to separate variant characteristics from the component and to choose the technological solution that causes the least internal variety. Our final solution is visualized in Figure 5.

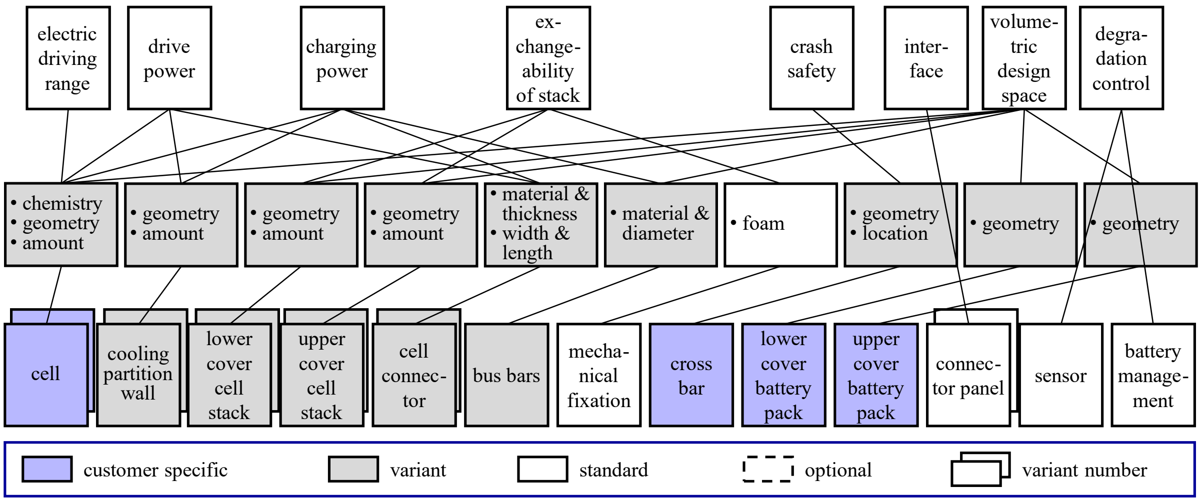

Figure 5. Final VAM of the battery pack

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In the following we describe some examples. Regarding the cells, we draw the conclusion that the company should offer all available cell chemistries and cell shapes in order to provide optimal solutions regarding usage of the volumetric design space in battery packs, desired electric driving range and charging power. However, the swelling of the cell shall be realised via embedding the cells in a foamed cell stack cover. The mechanical fixation therefore becomes a standard component as the technical characteristic retainer is not chosen. The cells are realized without the integrated foam independent from their cell chemistry. The cooling circuit is realised in the form of the partition wall, since it causes less internal variety compared to the cooling plate, as described above. The cooling plate is therefore deleted from the VAM and the cooling partition wall is now part of every product variant (non-optional, continuous line). To define reasonable cell stack sizes, the VAM does not provide sufficient support. A detailed analysis of the packaging of the cell stack in the battery packs of different products is required.

3.4. Potential module drivers

Based on the variety-oriented design of the battery pack it can now be modularized using the first steps of LPM. Therefore, some use case specific module drivers and their characteristics for different life phases will be introduced in this section. An overview of the module drivers can be found in Figure 6. The module drivers added for this specific application are printed in bold and described below.

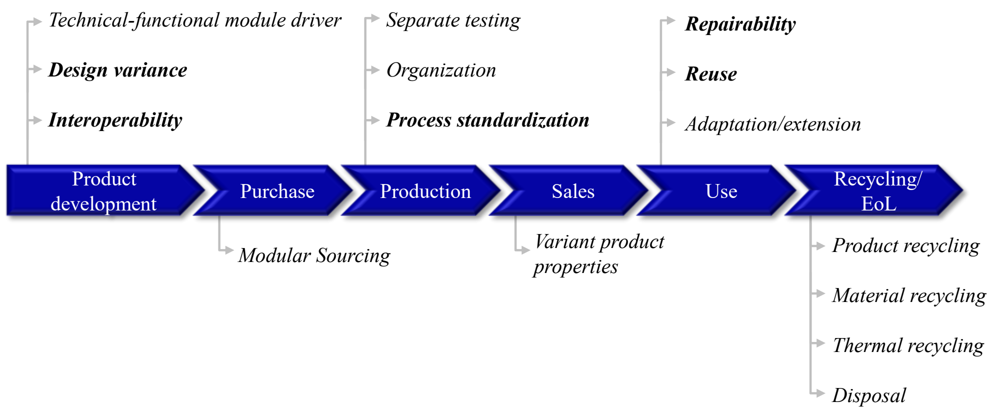

Figure 6. Overview of module drivers per life phase

With regard to development, Arora et al. (2018) consider a modular design to be crucial in order to compensate for the batteries high manufacturing costs. They go on to explain that for a successful modular architecture of a battery pack, thermal modularity in particular must also be given and matching the mechanical modularity, so that the modularity of different disciplines must be harmonized here. For this aspect the module driver "interoperability" is added and the specification in this case would be "thermal". This means, that multiple modules should be flexibly combinable and stackable. The same is true for electrical interoperability in terms of voltage level and power supply requirements. Rothgang et al. (2015) address the conflicting goals of high charging performance and high capacity by means of a modular design in which high-performance and high-energy cells are combined and connected via a dc-dc converter. Another aspect is the ongoing development in the field of cell chemistry and the associated uncertainty when selecting a cell type. Here, a modular design can simplify the adaptation of new cell chemistries and thus reduce uncertainty (Arora, 2017). This is taken into account as the module driver "Design variance".

Another aspect is the commonal, cross-series use of modules to increase the number of units and the degree of standardization in the production. This aspect is considered as "Process standardization" for the production phase. With regard to the use phase, Picatoste et al. (2022) identify standardized components as enablers for better maintenance in their analysis. Etxandi et al. (2023b) also conclude that maximizing the first service life should be prioritized. In addition to their proposed reduction of battery capacity to what is actually necessary, a modular structure could also improve the service life of the overall battery by making it easier to replace individual, defective modules. So "Repairability" is a potential module driver chosen for the use-phase. Another possibility is the reuse or further use of

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batteries or parts thereof in a second use. In contrast to the reuse of entire battery packs, the reuse of individual modules offers the advantage that the modules can be reconfigured for a new application and thus can be better adapted to it. Moreover, modules in unsatisfactory condition can also be sorted out (Etxandi-Santolaya et al., 2023a). Therefore "Reuse" is also added as a module driver for the use-phase. Although the reuse of modules can increase the effective service life of the batteries, efficient recycling also offers greater potential to reduce the demand for primary raw materials by providing secondary raw materials (Helander and Ljunggren, 2023). Recycling is already part of the module drivers proposed by (Erixon et al., 1996).

For a real use case, the next step would be life-phase harmonization, in which the various modules and views are discussed and harmonized in order to achieve the best possible compromise. However, the fictitious use case ends here, as the main focus in this case was on the application and use of the VAM and MIG on a product of high relevance multiple disciplines (mechanical and electrical engineering, and thermodynamics).

4. Discussion

In the following, we reflect upon the application of the Integrated PKT Approach in the fictitious use case in order to identify potential starting points for its improvement.

While the Integrated PKT Approach is typically used to analyse an existing product family with regard to reduce the internal variety while keeping a high external variety, this contribution used the approach's tools to first analyse a product concept based on all existing technologies on the market. The goal was to derive a modular product concept for a modular battery pack of a fictitious company, that wants to provide the demanded variety at the market with as few variant components as possible. The tools therefore had to be slightly adjusted to the new use case.

During the application, we could not decrease the number of variant components significantly, but we reduced the number of variants of some components in our proposed solution. We standardised the mechanical fixation of the cells within the battery pack and reduced the variety of the cooling system (see chapter 3.3). The definition of cell stack sizes to reduce the number of variants could neither be supported by the VAM nor the LPM. A separate tool for packaging is required, which delivers module drivers for clustering the cells to reasonable modules within the battery pack. However, the LPM supports the identification of components that should belong to the module cell stack to enable its use in different products and sustainability.

When considering multi-disciplinary products, the methods and approaches used must be adapted accordingly in order to better consider and reflect the collaborative character. For example, the level of consideration of the components must be defined according to the system of interest. In the case of multidisciplinary systems, in which the electrical distribution and cooling make up a decisive part of the functionality, these must be considered as discipline-specific components (see chapter 3.3., 2nd paragraph). In the context of mechanic products, their visualization in the variety-oriented product design, for mainly mechanic products, is usually an arrow to represent the flow in the MIG. This visualization has to be changed towards the representation as a component. The VAM can be adjusted accordingly and visualize the flow as a component with the corresponding colouring for variant, standard or optional components. This has been done with the respective components in Figure 4 and 5. Within the MIG, if the representation as coloured flows is kept due to easier illustration of the cables' location (see realization in Figure 2), there is no possibility to include information concerning variety.

With regard to the multidisciplinary system and its higher complexity, the technical-functional relations increased compared to mechanical products and thus impeded the one-to-one mapping and the separation of variant characteristics of components. For this reason, we could only reduce the number of variants of some components, but not the number of variant components significantly (compare cell and cooling plate in Figure 4 and 5).

Besides, the visualization of different structural concepts of battery packs was not possible within one MIG. The MIG (Figure 2) was used to provide an overview of the general components within a battery back and possible arrangements. If the company wants to offer different cell geometries, the structural concepts differ greatly. It is hardly possible to visualize different structural concepts within one MIG, although they share similarities of a product family. Figure 2 therefore only shows one possible

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arrangement of components. The different cell geometries labelled with the abbreviation CEL had to be shown in different cell stacks (see cell stacks with cells at right side of Figure 2). For each concept, a separate MIG or part of the MIG is needed.
As the component analysis in the method has not been changed and the level of consideration has merely been adapted, this has no influence on the process or the way the method works. Overall, the method's tools need some adjustments which is easily done in the case of the VAM, but needs careful consideration in the representation of the MIG.

5. Conclusion and outlook

In this contribution, the Integrated PKT Approach has been applied to a battery pack within a fictitious use case. The aim was to evaluate the approach's capability to support the design of multi-disciplinary products that face today's challenges in terms of sustainability and are characterized by target-conflicts. Therefore, the development of a battery pack for use in various scenarios and products like e-scooters, cars or stationary storage systems was chosen as use case. At first, the possible solution space was identified, and transferred into a morphological box, which was the basis for the three-layered VAM. This way, the external variety is linked via technical features to the components that represent the internal variety. True to the VAM's usual application, the visualization tool was then used to optimize the structure. Subsequently, case specific module drivers have been identified based on literature. This builds the basis for a strategic modularization for all relevant product life phases as part of LPM.
Based on the fictitious use case, some adaptions for the application of the Integrated PKT Approach to mechatronic products have been identified and starting points for improvements to the approach where derived. The realization of this potential could be addressed in further research. One possible aspect here is the consideration of spatially extended components such as wiring if they are not only to be considered as flows in the visualization. Since the basic suitability of the Integrated PKT Approach for battery pack design could be ascertained, from a scientific perspective it would be of interest to apply it in the context of an industrial use case to further detail and elaborate the various visualizations and tools and to possibly identify further potential for improvement. In addition, different business models such as product service systems and their impact on sustainability and product structure should be included in further research. Further research could also address the topic of sustainability in modularization as so far only a few sustainable module drivers have been considered. As of now, the DfV-tools lack some kind of consideration of sustainable aspects that should be developed in the future.

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https://doi.org/10.1017/pds.2024.52 Published online by Cambridge University Press