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Analyzing decision-making in automotive design towards life cycle engineering for hybrid lightweight components

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Abstract

Lightweight design is a major trend in automotive large-scale production. The introduction of innovative materials and combinations, e.g. through hybrid components, is driven by ambitious emission targets addressing the vehicles' use phase. Various design options as well as potential trade-offs to other life cycle phases demand sophisticated decision support. The presented research addresses current design processes of OEM and engineering service providers on a component level. Structured workshops serve as a method towards identifying, characterizing and generalizing decision points, preparatory activities and interfaces alongside product development. The obtained results build the foundations for the development of IT supported engineering tools.

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1. Motivation

In automotive industry consumer demands rise continuously. Every new vehicle generation is expected to outperform its predecessor regarding fuel economy, safety and comfort. Thus, vehicle weights used to increase with every new generation. Lightweight strategies are applied to oppose this trend and comply with legal emission targets, e.g. EU directive 443/2009. This encompasses the development of new car body concepts and the utilization of lightweight materials, e.g. ultra-high-strength steels, aluminum, or fiber reinforced plastics (FRP) [1]. As conventional lightweight strategies for mass-produced car bodies reach their limits, one promising path is the combination of metallic materials and FRP on a component level in the so called multi-material design or hybrid design [2].
One key target vehicle development is the improvement of its environmental performance over the life cycle. This is typically reflected through break-even calculations based on life cycle assessment, e.g. [3]. Environmental hotspots for designs incorporating innovative lightweight materials are shifting from the use phase to raw materials provision and manufacturing as well as end-of life. This is induced by a larger demand for energy and resources in the respective phases. Recent studies indicate that for car body components especially the use of carbon fiber reinforced plastics (CFRP) leads to significantly higher primary energy demands compared to steel or aluminum alternatives. Use phase energy savings through weight reduction may only compensate these added impacts when leveraging the CFRPs mechanical advantages in component design [4,5]. Additionally, the environmental performance directly relates to the components cost structure and thus their economic competitiveness. Against this background, a meaningful decision support for multi-material design on a component level needs to be developed. This integrates perspectives on weight, mechanical performance, cost and environmental performance. A foundational step is the analysis of modern automotive product development and its relevant decision points. As large-scale vehicle development is typically performed through concurrent engineering, decisions are influenced by different stakeholders across the value chain. The presented research addresses these interrelations. It aims at identifying starting points and requirements for methods and tools that provide usable and robust decision bases throughout the development of components.

2. State of the art

The concept of life cycle thinking enables a perspective on all phases of a product life cycle: From raw materials provision, over manufacturing, use and finally the end-of-life. This

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extends the traditional focus of a manufacturer from aspects that have an instant relation to business performance, e.g. manufacturing costs or the fulfillment of external requirements. Life cycle engineering (LCE) describes engineering activities to operationalize this perspective towards supporting an informed decision-making [6]. A key success factor for LCE-oriented decision support is its integration into the product development processes and the companys organization [7]. One main aspect of LCE is the identification of improvement measures and the development of targeted innovations [3]. The presented research focuses on the environmental perspective of car body components throughout their life cycle. Thus, LCE methods are observed that integrate life cycle thinking into product development to foster environmentally conscious product designs [6]. Following the foundational dilemma in product development, a gap between determination and emergence of product impacts can be observed between early and later stages of product development [8]. Early stages cover the development before the product specification is set when most decisions regarding the product are still due. One core finding is that a decision support should be done as early as possible to ensure a lever that actually affects the products environmental performance. Nevertheless, it is observed that the availability and quality of relevant data is low in early stages [9]. In contrast, in the later stages the detail of engineering is very high and foundational product specifications are set. Thus changes that significantly influence the environmental performance of the product and its components are unlikely to occur [10]. When regarding automotive product development, the automotive value chain needs to be considered which is organized in several levels, so called tiers. The car manufacturer (OEM - original equipment manufacturer) stands on the superordinate level. OEMs typically hold the responsibility for the entire vehicle, its series development and final manufacturing, usually including press shop, car body shop, paint shop and final assembly. On the supplier level are developers and producers of modules (tier 1), systems (tier 2) and parts (tier 3) with the current research focusing on the first tiers. Tier 1 suppliers may also provide the module integration in the car as a service. Suppliers can also act as development partners in the series development of cars. In this case they either develop modules on their own or develop modules in the mandate of the OEM. In addition, a combination of the engineering service and the contract manufacturing by suppliers becomes increasingly common (Figure 1) [11]. There have been similar approaches to analyze product development in the light of life cycle engineering. For example, Bhamra et. al. and Poole et. al. focused on environmental aspects of the product development process of companies in the electronic and electrical industry in Europe and the USA [9][10]. Therefore, a survey among 30 companies was conducted. A selection of the key findings is listed in Table 1.

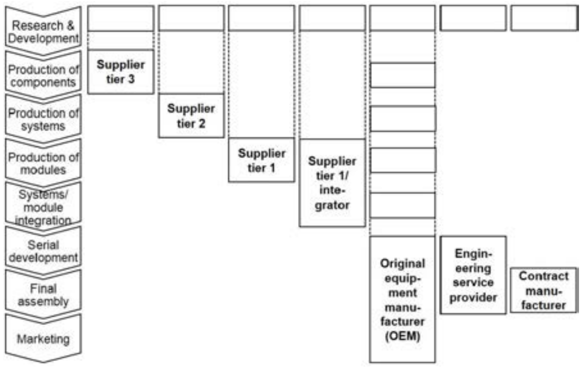

Fig. 1. The automotive value chain according to Koch et al. [11]

Table 1. Success factors for implementing ecodesign in product development, excerpt from Bhamra et. al. [9] and Poole et. al. [10]

Development process:
Pre-specification environmental design changes have greater impact on the environmental profile of the product; the later you introduce life cycle design in the design process the harder it is to affect the environmental profile.
Once the **specification is written, only incremental changes** in the environmental impact of products and processes are possible
One way to implement ecodesign is **to treat it simply as good design, based on existing concurrent engineering** or total quality philosophies.
Design methods and tools:
At all stages of design **designers often only want a tool which will allow quick alternative analysis enabling them** to make decisions about which material or other option to take.
Life cycle design can be implemented, in part, in the form of a suite of DFX tools. It thus **can be easily integrated into concurrent Engineering**
Simply having life cycle design tools available for designers is not sufficient to ensure effective implementation.
Management procedures are more crucial and tools should be regarded as an aid to management.

These insights give indications and fundamental understandings that need to be validated or adapted for the analyzed setting of automotive car body design. Differences regarding the company position in the value chain and the specifics of their decision processes are only briefly discussed. Other approaches consider these differences, but do not cover the challenges of an environmentally conscious product design. In this field, Grochowski et. al. proposed a multi-layered product development process to individually consider the different product development process specifics [12]. The focus of the analysis lies on the series development of hybrid lightweight components for an automotive application. The automotive series development usually consists of three to four characteristic phases: The specification of the product, the development on concept and detail level and finally the preparation for production [13]. A generic automotive development process is shown in Figure 2.

The product specification and concept development are considered equivalent to the early stages as discussed in Bhamra et. al. [9]. There is still flexibility and not all properties are set. As the development continuously proceeds and more and more specifications are made this flexibility decreases. During the later stages of development, with the detailed development and the preparation for production, the focus lies on the real-

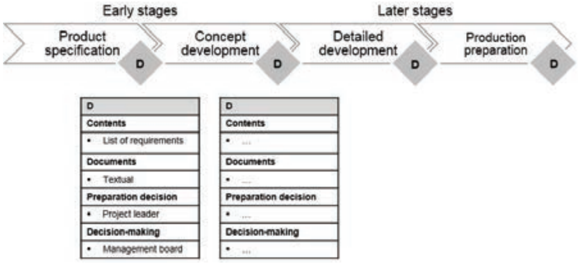

Fig. 2. Automotive product development process following [13,14] and decision situations

ization of selected product concepts. The series development is usually concluded with the start of production (SOP) and finally the launch of the product.

3. Methodology

The presented research aims at the development of methods and tools towards a life cycle oriented hybrid lightweight design of automotive components. Against this background, different actors along the automotive value chain are analyzed. Within this setting, the following research demands are investigated:

1. At which point of the value chain are the main levers that influence the decision-making for a life cycle-oriented component design?
2. How should use-case specific and meaningful decision support be shaped in order to incorporate a life cycle perspective?

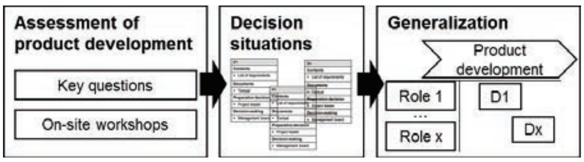

Fig. 3. Research methodology

The research demands are assessed applying a bottom-up approach (see Figure 3). Four companies taking different roles in the automotive value chain are analyzed through a structured process. First of all, a generic characterization of each company is executed based on key questions. In parallel, on-site workshops are performed. The results are then generalized and become the starting points for decision support. The four companies being involved in the research are described in Table 2. For the given setting company 4 is an OEM and acts as a customer of the other companies in terms of both engineering services as well as parts, systems and modules manufacturing. Companies 1, 2 and 3 are suppliers and engineering service providers on different tiers of the automotive value chain and differ significantly in their core competencies.

Table 2. Companies involved.

Company description
Company 1 acts as an engineering service provider involved in product development projects at different OEMs.
Company 2 is an SME specialized in composite component manufacturing for series applications in aerospace and automotive industry.
Company 3 is a material supplier for automotive applications as well acting as a consultant for product design and manufacturing
Company 4 is an original equipment manufacturer (OEM) active in vehicle mass production

3.1. Characterization of product development environments

An initial analysis is performed through key questions in order to achieve a holistic understanding of the internal and external boundary conditions (see Table 3). This stage is initiated in preparation to the on-site workshops and completed during their execution. As a foundation general information on the companies is assessed. This stage includes the size of the company (total employees, employees in research and development, financial performance indicators), the mainly served industry sector and the core business. The key questions help to describe the companies' product development environment from the perspective of life cycle engineering.

Table 3. Key questions characterizing the product development environments.

Key questions
What are the typical stages of the product development process? How does the OEM process influence the tier processes?
When are the product characteristics set, so that product changes would need a formalized modification management?
At which point in the development process is detailed engineering data (bill of material, CAD-drawings) at hand?
Which stage has the highest potential to influence and support decisions on environmental life cycle issues?
Who are the decision-makers during development? What is the authority of those deciders in regard to technical and financial specifications?
Does the company have targets for an environmentally conscious product design? Are those targets qualitative or quantitative? How are the targets implemented and pursued?

3.2. On-site workshops

The on-site workshops bring together actors holding complementary roles within the product development of the organizations studied. This step is crucial even if a structured product development is implemented in all organizations. The life cycle oriented development of innovative car body components needs to bring together competencies from a strategic perspective (high investment volumes and risks, compliance), operational product development (new design paradigms), materials engineering and production engineering (varying material behaviours and equipment for processing), business process management (potential adaptions of as-is processes) as well as experts in environmental life cycle evaluation. Furthermore, interfaces to other organizations as well as variations from the standard procedure are discussed and evaluated.

The selection of participants is coordinated with the middle management level to ensure exhaustive organizational knowledge and experience in the addressed fields. During a half-day meeting the automotive component development processes from project initiation to production preparation were discussed and documented in the Business Process Model and Notation (BPMN). Another notation supporting the intended perspective is the so-called Decision Model and Notation (DMN) provided by the Object Management Group (OMG) [15]. This notation extends BPMN by focusing on knowledge artifacts required for a certain decision and its underlying rules. Decision points (D) are described for each company by the following elements:

- Activities and contents of decision
- Role decision-making
- Role preparatory activities for decision
- Associated documents and product data (digital/ physical)

In result, two to five situations with a high degree of specification of life cycle impacts are derived from each companies' development processes. These are described with respect to contents, required information and involved responsibilities.

3.3. Generalization

The intended research outcome is a set of generic decision points that serve as a basis for the development of methods and tools towards a life cycle oriented component design. As a foundational step different vocabulary regarding design stages and roles needs to be aligned by comparison on a content level. Subsequently, background information and interfaces are added through the evaluation of the key questions.

4. Life cycle oriented component development

4.1. Product development in the automotive value chain

All studied companies follow structured design processes for automotive components intended for large scale production. The design processes are organized according to defined milestones. While all companies follow proprietary processes, projects that were initiated by OEM orders always implied an orientation at the customer processes. With the progress of development projects, the sophistication of the product specification increases. This is reflected in the applied methods and tools, from verbal descriptions in the very early stages to CAx tools in later stages.

Tracking and tracing requirements throughout the development process is well established. At suppliers and engineering service providers, requirements typically originate from the OEM order. Demands related to lightweight design, e.g. geometry, material choice, weight targets or manufacturing processes, would follow standard processes. Life cycle considerations, e.g. recyclability, design for disassembly or life cycle assessment, are administrated by the OEM and translated to requirements for the vehicle development projects. Two of the companies are able to execute environmental life cycle analyses. However, some partners state that at present conventional materials and manufacturing processes are still dominating large-scale production. All companies apply an active modification management to secure that required targets are met for the final product. Typically, the selection of concepts marks a distinctive event from whereon modifications would imply disproportionate delays as well as additional cost for the development project. Taking the OEM perspective, lightweight targets and the respective component development are main considerations when initiating and executing vehicle projects. Typically, design alternatives using innovative materials are environmentally and economically evaluated as technology innovation projects before being considered for series development. When reaching the desired technological maturity, the consideration is a matter of the respective business case. Introducing these alternatives extends the solution space for respective component development, but will follow established decision routes.

4.2. Roles involved in component development

Analyzing the development of car body components in the automotive value chain, it is inherent that tasks vary according to the scope of the company. Despite these differences as well as different degrees of organization due to company sizes, some similarities could be identified. The following roles are present at all companies studied. A role in this context refers to a rather task-driven classification and is not necessarily bound to one or more persons fulfilling the functions described:

- **Design engineers and computation engineers:** Operative instances of product development developing and elaborating feasible solution concepts.
- **Project management (technical):** Technical supervision of several development projects as well as reporting duties regarding project progress.
- **Project management (economical):** Responsibilities for calculation of offers and tracking of project progress towards calculated cost; reporting duties.
- **Management boards:** Instance of management responsible for business units or divisions. Decision-making powers regarding project initiation, continuation and central technical issues, e.g. innovative concepts.

4.3. Decision points in component development

Three decision points (D2 to D4) in the area of influence of suppliers and engineering service providers could be identified as related to the component life cycle performance. These are illustrated in a matrix graph, opposing roles and phases of product development (Figure 4). Detailed development is neglected due to the high degree of component specification in all cases. The OEM perspective is reflected in the customer perspective. Figure 5 gives an overview of the interconnection of decision points and extends them by the OEM level (D1).

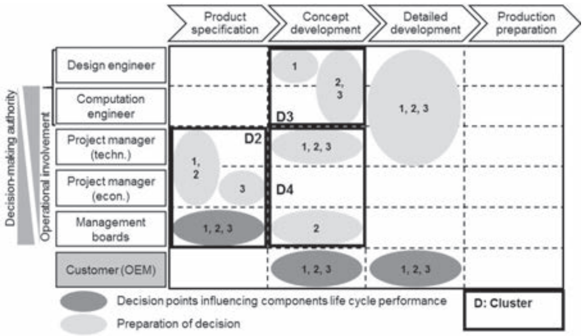

Fig. 4. Clustered decision points at suppliers and engineering service providers.

In a typical scenario, the component development process is separated by the vehicle development and the component development itself. While the vehicle process is one of the key processes of an OEM, component developments are executed at specialist departments or assigned to engineering service providers. As one of the initial steps of vehicle development qualitative and quantitative targets are set. These are often oriented at predecessor vehicles (e.g. decrease overall weight by a factor "x") but also influenced by strategic considerations (e.g. marketing benefits through innovative technologies) or external boundaries (e.g. new emission targets). Succeeding, the target setting is broken down to the component level (D1). This step is also based on reference components, but takes boundaries from the chosen design approach into consideration (factor "y"). The following step would be the component specification where main properties and requirements are defined. If e.g. weight and geometrical targets are set based on preceding (conventional) designs, the solution space for novel designs and thus material choice is strongly narrowed down. Vice versa, a material substitution needs to be considered in the vehicle process to enable a respective component development.

The component specification is then handed over to the component development process. This encompasses geometrical requirements as well as technical and economic performance requirements, e.g. component weight at a certain cost. At the component development, an initial evaluation (D2) checks for economic and technical feasibility. In the case of external service providers this stage is necessary towards calculating a competitive offer. The following decisions (D3 and D4) deal with the development of concepts and their final selection. The solution space is thereby oriented at delivering technical feasibility while meeting set specifications. D4 requires the evaluation of all concepts regarding relevant performance criteria. Subsequently, the components will be elaborated through detailed development.

A main observation is the strict top-down character of the current development process. The OEM provides a relatively narrow solution space based on the vehicle process. At the component level this leads to structured design processes with only a limited scope of action for novel (lightweight) approaches. At the same time, environmental life cycle performance of components is only considered indirectly, e.g. through weight targets. The depicted process describes an idealized case. Due to boundary conditions, e.g. the adaption of production facilities, environmental life cycle impacts would be strongly influenced.

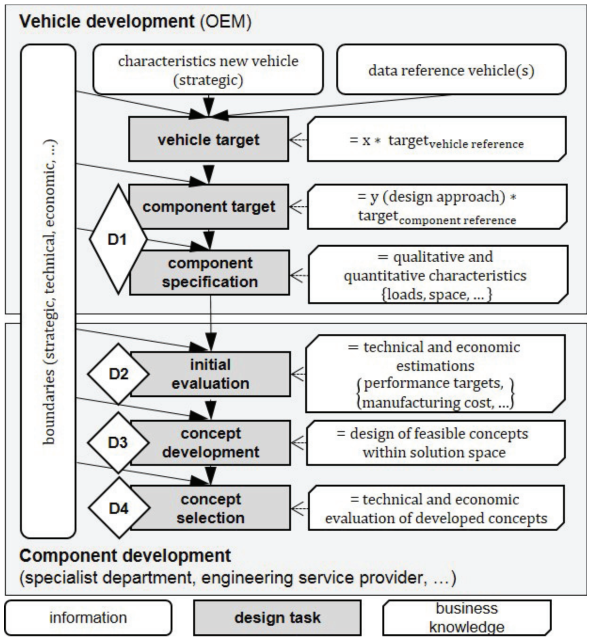

Fig. 5. Decision points in automotive component development (DMN notation).

5. Requirements for decision support

Following the clarification of product development activities and boundary conditions, the second research question aims at deriving requirements for a meaningful decision support towards a life cycle oriented component design (See table 4). Concurrent engineering presents the state of the art in automotive development. The vehicle process is typically split from component design, which is performed either at internal specialist departments or engineering service providers. Thus, a strong focus should be set at the interfaces between the actors. One main trigger is the interaction in the target and specification process for components between vehicle process and component development. Hybrid lightweight components typically require a change of the vehicle design beyond the component itself. Through the combination of different materials benefits can be leveraged and functional integration to adjacent components is enabled. If the component specification is strongly oriented at preceding designs, the scope of the component process is restricted and novel design solutions are likely to be dismissed. Thus it might be beneficial to provide design and evaluation methods that consider larger assemblies, e.g. front ends. While a strong interaction between vehicle and component process triggers design innovations, additional efforts for both processes need to be evaluated. Examples are person hours and possible delays in the overall vehicle process. One approach in this context might be a steady exchange of the OEM with actors in component development. This might lead to the identification of favorable design alternatives to be considered during component specification and benchmarked for different vehicle applications in component development.

Targeting of environmental performance is executed on the vehicle level and has been introduced to the component specification. Further approaches towards tracing component contri-

Table 4. Requirements for identified decision points (DP)

Requirements	DP
Focus on the interfaces between OEM and tier levels	all
Flexible approaches for component specification including allocation of product targets to components	D1
Methods for integrated assessment of environmental, technical and economic performance	D2-
Integration of environmental into current technical and economic performance criteria	D4

butions during component development would increase transparency and thus decision quality. This transparency could act as a stimulus for outperforming both preceding and competing designs. Following Bhamra et al., an implementation should be integrated in parallel to current technical and economic performance criteria.

Assuming a given design freedom through the previously described measures, an equivalent consideration of hybrid lightweight design alternatives needs to be enabled in component development. The initial evaluation requires an ad hoc comparison of specified components compared to established alternatives. As mainly databases from preceding projects are used for this stage, complementary data needs to be provided for hybrid lightweight designs, e.g. design effort or prospected component cost. The component development could be assisted by design rules, e.g. load-specific geometries for metal-FRP hybrids, that facilitate the generation of technically feasible solutions. At the concept evaluation stage automated assessment of life cycle criteria based on product data management tools (PDM) or integrated in design tools might be promising.

6. Conclusions and Outlook

The presented research aims at the identification of crucial decision points and their characteristics within the development of automotive car body components. A special focus is set on the impact on environmental performance criteria over the life cycle of lightweight components. In that course, four companies taking different roles in the automotive value chain are analyzed. Based on a structured assessment approach, encompassing key questions and on-site workshops, four decision points are identified. These are then analyzed and prioritized with respect to a use case specific life cycle design.

Based on fundamental insights into product development and its activities, several starting points for further research are opening up. Firstly, the research setting is built around a limited set of actors with only one OEM and three suppliers and engineering service providers. A validation of the key results on a broader base (e.g. survey) is seen as essential. Furthermore, the identified requirements and boundary conditions need to be translated into one or more prototypical methods and tools which enable specific decision support for the described scenarios. An accompanying development of these tools to one or more component design projects is strongly advised. This especially refers to the enhancement of robustness and the provision of suitable information and visualization for the respective partners and roles within product development.

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