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ORIGINAL PAPER

Potential impact of additive manufacturing and topology optimization inspired lightweight design on vehicle track performance

Jan A. Tschorn[1] · Daniel Fuchs[2] · Thomas Vietor[3]

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Abstract
This paper describes an interactive approach for analyzing the impact of the enhanced design freedom in additive manufacturing (AM) combined with topology optimization. The main goal is to identify weight saving potentials on a holistic vehicle level and evaluate the influence on vehicle performance by means of lap time savings. Therefore lightweight use cases enabled by AM are gathered in a database. Projecting the weight reduction rates of this database to a sports car as reference vehicle by means of a weight list, CAD data and a part relation analysis leads to an overall weight saving potential. This analysis shows significant weight saving potentials for each technical section of an already lightweight design focused sports car, namely the Bugatti Chiron. The improvement in track performance considering the weight savings is put into perspective by means of lap time simulation on the Nürburgring Nordschleife and corroborate the identified weight saving potentials.

Keywords Ligthweight design · Topology optimization · Additive manufacturing · Vehicle concept · Part relation analysis · Technical up-scaling · Simulation of vehicle racetrack performance

1 Introduction

Since the beginning of aircraft and vehicle development, lightweight design principles were established, acknowledged and are evolving according to technological progress and engineering capabilities. Nowadays development goals with a focus on lightweight vehicle design emerge from differing drivers, e.g. to improve driving performance or decrease overall emissions [1]. Besides advancements in material and manufacturing technologies such as increased usage of laminated fiber composites [1], progress in simulation methods particularly in the field of topology optimization can be considered a key element in lightweight design principles. The capability to optimize part topology towards stiffness or strength targets based on *Finite Element Methods* (FEM) enables purposeful lightweight design of parts [2]. As described in the field of research *Interactive Design* a purposeful interaction of those engineering design methods with the designer is key, requiring experts knowledge on the one hand and human centered tools on the other [3]. The optimized geometries often consist of complex shapes that—depending on the application—might be challenging to manufacture and are therefore restrained to process-related manufacturing restrictions. Thus the combination of topology optimization methods and manufacturing processes with high degrees of design freedom such as Additive Manufacturing (hereinafter referred to as AM), provides enhanced potential for lightweight design. This research quantifies the potential impact of the combination of lightweight design through topology optimization and AM related design freedom. To determine the impact of this potential on vehicle race track performance, lap time is chosen as comparative value.

Jan A. Tschorn and Daniel Fuchs have contributed equally to this work.

✉ Jan A. Tschorn
jan.alexander.tschorn@volkswagen.de

Daniel Fuchs
daniel.fuchs@volkswagen.de

Thomas Vietor
t.vietor@tu-braunschweig.de

1 New Technologies, Bugatti Engineering GmbH, Gustav-Hertz-Straße 2, 38448 Wolfsburg, Niedersachsen, Germany

2 Group Innovation, Volkswagen AG, Berliner Ring 2, 38440 Wolfsburg, Niedersachsen, Germany

3 Institut für Konstruktionstechnik, Technische Universität Braunschweig, Langer Kamp 8, 38106 Braunschweig, Niedersachsen, Germany

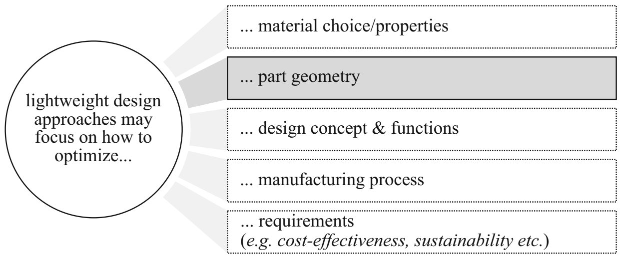


Fig. 1 Overview of lightweight design strategies with focus on part geometry, adapted from [4]

1.1 Geometry based lightweight design

Following *Kaspar* and *Vielhaber*, several lightweight design strategies can be differentiated (Fig. 1). To achieve maximized weight savings during the vehicle development process those lightweight approaches should be taken into account collectively. The following analysis however focuses on geometry-based lightweight design approach only. The main objective of *geometry-based lightweight design* is to minimize the mass of load-bearing structures according to its requirements by optimizing load distribution and shape of parts or assemblies. Considering further strategies, shown in Fig. 1, such as concept- and function-based methods, would increase the complexity of this analysis significantly and complicate the comparability as well as the transferability of weight savings in-between use cases, parts and assemblies. Closely related to *material*- and *geometry-based lightweight strategies* are weight saving potentials due to optimized manufacturing and assembly processes [4]. Although AM plays a central role in this analysis, the focus is on the correlation between topology-optimization methods and AM by collectively realizing highly optimized shapes rather than on the manufacturing process itself.

1.2 Design for Additive Manufacturing and its potentials

Over the past 30 years, the field of AM has grown and matured, reaching acceptance as a certified manufacturing technology in various industries, such as aerospace, health care and automotive [5–7]. Along with the advantages of AM to efficiently produce small lot sizes locally and on demand [7,8], its design potentials and restrictions are being explored in the field of research *Design for Additive Manufacturing* (hereinafter referred to as DfAM) [7,9–12]. Besides AM potentials, e.g. *Reduced time to product/market, Assembly cost reduction*, etc. the feasible design complexity is inspiring engineers to develop alternative part geometries resulting in innovative technical solutions often portrayed in show case applications.

Kumke ea. introduces a systematic network of AM related levers and value propositions enabling an overview of AM design potentials. Within this network systematic levers are categorized into four Groups: *Material*, *Functional*, *Form* and *Hierarchical Complexity*. For this work, those AM Potentials which can be derived from the two last categories are most relevant, since these AM potentials propel *lightweight geometry-based design* by topology optimization significantly [10].

1.3 Identification of the problem and aim of this study

The state of the art on the potential impact of AM on automotive vehicles is often limited to the part or assembly level [13]. Regarding the productivity capabilities and the resulting production costs of AM technologies, the identification of a business case for automotive series applications in direct comparison with conventional established manufacturing technologies is often challenging [14]. Crucial for a purposeful usage of AM technologies are therefore those applications that by exploiting AM benefits result in customer-targeted additional value propositions [10,14]. Consequently it is necessary to analyze the potential impact of AM on automotive vehicles holistically. This way the customer-targeted additional value proposition can be estimated and put into perspective.

Automotive vehicles consist of complex assemblies and components that are mutually dependent on each other, making holistic analysis challenging. Several approaches on how to additively manufacture major parts or even entire vehicles are known to the public [15–18]. Unfortunately only a few of those sources seem to rely on scientific data or methods, subsequently leading to uncertainty about the intrinsic additional value proposition in the assessment of AM technologies for the automotive industry. Furthermore there is a lack of methods and tools for up-scaling technical principles to complex products such as an entire vehicle. Those tools are necessary for an estimated and quantified additional customer value in its entirety induced by the technical innovation. Therefore an interactive approach crossing different knowledge engineering tools applicable to the early phases of the design process is necessary [3]. The aim of this study is therefore to estimate and quantify the potential impact of topology optimization and AM inspired lightweight design on a holistic vehicle level relying on a use cases database. The main additional customer-oriented value proposition chosen for this analysis is the track performance of a sports car, as this property is one of the main drivers of lightweight design in this vehicle segment. To evaluate the track performance the lap time on the Nürburgring Nordschleife is chosen as the main result parameter. Furthermore this study proposes an interactive

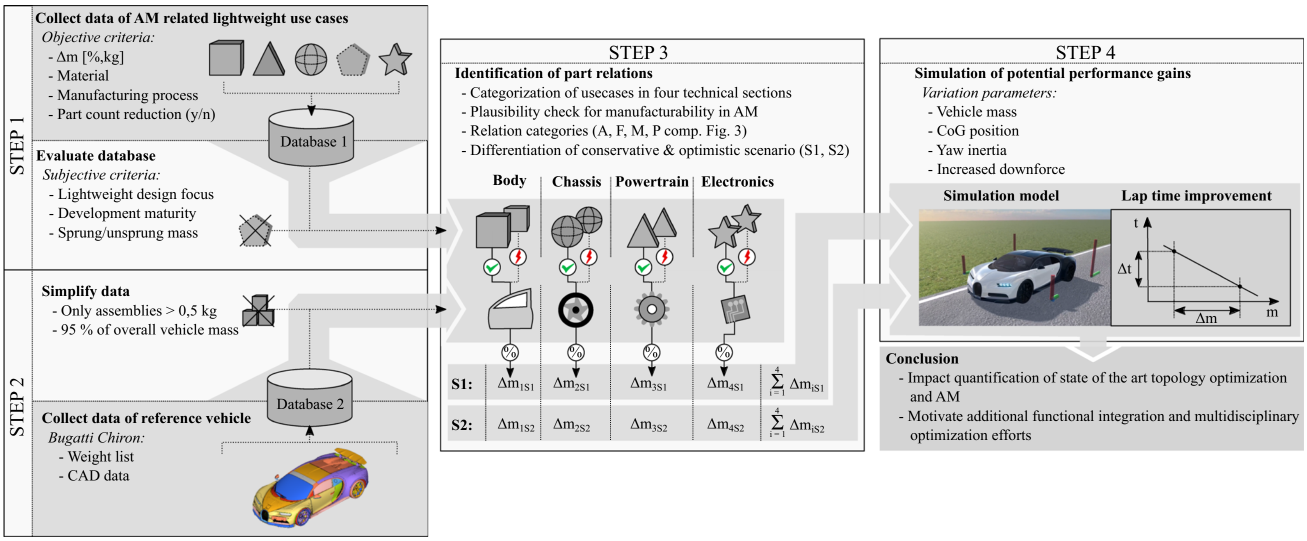


Fig. 2 Approach overview relying on an interactive part relations analysis and knowledge based engineering tools

approach on *technical up-scaling* based on identification of part relations.

2 Methods

2.1 Approach overview

The chosen methodological approach for this analysis is outlined in Fig. 2.

The basis of this work is formed on data collected from exemplary applications and use cases of additively manufactured vehicle components with a focus on lightweight design. These components are partially known to the public through literature and to some degree communicated internally in a corporate environment (Step 1 Fig. 2). According to most of the applications published in the AM lightweight design context this analysis is focused on metal components only. The collected data were subjectively evaluated and filtered taking development maturity, lightweight design focus and sufficiency of information into account (Database 1 in Fig. 2). To enable a lightweight focused analysis of the impact of the combination of AM and topology optimization on a vehicle in its entirety a sports car (Bugatti Chiron) was chosen as a reference vehicle. Crucial for this purpose were the weight list and the CAD data of the reference vehicle (Step 2 and Database 2 in Fig. 2). 3D data and digital vehicle databases are enabling the developer to identify relevant components and part relations interactively. Relying on Database 1 and Database 2 as an input an identification of part relations was carried out in Step 3. The technical sections in focus of this analysis were the vehicle body, chassis, drive train as well as the electronics. Database 1 and 2 were therefore structured accordingly.

For the identification of part relations between Database 1 and 2, four relation categories were defined (Fig. 3).

Based on the identified part relations between Database 1 (exemplary applications) and Database 2 (reference vehicle) in Step 3 the percentual weight saving potentials were transferred to the reference vehicle. These weight saving potentials were added up corresponding to it's technical sections Δm_i resulting in

$$\Delta m = \sum_{i=1}^{4} \Delta m_i \tag{1}$$

as input variable for simulation purposes. With the total weight savings and an analysis of further vehicle parameters e.g. center of gravity (CoG) shift, the lap time gains for various scenarios were determined and evaluated by means of a vehicle dynamics simulation (Step 4 Fig. 2). The individual process steps will be elaborated in more detail below.

2.2 AM data collection

The database for this analysis was built from published applications of AM on metallic vehicle components with a focus on lightweight design. Parts with an insufficient database or development maturity were not taken into account for further examination. The following relevant key attributes for the AM use cases were gathered in the data collection (Table 1).

2.3 Identification of part relations and scenarios

In order to take the uncertainties when identifying part relations and transferring potential weight savings into account two scenarios were considered, whereas Scenario 1 followed

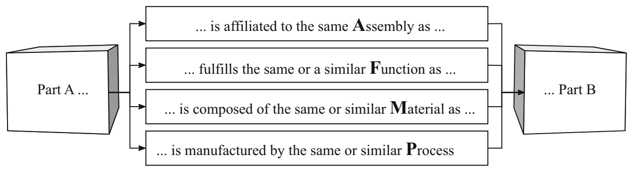


Fig. 3 Chosen categories to identify part relations (A F M P)

a conservative perspective and Scenario 2 represents an optimistic approach. However for both scenarios the identified part relations were checked subjectively for plausibility in terms of manufacturability.

Scenario 1 considered the percentual weight savings of the component with the highest amount of identified part relations. Based on practical experience high percentual weight savings indicated additional lightweight design approaches, a low development maturity or a low lightweight design focus of the original vehicle part. Therefore the weight saving of all identified vehicle parts with part relations were capped at 30 %. Based on [19] a build envelope limitation of 1 m^3 was assumed for the AM process. Furthermore, the assessment of the lightweight focus of the AM use case and the corresponding component of the vehicle to which the weight saving potential was transferred was taken into account. If the vehicle component already had a high lightweight focus and original part of the AM use case was only considered decent in that term, the assumed weight saving potentials were halved.

Scenario 2 also took the percentual weight savings of the part with the highest amount of identified part relations. In this optimistic scenario however, there was no limitation for the weight savings and no space limitation for the AM process.

2.4 Simulation approach

To simulate lap time alterations a validated model of the reference vehicle was necessary. For this purpose the AVL VSM simulation software and a validated vehicle model from previous studies [20] were chosen. The vehicle physics are represented by a nonlinear two-track model with 16 degrees of freedom. The tire characteristics are described via Pacjeka files based on tire test bench measurements. The simulation technique is a driver model based approach, for which the vehicle trajectory is determined in advance according to [21]. The approximate 20.5 km long Nordschleife of the Nürburgring was chosen, because of its well known characteristics and comparability. Figure 4 shows the track profile with the respective speed profile of the reference vehicle.

Table 1 Objective and subjective attributes collected/assigned in data collection

Objective/quantitative	Subjective/qualitative
Application	Lightweight focus
Manufacturing process	Development maturity
Material	
Part count reduction	
Weight savings	

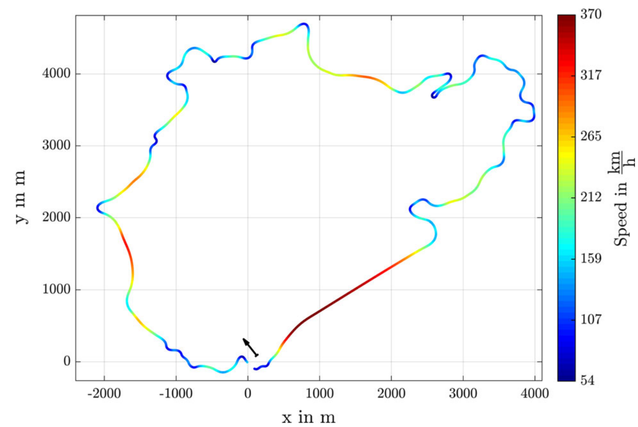


Fig. 4 Racetrack Nürburgring Nordschleife with respective speed profile of the reference vehicle

2.5 Parameter variation

Based on the identification of part relations for all technical sections of the reference vehicle, the overall weight saving potentials were determined. These potentials also have an impact on other vehicle parameters such as the CoG position and the yaw inertia I_Z. To predict the potential shift of the CoG an estimation based on an equilibrium of forces regarding the axle load distribution was carried out. To put the influence of weight reduction and its distance to the CoG on the vehicle yaw inertia into perspective, a basic calculation was performed as shown in Fig. 5. According to the estimation made with the approach above, the yaw inertia of the reference vehicle was adjusted with respect to the relative positions of the identified assemblies of the reference vehicle.

In addition to the considered parameter dependencies, mass savings enable opportunities to increase vehicle performance further. Therefore the influence of adapted aerodynamics was considered. For this purpose, the bearable downforce at top speed was increased assuming the load capacity of the chassis of the initial reference vehicle remains the same. The necessary resulting alteration of the downforce coefficient Δc_D for the simulation was determined with equation (2).

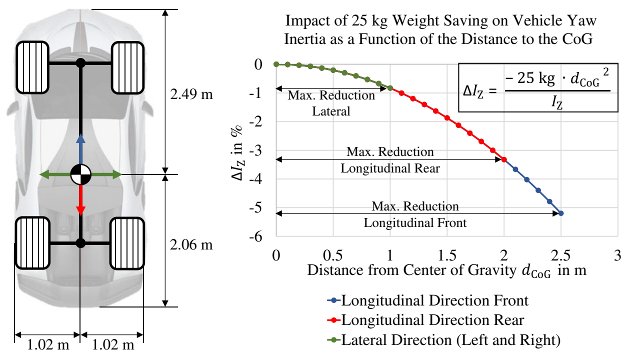


Fig. 5 Vehicle yaw inertia sensitivities for the reference vehicle

$$\Delta c_D = \frac{2 \cdot \Delta m \cdot g}{\rho_L \cdot A \cdot v_{max}^2} \tag{2}$$

The additional downforce was divided according to the prevailing aerobalance and assigned to both the front axle $\Delta c_{D,F}$ and the rear axle $\Delta c_{D,R}$. The well-known trade-off between drag and downforce in vehicle development was also taken into account by a vehicle-specific parameter relation known from previous investigations [20]. In summary increased weight reduction leads to increased vehicle downforce in addition to increased vehicle drag accordingly.

3 Results

The main results generated in this work are derived from the *identification of part relations*, the *up-scaling of weight savings to a holistic vehicle level* and the *track performance simulation*, which are described in more detail in the sections below.

3.1 Identification of part relations

We gathered and analyzed 45 exemplary automotive applications in which weight savings were achieved due to topology optimization and AM. Those applications are mostly known to the public and communicated either by OEM's or suppliers. Due to insufficient data we were not able to consider 16 of those use cases. The 29 remaining examples focus on metal only applications, consisting either of steel, aluminum or titanium. The weight savings communicated in those exemplary applications differ between 10 and 75 %. An exemplary overview of use cases for the main technical sections of the vehicle is shown in Table 2.

As shown in Fig. 3 four different part-relation-categories were identified which are potential indicators for similarities between parts of different vehicles or assemblies. Based on these categories part-relations throughout the reference vehicle were identified and some examples are shown in Table 3.

With this procedure weight savings were firstly estimated and added up for each technical section and thereafter for the whole reference vehicle.

3.2 Up-scaling of weight savings to the holistic vehicle level

An extract of the results of the technical up-scaling approach, with which the weight savings of the use cases were projected to the reference vehicle, are shown in Table 3 for both conservative *S1* and optimistic *S2* scenarios. The Table shows one examplary *identified part relation* between *part/assembly of the reference vehicle* and *use case* for each one of the four considered *technical sections*. The *total mass* and the eventually *considered mass* of the *parts/assemblies*, which was used for the projection of the *weight reduction*, are listed in this overview. The difference between *total mass* of the *part/assembly of the reference vehicle* and the eventually *considered mass* describes, in this context, the relation of parts that have been rated as plausible applications for AM. Besides the *weight savings*—from the *weight reduction* rates derived—for each *part/assembly*, the sum of *weight savings* for each *technical section* and the *overall sum* are also displayed in the two scenario-specific right-hand columns of this chart.

According to the boundary conditions of the scenarios described in the *Methods* section, identified part relations often contribute differently to Scenario 1 and 2. In the case of an equal weight saving contribution to both scenarios, either the build envelope limitations or the weight reduction threshold of 30 % of Scenario 1 were not affected. According to this analysis the total weight saving potential adds up to approximately 4 – 6 % of the total vehicle weight.

The total result of the part relation analysis was transferred to the CAD-Model of the reference vehicle as illustrated in Fig. 6. Here the location of the main assemblies with weight saving potential is visualized in the vehicle's design space. The technical sections of the vehicle are illustrated in different colors. Here the vehicle front and rear segment, as well as the drive train, can be identified as areas with major weight saving potential. Note that this distribution might only apply to vehicles based on a fiber composite monocoque design.

3.3 Track performance simulation

The lap time simulation results are displayed in Fig. 7. As mentioned in Sect. 2 the weight savings (WS) and weight savings with adjusted aerodynamics (WSA) were taken into account both for scenario 1 and 2. Throughout the simulation the overall vehicle weight was gradually reduced (black scatter points). Based on these scatter points a linear regression (LR) was carried out (black line). A potential shift of the center of gravity (CoG) in both longitudinal and vertical

Table 2 Exemplary overview of automotive applications and gathered data

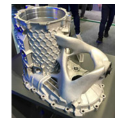
Technical section	Body	Chassis	Drive Train
Application	Spaceframe node [22]	Brake calliper [23]	Electric drive housing [24]
Figure			
Weight savings	25%	41%	32%
Material	AlSi10Mg	Ti6Al4V	AlSi10Mg
Development maturity	Functional prototype	Functional prototype	Functional prototype

Table 3 Examples of identified part relations and their projected weight savings for each technical section of the reference vehicle

Technical section Part/assembly of reference vehicle	Total mass [kg]	Cons. mass [kg]	Identified part relation to use case	Part relation categories	Weight reduction [%]	Weight savings [kg] S1	S2
Body						**11.80**	**22.68**
Frame Section (front)	35.52	11.84	Spaceframe-node [22]	AFMP	25%	2.96	8.88
Chassis						**18.42**	**21.06**
Wheel-Drive (front)	13.77	10.31	Wheel-Carrier	AFMP	15%	1.55	1.55
Drive Train						**58.30**	**72.43**
Final Drive (rear)	38.00	11.16	El. Drive Housing [24]	AFMP	32%	3.35	3.53
Electrics						**1.40**	**2.31**
Miscellaneous Brackets	1.84	1.84	Bonnet Hinge	FMP	23%	0.42	0.42
Overall sum of weight savings						**89.92**	**118.50**

directions was taken into account. The influence on the lap time savings is displayed by the blue (worst case shift) and red (best case shift) line which also represent a linear regression of the discrete simulation points. For the conducted parameter variations two lap time saving value pairs were calculated for both scenarios. These are listed in Table 4.

4 Discussion

The aim of the study was to assess the potential impact of AM lightweight design on a holistic vehicle level relying on resilient use cases. To put the customer related value proposition into perspective the lap time performance of the vehicle was chosen as the objective criterion of this analysis.

By following the introduced approach we were able to identify the saving potentials for vehicle weight and lap time on a holistic vehicle level with a focus on topology optimized AM manufactured metallic components. The identified potentials have a significant impact on vehicle weight and performance for a reference car with an already high lightweight design focus. The aforementioned approach therefore turned out to be a suitable method to investigate the potentials of a technical innovation on a vehicle in its entirety, particularly for weight savings and their impact on the performance of the vehicle. Furthermore the method enabled the identification of potential applications for topology optimized additive manufactured parts and showed that design freedom enabled by AM should be considered in performance oriented automotive engineering.

Even though topology optimization methods are often associated with AM, weight savings might also be achieved by combining topology optimization and conventional manufacturing processes. Nevertheless, as the reference vehicle was a sports car, it was already subject to a high lightweight focus during development and therefore took advantage of several lightweight methods as such.

Noticeable is also that at least 50 % of the considered usecases utilized AlSi10Mg as material for structurally optimized vehicle parts. Even though this analysis sets no focus on material based lightweight design strategies (Fig. 1) it is worth mentioning that further lightweight potential is con-

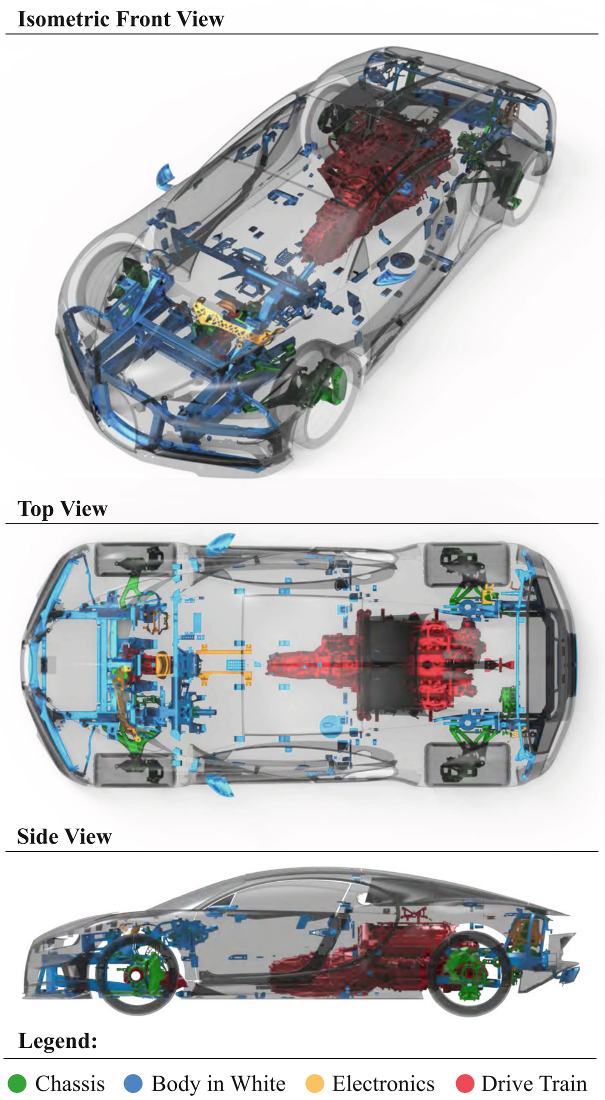


Fig. 6 AM relevant Parts and Assemblies (optimistic Scenario)

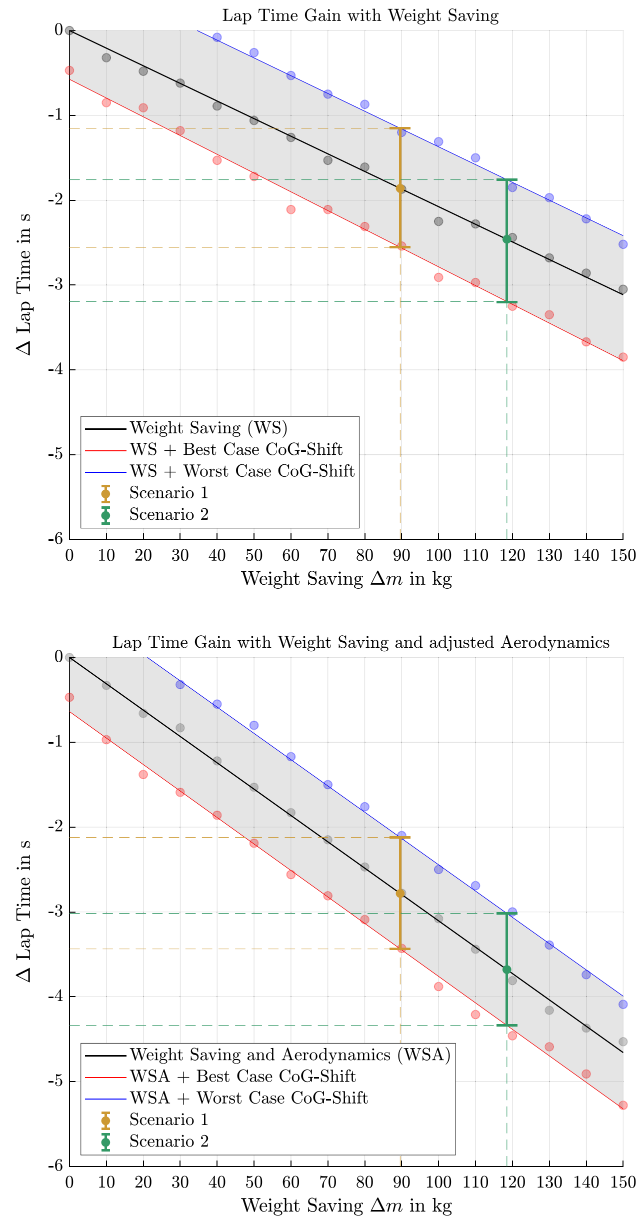


Fig. 7 Lap Time Simulation Results. The change in lap time (s) was plotted against the change in mass (kg)

ceivable considering alternative AM Materials with superior material properties such as e.g. Scalmalloy® [25]. Regarding the high costs of those alloys, they are mostly applied in aerospace and healthcare industry. Therefore further research is conducted to develop alloys suitable for automotive industry requirements e.g. *BMBF Project–CustoMat 3D* [26].

The design freedom enabled by AM exceeds the capabilities to realize complex part shapes derived from topology optimization only, as most cases nowadays mediate. Further AM related design potentials towards functional, hierarchical (e.g. lattice structures) as well as material complexity were not taken into account in this analysis [10]. To do so, additional lightweight design strategies (Fig. 1) and novel design methods towards functional integration and multi-physics design need to be considered. To optimize the design of parts on a holistic vehicle level in such a way that AM design potentials are fully exploited, the tools and methods to do so are essential. Those are still to be developed to enable engineers to create innovative, interdisciplinary and highly optimized designs that combine AM design potentials purposefully. Note that in total ten of the AM use cases considered in this analysis achieved also a part count reduction in the respective assembly. For complexity reasons resulting collateral effects due to those part count reductions could not be fully prevented. Additional weight saving potentials arise if also non metallic parts are taken into consideration.

Table 4 Potential lap time savings for scenario 1 and 2 considering weight savings only (WS) and weight savings with adjusted aerodynamics (WSA)

	Scenario 1	Scenario 2
WS	1.15 – 2.56 s	1.76 – 3.2 s
WSA	2.12 – 3.44 s	3.02 – 4.34 s

Automotive vehicles consist of a high number of assemblies, components and parts. As such, considerations of an entire vehicle are complex. In order to reduce complexity but still be able to consider the entire vehicle in the analysis, only assemblies with a mass greater than 0.5 kg were taken into account. The assemblies thus considered account for 95 % of the overall vehicle weight. In this analysis a high lightweight potential was identified. However, the lightweight design focus of the gathered use cases could only be rated subjectively, which leaves room for error in the projection of weight reduction rates to the reference vehicle. Further the development maturity of most of the use cases was classified as “prototype” or “functional prototype”. Therefore weight savings communicated and gathered in the data might not correspond to weight savings which are achievable in the manufacturing of serial parts.

The aim of the chosen parameter variation approach for the lap time simulation was based on a comprehensive consideration of the entire vehicle. Regarding the parameter dependencies between weight savings and CoG position, an additional outcome of this paper is that the exact determination of the CoG shift is not possible when using technical up-scaling. Even with high quality CAD data due to the amount of considered assemblies without the exact information in which position the projected weight savings occur and how the final part geometry turns out, only an estimation can be provided (Fig. 5).

The discontinuous behavior (simulation points Fig. 7) when varying the vehicle mass or CoG position step wise is strongly dependent on the chosen simulation technique using a driver model based approach. The linear regression was performed with respect to the linear behavior of the mass sensitivity and considered as a reasonable approach to display the lap time gains for the reference vehicle.

5 Conclusion

A holistic lightweight optimization, taking advantage of AM design potentials, has the capability to impact overall vehicle performance independently of reasonable manufacturing costs. The aforementioned interactive approach successfully explored potential impact of a technical principle on a holistic product, defined in this paper as technical up-scaling. In particular the conducted identification of part relations is a useful principle to identify appropriate applications with weight saving potential on a holistic vehicle level and enables the designer to prioritize those parts for further improvement. The combination of the presented steps can be an helpful approach for an interactive determination of design potentials of AM. From the authors perspective, in addition to the definition in [3], the introduced approach underlines once more that *Interactive Design* consists of designer focussed product development methods combining both physical and methodological emphases. The physical focus relating to the consideration of interactions between physical variables, boundary conditions and dependencies in the realization process of product functions and requirements. The methodological aspects focussing on customer oriented conceptual design methods in order to enable interdisciplinary product development particularly regarding its complexity.

With respect to the identified weight savings, the simulation results show possible lap time reductions of over four seconds on the Nürburgring Nordschleife if aerodynamic adjustments are taken into account. These lap time savings are significant but should be considered with respect to the length of the race track, which for the Nürburgring Nordschleife is over 20 km. The lap time savings would therefore not be as great on a shorter, regular race track.

In order to exploit the full potential of AM-design freedom, design solutions with a focus on functional integration and multi-disciplinary optimization are indispensable and therefore necessary. Functional integration has the potential to save even more weight e.g. through part count reduction and can also increase vehicle performance in terms of interdisciplinary functions such as heat management leading to increased durability and consistency. Further collateral impact on vehicle properties is not simple to be determined. Therefore geometry changes through part count reduction or additional weight savings via the reversal of the “weight spiral” are possible. Specifically for the determination of further potentials from functional integration, interactive design methods such as the presented approach are helpful to locate potential parts and functions on assembly level and to subsequently optimize their integration in the vehicle. Additionally the handling properties are also positively affected by the reduction of vehicle mass and inertia. Further ways to predict the impact on the design space of potential parts and therefore the collateral effect on the vehicle package should be investigated as an enhancement of this approach. The impact of the vehicle weight on other attributes such as the handling properties can be evaluated by taking additional simulation and evaluation approaches into account. In this case an objective handling evaluation tool based on simulation data of handling maneuvers can quantify the improvements for certain weight savings. Additionally also further customer benefits such as studies towards the effects of weight savings on fuel consumption and cost related analysis on the topic of high-level AM propagation in vehicle conception are not just suggested by the authors but also field of interest of design engineers in a corporate environment.

The main finding of this paper is the quantified weight saving potential for a vehicle in its entirety. This was done considering only geometry focused lightweight design principles combining topology optimization and AM related design freedom for metallic parts. The weight reduction rates, derived from a gathered database of AM lightweight use cases, were transferred to a reference vehicle based on identified part relations conducted with the introduced technical up-scaling approach, resulting in significant weight reduction potentials for an entire vehicle. The impact of the derived weight savings on the track performance of the vehicle of reference was determined through lap time improvements by means of a vehicle dynamics simulation. From the authors point of view – confirmed by design engineers in a corporate environment – the results achievable with the introduced technical up-scaling approach can be considered as a reasonable, educated and estimated quantification of the disruptive design potential of metal based AM technologies on vehicle track performance.

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Declaration

Conflict of interest The authors declare that they have no conflict of interest.

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