Cars on Weight Loss: The Development of a Methodology for the Topology Optimization of Monolithic Components – Emerging Trends, Challenges and Opportunities

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Abstract

Topology optimization plays a key role in the production of strong, lightweight functional parts. It uses mathematical algorithms to create optimized geometries under given constraints while at the same time improving performance. The conventional design process is time consuming and requires high technical expertise. The raisons d'etre for using algorithms is to reduce part development time and to keep the computational cost low. Further reduction in cost through weight savings can be realized though monolithic (one piece) design. In this method, weight reduction is achieved through the elimination of bolts, nuts and other joining material. Combining topology optimization with monolithic design also blends the benefit of weight reduction with the simplification of the assembly process. To reach optimum weight, an effective part development process requires a methodology which takes into account the objective function and all the constraints. The methodology can be used from the early stages, throughout the design process. This provides a step-by-step approach to the design process and keeps iterations to a minimum, thereby reducing the product development time. This research therefore focuses on the trends in the development of a methodology for the topology optimization of monolithic vehicle components. It also highlights the challenges and opportunities, placing emphasis on the vehicle aftermarket industry components.

Keywords
Methodology, Topology Optimization, Monolithic Components, Design.

1. Introduction
The design industry has taken great strides in technological advancement, driving almost everything from autonomous vehicles to aircraft parts and spaceship components. Engineers create millions of alternative designs so as to create highly optimized products which best satisfy the set parameters. Design flexibility, lightweightness, improved performance and energy efficiency are critical in today's designs. Thus, putting cars on weight loss brings a wide range of benefits, chiefly among them reduction of fuel consumption, emissions and raw material usage. One of the technologies that cannot be left out is topology optimization. When it comes to product design, topology optimization reduces weight and material input (Berrocal *et al.*, 2019). It uses mathematical algorithms to create components which have optimum weight distribution within a given domain (Vatanabe *et al.*, 2016). The engineer identifies where material is to be placed in that domain under the given constraints (Sigmund and Maute, 2013). It is different from another vastly used weight reduction technology, material substitution in that material substitution replaces the part material without changing the part geometry, while topology optimization changes the part geometry without replacing its material (Chirinda and Matope, 2020). Topology optimization repeatedly analyzes and modifies the design, exploring the possible solutions in order to create an optimized geometry and improve performance (AMFG, 2018). Combining topology optimization with monolithic (one piece) design blends the benefit of weight reduction

with the simplification of the assembly process. Producing a 'one piece' component part eliminates the joining processes such as welding, bolting and riveting. As such, the research seeks to explore topology optimization and its combination with monolithic to reduce weight and minimize assembly time.

It is imperative to also note that contrary to the belief that topology optimization and generative design are similar, they are, in actual fact, different. Generative design uses topology optimization (Oh *et al.*, 2019), and not vice versa. Topology optimization is a foundational or enabling technology upon which generative design is built. Other foundational technologies include biomimicry and morphogenesis (Chen *et al.*, 2018). Topology optimization creates one output optimized design from one existing part, while generative design creates many design options (Vlah *et al.*, 2020). Generative design conducts design exploration and quickly generates thousands of design possibilities subject to given constraints (Jang *et al.*, 2020). This too may be for a product which may not be in existence, while, topology optimization is well suited for scenarios where the designer already has the component's geometry and needs to reduce its weight. Topology optimization requires human input to create the CAD file, subject to the objective function and constraints. In generative design, artificial intelligence is used to determine the optimal material distribution and create many possible solutions by itself, thus the machine is the designer (Oh *et al.*, 2018).

Once topology optimization is factored in at the early stages of the design process, it offers a wide range of alternative solutions than what is manually possible (Krish, 2011). To reach optimum weight, an effective part development process requires a suitable methodology (Olason and Tidman, 2010). Many engineering marvels have previously been developed using the conventional design process, which is: define the need, analyze the problem, generate concepts, develop a solution, construct and test the prototype, manufacture the product, and finally, launch the product (Wynn and Clarkson, 2018). However, this process has a negative feedback loop, and this slows down the design and development process. In addition to that, the product design process may have conflicting objective functions. As a result, it is time consuming and requires high technical expertise. This can be improved through computational modelling and simulation, but this is also a long process which requires many iterations before an optimum design is obtained (Fang, 2007). The conventional design process only implements ideas, but do not develop them. Imagination is limited to the engineer (Akella, 2018). Hence, a methodology for topology optimization offers a solution to these challenges by eliminating the human input and accelerating the design process. It is against this background that this paper presents the emerging trends, challenges and opportunities in the development of methodologies for topology optimization of monolithic components.

The paper is structured as follows: Section 2 focuses on the emerging trends in the development of methodologies for topology optimization for monolithic components. This is followed by Section 3, which looks at the challenges involved in the implementation of the methodologies and the potential solutions that can mitigate the challenges encountered. It is important to look into the future, and Section 4 looks beyond the horizon as the opportunities are explored. The research is then concluded on Section 5.

2. Emerging Trends in the Development of Methodologies for Topology Optimization of Monolithic Components

Today's vehicles are aerodynamically optimized in order to achieve extremely high-speed performance. An example of such a high performance car built for high speed is the Bugatti Chiron Super Sport. The car reaches 97 km/hr. in 2.3 seconds, and tops 490.484 km/hr. (Bugatti Automobiles, 2021). The aerodynamic design reduces drag, improves performance, and reduces fuel consumption. In addition to that, the car has low ground clearance. This lowers the center of mass and increases stability (Mayank *et al.*, 2017). The low ground clearance also produces a vacuum with the ground, which results in a suction force that keeps the car sticking to the ground, further improving stability. An addition to these aerodynamic and stability features is lightweight design of a rear wing through topology optimization. The topologically optimized design is shown on Figure 1 below.

Figure 1: The Bugatti Chiron rear wing travel and adjustment system (Bugatti Automobiles, 2018)

The purpose of the rear wing is to improve aerodynamic performance and to press the car down at high speeds. This, together with a low center of mass and low ground clearance makes the car even more stable. The Siemens generative design software was used to topologically optimize the rear wing travel and adjustment system for the Chiron Super Sport. (Siemens, 2018). Figure 2 below shows an illustration in the step-by-step methodology taken by Siemens and Bugatti Automobiles in the innovation process.

Figure 2: Siemens and Bugatti step-by-step methodology (Siemens, 2018)

The methodology shows combination of topology optimization and monolithic design. The total number of individual parts is a key measure of quality. Fewer parts eliminate the joining processes as there is no need for welding, bolting, riveting and further assembly of individual components (Boothroyd *et al.*, 2011). The joined points may also act as points of weakness, which reduces product life. It is also important to note that the joining material increases product weight (Meng *et al.*, 2019). Monolithic design therefore facilitates a combination of part number and weight reduction, leading to products which are stronger, lighter and durable.

The rear wing was monolithically manufactured using additive manufacturing. This would not have been possible had the conventional manufacturing methods like machining was used. Part count was reduced to 1, and this eliminated the need for manufacturing different component parts with subsequent joining. The redesign showed a 50% weight reduction while its rigidity was maintained. Figure 3 below shows the rear wing attached to the Bugatti Chiron Sport.

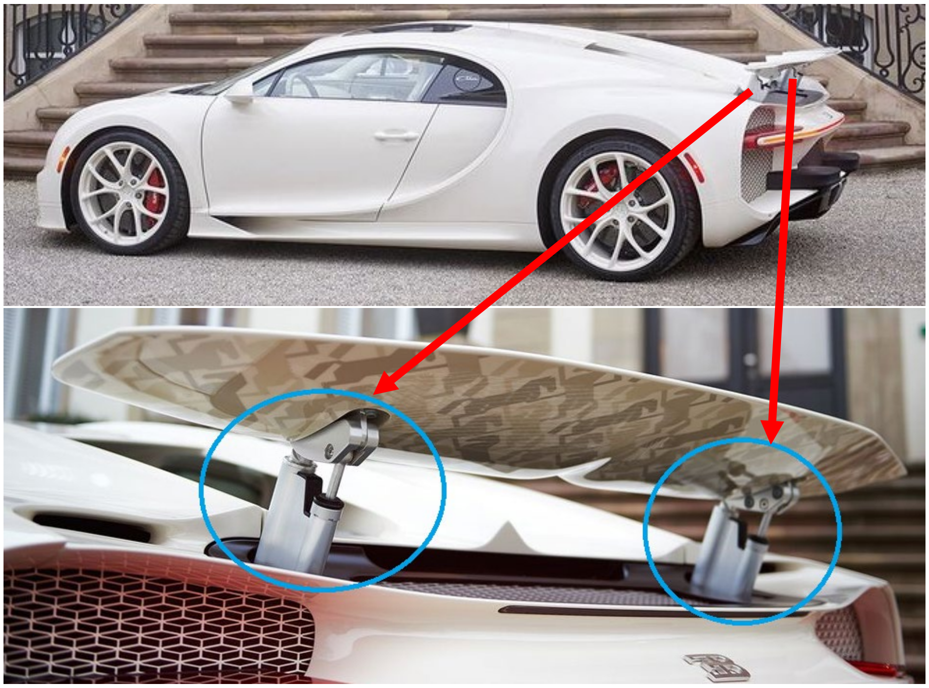

Figure 3: Rear wing is shown as attached on the Bugatti Chiron Sport (Hoffman, 2019)

Some researchers have focused on the manufacturability of topologically optimized monolithic thin-walled structures. Monolithic thin-walled lightweight load bearing sheet metal structures affect our day-to-day life. Examples include the vehicle chassis, canopy, and roof tent, the airplane fuselage, the oil storage vessels, just to name but a few. These are thin walled and have stiffeners such as ribs, spars and stringers, in order to prevent them from buckling under pressure from external forces (Carrera *et al.*, 2013). Ayinde 2020 developed a computational methodology for thin-walled sheet metal structures. The methodology combined the optimal design with manufacturability. The focus was on the vehicle body, and results demonstrate the effectiveness of the methodology (Ayinde, 2020).

Topology optimization has also been combined with machine learning in order to accelerate the design process. Chi et al., 2021 proposes a topology optimization framework which is based on machine learning. Topology optimization is an iterative process, often involving hundreds of iterations before the optimal solution is reached (Rozvany, 2009). For large scale design, or when many new designs are involved, the process becomes computationally intensive. This framework exploits data from topologically optimization iterations. This is done during the optimization process. That is, online training is done during the process. This is contrary to the machine learning models which are trained before the topology optimization process is done. The framework also learns from the historic topology optimization data, which it then uses it to predict the sensitivities without requiring the iteration process (Chi *et al.*, 2021). By reducing human interaction, the framework significantly reduces product development time for the optimization of monolithic components.

Research was conducted for Volvo Cars in Gothenburg, Sweden, and the purpose was to develop a methodology for the topology and shape optimization, using the rear lower control arm as a case study. The methodology was divided into two sections, the first one focusing on the topology optimization of the part. This is where the design space, objective function and constrains, boundary conditions, and multiple load cases were taken care of. It also focused on the manufacturability, and design constraints associated with the manufacturing process are factored in. The second section focused on the shape optimization, taking into consideration the plastic deformation and fatigue life. Four trials were performed and the selected approach resulted in a weight reduction of 3.6 kg being achieved while stiffness requirements were not compromised (Larsson, 2016).

3. Challenges and Potential Solutions

3.1 Disparities between optimum design and cost-effective manufacture

The major challenge is the disparities that rise between optimum design from the topology optimization and cost-effective manufacture. The most efficient design which meets the design specifications at the minimum cost may not manufactured be cost effectively (AMFG, 2018). The difference between topology optimization and generative design is that the later considers manufacturability of the part (Vlah *et al.*, 2020). Topology optimization often results in complex components (Christiansen *et al.*, 2015). The solution would be optimal in the design process, but difficult to manufacture. As a result, cost effectiveness may be lost if the manufacturability of the part is not factored in from the beginning of the design process. This can be solved by incorporating the manufacturability of the part from the early stages of the design process. It is further explained in the Section 4.2.

3.2 Complex designs are difficult to manufacture monolithically

The manufacture of complex designs in a single shot is difficult when the conventional manufacturing methods are used (Olsson *et al.*, 2017). These are the common manufacturing methods used by many companies. To manufacture the complex products, the casting and injection molding methods will require complex dies. As for the subtractive methods, they are not able to do internal channels like holes and pockets. The product will have to be broken down into many pieces, with the need for final assembly. As such, the higher the complexity, the higher the number of parts. This calls for a universal methodology which can be applied on both the monolithic design and each of subassembly in the case of a design which has more than one piece.

4. Opportunities

4.1 Topology Optimization of Monolithic Components for the Deep Drawing of Sheet Metal Parts

Topology optimization has previously focused mainly on the automobile primary market industry components such as brackets, the suspension, the chassis, the engine cradle, the engine mount, the uprights and the brake pedals. Very little to no attention has been paid to the after-market industry components and sheet metal parts. This presents an opportunity for research. It is a well-known fact that topology optimization is usually associated with the additive manufacturing process (Brackett *et al.*, 2011). This is due to the complexity of the resulting products, which makes it difficult to produce them using other conventional manufacturing methods such as casting, forging, extrusion and machining. The deep drawing process, unlike the majority of the conventional manufacturing methods, is well adapted for manufacturing geometrically complex sheet metal components and for improving the strength of that material through strain hardening (Groover, 2010). For the production of sheet metal parts, the deep drawing process can be used to produce a monolithic part in one shot. This has the following benefits: reduced part number, lightweightness, high raw material utilization, and high mechanical strength through strain hardening.

4.2 Methodology that Combines Topology Optimization with Manufacturability

Many times, topology optimization focuses on the design aspect only, neglecting the manufacturability of the resulting design. At times this renders the design optimum but non-manufacturable (Liu and Ma, 2016). Manufacturability is an important aspect of the design. 80% of the product cost can be calculated once the design process is finished (Anderson, 2020). The design process will determine the manufacturing method for the component. Hence, it is of paramount importance that manufacturability is factored in at the early stages of the design, via the methodologies that combine topology optimization with the final manufacturing process. There is also room for the methodology to combine topology optimization with hybrid manufacturing. This takes advantages of the capabilities of both the subtractive and additive manufacturing methods.

5. Conclusion

Topology optimization is very important in enabling the production of strong, lightweight functional parts. It uses algorithms to reduce component weight and material input. The purpose of the research was to present the emerging trends, challenges and opportunities in the development of methodologies for topology optimization of monolithic components. Having methodology as part of the design process helps to eliminate the long iterations that are done in topology optimization. It also eliminates human input and accelerates the product design process. The majority of the methodologies do not factor in manufacturability and as such some optimum designs are not economic to manufacture. These disparities between optimum design and cost-effective manufacture call for the incorporation of the manufacturability of the part from the early stages of the design process. Topology optimization usually results in complex designs and these are usually difficult to manufacture monolithically when the conventional manufacturing processes are involved. As such, a universal methodology which can be applied on both the monolithic design and each of subassembly in the case of a design which has more than one piece, is needed. One area of interest which has not yet been fully explored is the area of topology optimization of monolithic components for the deep drawing process for sheet metal parts. Combining topology optimization with monolithic design for the deep drawing process blends the benefit of weight reduction with the simplification of the assembly process. Other benefits include reduced part number, lightweightness, high raw material utilization, and high mechanical strength through strain hardening. The topology optimization technology is usually used for the vehicle primary market products such as brackets, and this is combined with additive manufacturing. It is important to note that the deep drawing process can manufacture sheet metal parts in one shot. This can be utilized for the after-market industry production of products such as the roof tents and canopies.

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