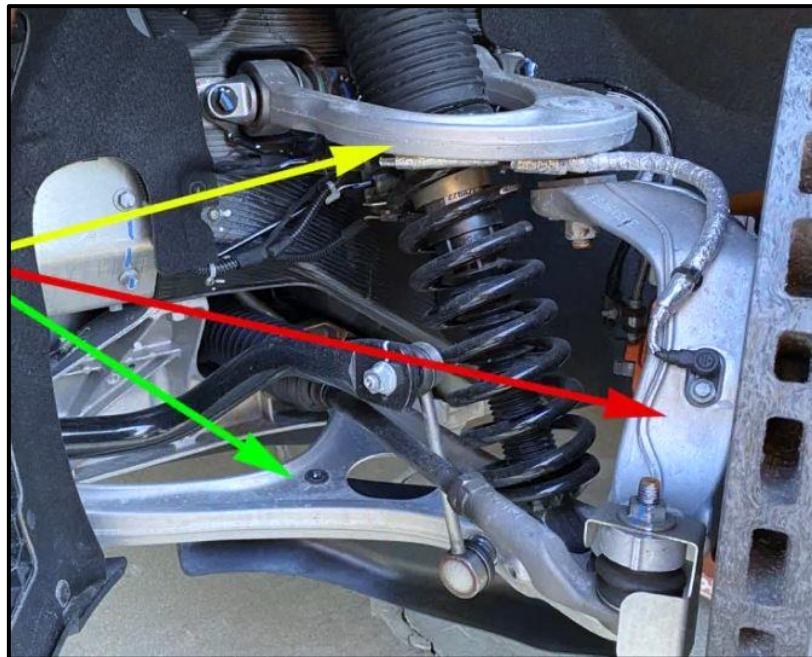


The Application of Advanced Topology Optimisation and Additive Manufacturing in Weight Reduction of The McLaren 720s Suspension Upright.



Masters Project Proposal
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1. Introduction

1.1. Project introduction

Weight reduction of high performance vehicle components is a key parameter during the design process, and the selection of suitable materials is crucial during the manufacturing stage. As such, automotive industries are working on various advanced technologies to improve component design and increase manufacturing efficiency (Dumbre *et al.* 2014; Vemula *et al.* 2019). Reducing vehicle weight will positively influence fuel economy and in turn, limit the emissions of ICE powered cars. For today's automobiles, a 10% weight reduction contributes to a 6% fuel economy improvement, as evident by Taub *et al.* (2019). Likewise, Joost (2015) cited that for battery electric vehicles (BEV), reducing vehicle weight directly enhances the driving range, confirming that a 10% weight saving can improve the range by approximately, 14%. Furthermore, reducing components mass maximises vehicle handling, and in particular, the weight of the suspension assembly says Taub *et al.* (2019). Managing the unsprung weight enhance tires traction, which is the key mechanism to improving handling. Wang and colleagues (2019) results revealed that vehicle dynamic performance, including, vehicle planar and spatial motion, are negatively affected as the unsprung mass increases.

Weight reduction can be accomplished via the selection of alternative lightweight materials, such as, high-grade aluminium alloy, titanium, and even composite materials (Cao *et al.* 2008). However, with the advances in design methods, weight reduction can also be achieved by minimising the amount of material needed to support the structural loads. Notably, Xia (2016) mentioned that the application of topology optimisation (TO), has been identified as one of the most effective tools for least-weight and performance design. TO is a well-established method in the aerospace and automotive industry, however, the main drawback of TO as expressed by Schuh *et al.* (2020), is that the final optimised results are complex in shape, and very difficult, if not impossible, to manufacture using traditional manufacturing methods (e.g. Machining, Casting, Forging, etc.). Consequently, Schuh and colleagues (2020) cited that, with the advancement of Additive Manufacturing (AM), also known as 3-D printing, it is now feasible to fabricate the complex TO structures directly from the designed CAD data. As an example, Porsche has already applied AM technology in

several areas, including, the release lever for the clutch of Porsche 959 (Aktiengesellschaft. 2020). Additionally, Bugatti was the world's first auto-company to produce eight-piston monobloc brake caliper, via the application of AM technology using titanium alloy material (Bugatti Automobiles. 2018).

Steering upright (knuckle) is the most stress sustaining and critical components in the suspension assembly, it is the pivot point of the steering and suspension system, which enables the front wheel to turn and supports vehicle mass. In particular, the weight of the upright in a double wishbone geometry represents a significant portion of the unsprung mass. Thus, reducing the weight of the upright is fundamental in improving suspension performance (Bhardwaj *et al.* 2018; Chaudhari and Khairnar. 2020; Mantovani *et al.* 2021), especially for the high-end super cars, such as, the McLaren 720s; which will be the case study in this project.

Despite the vast amount of literature currently available regarding TO and AM, there remains a limited number of studies focusing specifically on the design optimisation of steering upright. Further, these studies are limited due to their focus upon the case of Formula SAE suspension, which is a vehicle designed for racing track only. As such, this project will expand the evidence-base and make a novel contribution by utilising a topology optimisation design methodology, to suit the additive manufacturing process, within a new context of an automotive case study; a road-legal sports car, the McLaren 720s suspension upright. Furthermore, this masters thesis will discuss in depth the complete topological optimisation process, demonstrating every step in the redesign procedure, which is an identified gap and a critical section that is lacking from the majority of the available up-to-date literature.

1.2. Project Aims

- The primary aim of this project, is to introduce a new improved steering upright design for the McLaren 720s suspension, by implementing an advanced topology optimisation method. The complex shape of the 720s front upright and its severe operating loading conditions, necessitate the use of Altair's HyperWorks optimisation program. The highly advanced simulation-driven design approach that this software offers, will be the key in achieving an optimum lightweight design with maximum stiffness. Additionally, Solidworks will be used for the CAD modeling processes, and Geomagic Wrap will be utilised during the reverse engineering (RE) work of the standard 720s upright part.
- The second aim of this study is to contribute and add to the existing literature regarding product design for lightweighting, but with a further elaboration in the topology optimisation procedure. As such, this thesis will introduce a systematic approach on how to tackle components redesigning, for additive manufacturing technology.

2. Research and Literature

2.1. Topology Optimisation

As expressed by Stefano *et al.* (2019), structural optimisation aims to find the most efficient way to organise material in a component, with reference to loads and boundary conditions acting on the part. Objectives of structural optimisation includes weight reduction, stiffness maximisation, and resonant frequencies, and it can be divided into three main classes: Size optimisation which deals with dimensional optimisation, such as the cross sections of trusses inside a structure or the thicknesses of plates. Shape optimisation which deals not only with the shape of external boundaries, but also the shape of potential internal voids. Topology optimisation where the material is arranged in order to find the best distribution under defined boundary conditions (Bendsoe and Sigmund. 2013).

TO is a well-established numerical design methodology, which is recognised for its ability to generate lightweight mechanical components for the automotive and aerospace industries. Specifically, TO methodically alters the material distribution within a specified design domain of the structure, till an optimal solution is achieved, as explained by Abdi *et al.* (2018) and Clausen, Aege, & Sigmund (2016). This approach includes an iterative procedure of a numerical analysis for a specified domain, such as, finite element analysis (FEA), which is then followed by a sensitivity analysis, so that the material can be positioned only at the required stress areas. In consequence, this will lead to an established structural performance according to a set of targets and constraints (Dalpadulo, Pini and Leali. 2020).

Design of topology optimised components is increasing drastically, especially in the automotive and aerospace fields. There are multiple methods used for topology optimisation of structures, that operate based on the fundamental principles of material distribution variation. For instance, solid isotropic material with penalisation (SIMP), and bidirectional evolutionary structural optimisation (BESO), are two examples which fall under this category (Abdi *et al.* 2018). According to Victoria *et al.* (2009), both these methods are element-based approaches, meaning that a finite element or a property of a finite element is identified as a design variable (i.e., the density in SIMP method is an example of a design variable). Altair OptiStruct, which is the optimisation

algorithm designed to be used within Altair's programs, enables the application of SIMP method to real life components.

Numerous research has already addressed the application of TO along with AM technology in the automotive field, namely Mantovani *et al.* (2018), interpreted the numerical results of topology optimisation for structural component built via additive manufacturing, where a front steering upright of a Formula SAE racing car has been chosen for the case study. Sehmi *et al.* (2021) reviewed the refinement processes of topology optimisation for sheet metal manufacturing in the automotive industry. Similarly, Jankovics and Barari (2019) implemented AM and TO techniques to customise automotive structural components.

Schuh and colleagues (2020), utilised topology optimisation method to minimise the weight of manufacturing jig, and improve its functionality and adaption capability for each case. All simulations and TO in this study were performed with Solidworks 2019, where the optimisation process consisted of an iteration of TO, by constantly altering the constraints and objectives until a satisfactory result is achieved. Similarly, Mantovani *et al.* (2020), presented a topologically optimised steering upright design, by adopting a holistic approach that merged structural and manufacturing requirements.

Vemula *et al.* (2019) discussed the application of topology optimisation to parts designed for AM, where the research paper highlighted the main practical difficulties and opportunities along with the significance of identifying the cost-driven features during the conceptual design phase of the component. This study focused on a design approach with a case study of an automotive brake pedal, developing a methodology with respect to topology optimisation, by considering weight and manufacturability as constraints. The project was completed via the utilisation of the commercial software Altair SolidThinking (Inspire) and ANSYS. Furthermore, Abdi (2018), also investigated the design optimisation and additive manufacturing of automotive component, where a titanium brake pedal processed through selective laser melting (SLM) was developed.

Although TO does create optimal structures for a given constraint and design domain, it does not take manufacturability into account natively as indicated by Jankovics and Barari (2019). All design optimisation obtained from TO method, presents complicated

geometries and complex organic structures, that is difficult and often impossible to manufacture with traditional manufacturing (TM). However, the promising technologies of additive manufacturing, allows for the production of complex shapes due to their layer-by-layer approach, which will be discussed further in the next section.

2.2. Additive Manufacturing

Additive manufacturing (AM) as opposed to subtractive manufacturing, is a technology that is able to produce parts by adding material layer upon layer says Dalpadulo, Pini, and Leali, (2020). The implementation of AM can offer many benefits, including, the production of high performance complex components, the minimisation of design issues, investment costs, and developments time (Ford and Despeisse. 2016). Furthermore, the adoption of AM technologies proposes a new futuristic way of parts production, in which value chains are shorter, smaller, more localised, and collaborative, and promises significant sustainability benefits as evident by Gebler *et al.* (2014).

There are multiple technologies for metal additive manufacturing systems in the industry today, including: selective laser melting (SLM); direct metal laser sintering (DMLS); electron beam melting (EBM); and direct energy deposition (DED) or also known as laser metal deposition (Lewandowski and Seifi. 2016).

SLM method is a technology based on powder bed fusion, which uses a high energy power source to selectively melt or sinter a metallic powder bed. In the SLM process, the laser beam passes through a system of lenses and reflects by a mirror toward the platform surface. These mirrors are utilised to control the laser beam spot movement on the planar directions to the designed paths. After the powder is selectively melted in the first layer, the platform moves downward to enable a recoater blade to push another layer of fresh powder, on top of the previously built surface before the laser

scan process repeats (Zhang *et al.* 2017).

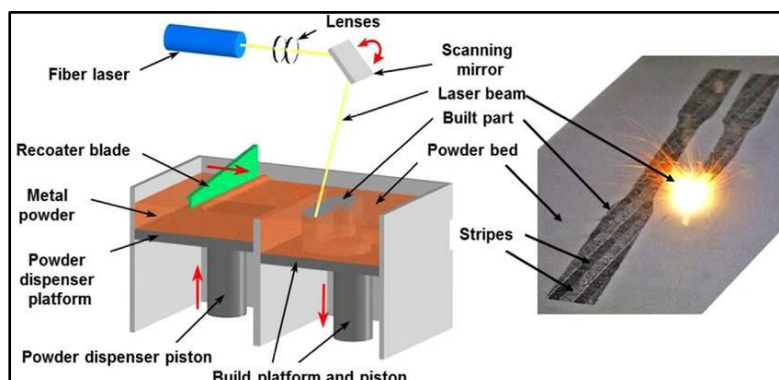


Figure 1: selective laser melting (SLM) method (Crales *et al.* 2017)

Energy Source (Laser/Electron Beam)

Powder Roller

Part Being Constructed

Loose Powder

Metal Powder

Powder Feed Tank

Build Tank

On the other hand, the direct energy deposition (DED), does not use a powder bed, rather, this method injects the metal powder or feeds the metal wire directly to the melting zone (metal am. [online]). DED techniques can further be divided into two categories according to Zhang *et al.* (2017), and are selected based on the feeding method. EBF represents the first category which uses metal wire as the feedstock, and LENS is the technique which uses metal powder flow as a feedstock.

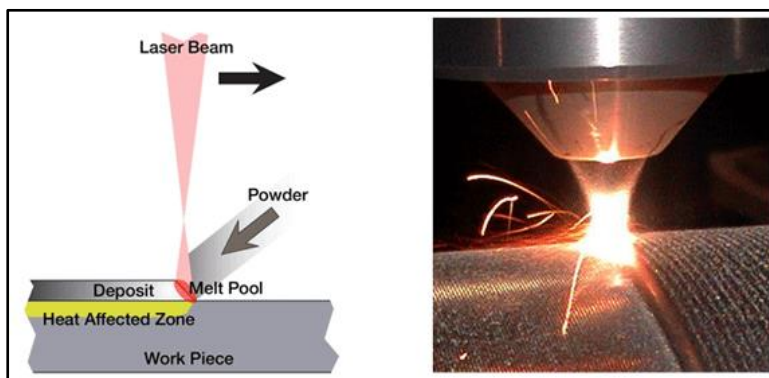


Figure 3: direct energy deposition (DED) method (Metal-Am. [Online])

3. Methodology

Design for additive manufacturing (DFAM) requires a different approach, as per the tradition design process. The differences between DFAM and conventional design were reviewed by Hallgren, Pejryd and Ekengren (2016). These authors described that *Designer-driven shape* is the method which is related to conventional design, as it depends considerably on the human designer driving the structural shape, contributing with knowledge and experiences about manufacturing to avoid costly produced parts. *Process-driven shape* in contrast, focuses on reducing manual interaction with a human designer to minimise design time and improve design performance.

DFAM which is the process intended to be used in the completion of this project, follows a process-driven shape approach, in the form of topology optimisation. As such, the advantage here is the capability to produce a high performance complex part via AM technology, which has the ability to produce (3-D print) parts in one step with minimal post processing (Jankovics and Barari. 2019). DFAM is receiving increasing attention as Dalpadulo, Pini, and Leali, (2020) mentioned. This last research paper also cited that the design of parts which are intended to be 3-D printed, is challenging and therefore, knowledge development, software simulation skills, processes and methodologies to fully benefit from AM are fundamental aspects.

The workflow of product optimisation for DFAM, has a fundamental methodology which forms the basis of any study related to AM and TO. Figure 4 demonstrates an example workflow presented by Dalpadulo *et al.* (2020).

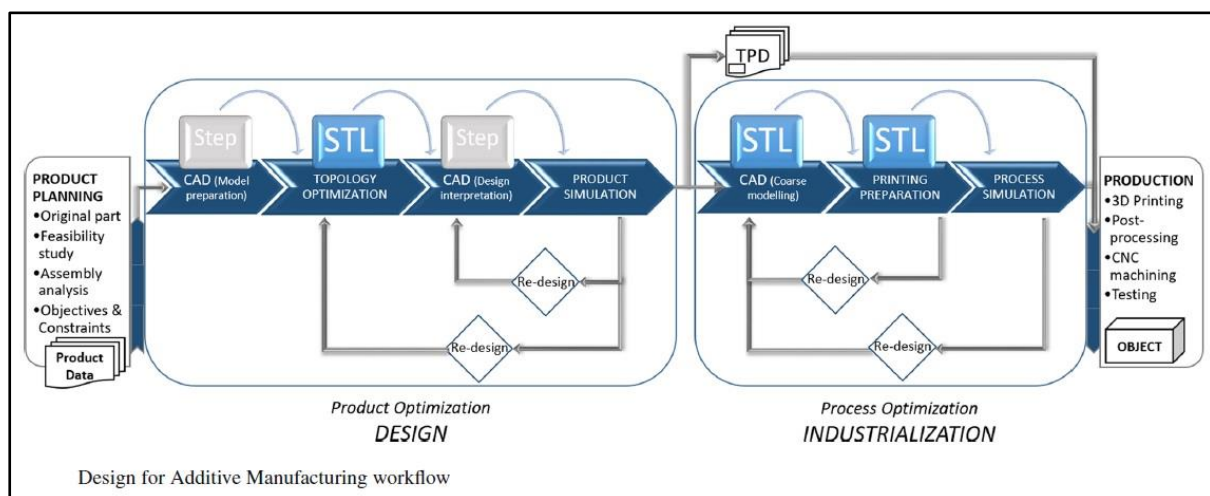


Figure 4: workflow of product optimisation for DFAM (Dalpadulo, Pini, and Leali. 2020)

In accordance with what has been discussed above, the methodology of this project is divided into 3 major phases, due to the nature of this project which involves a redesign and optimisation of an existing part. The first phase will cover the CAD modelling of the original (standard) McLaren 720s suspension upright, which will be completed via the application of reverse engineering techniques. The second phase, will cover the implementation of TO technology to improve component design, target weight reduction, and maximum stiffness. Finally, in the third phase of the project, the optimised structure of the component will be refined, in order to suit the AM process for upright production (metal 3-D printing).

3.1. Phase 1: Reverse Engineering of Original Part



Figure 5: 3D scanner Peel-3d
(capture-point. [Online])

The McLaren 720s original steering upright (Figure 6) will be reverse engineered, using a high-end quality 3D scanner, *Peel-3d* (Figure 5), with capturing accuracy of up to 250 microns, measurement resolution of 500 microns, and 250mm depth of field. This will generate a highly accurate points cloud file, which will be then transformed into a surface file model, and finally, refined to obtain a solid CAD model of the 720s upright. The software and tools that will be used to complete this procedure comprise Geomagic Wrap software for the scanning and files post processing, and Solidworks 2020 for the CAD modeling and refinement step.

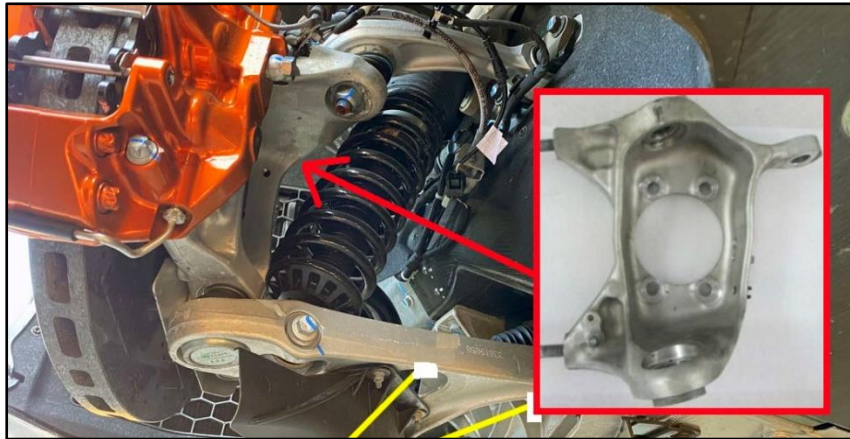


Figure 6: McLaren 720s original steering upright (Edmunds. 2020)

As evident by Kumar et al. (2013), the methodology of using reverse engineering (RE) techniques, to digitalise physical components for further CAE optimisation and development, has been widely recognised as a critical technique in the product redesign cycle. Specifically, RE enables the creation of surface models by three-dimensional scanning techniques, which will make it possible to redesign and manufacture a variety of parts and tools in a short development period says the authors.

During this phase, the design validation will also be completed, to ensure that the produced CAD model is highly accurate. This validation process will include both shape verification, via the alignment of the scanned file against the CAD geometry, and weight verification by weighing the physical part and comparing it against CAD model weight.

3.2. Phase 2: Design Optimisation Process

Second phase in the project methodology, will be divided into 3 sections:

- a- The original design will be investigated to highlight the performance of the stock 720s upright, via an advanced FEA simulation (both static and motion sim).
- b- The topology optimisation study will be carried-out on the component, by adopting solid isotropic material with penalisation (SIMP) method described earlier. This can be achieved using Altair's HyperWorks/OptiStruct software.
- c- Post completing the second phase and obtaining the topologically optimised part, an FEA investigation will be carried-out on the optimised structure, and compared against the original model. If the results are satisfying, the

optimisation will progress to the final phase, if not, the second phase will be revisited.

3.3. Phase 3: Model Refinement and Finalisation

After optimising the steering upright structure, the model which will be obtained from the topological optimisation will not be completely ready for manufacturing (3-D printing), and a refinement process will be necessary to finalise the obtained shape. This refinement process will be completed via the Altair Solidthinking (Inspire platform), using the PolyNURBS modeling feature, and further exported to Solidworks for design verification. Stefano *et al.* (2019); Vemula *et al.* (2019); Walton and Moztarzadeh (2017), and multiple similar studies, have implemented the proposed methodology on the design optimisation of their particular automotive-parts case studies.

4. Results Discussion

The advanced technology of TO and AM promises a high performance part that is light weight and with optimum stiffness. Results from the gathered literature, constantly show a significant improvement on the case studies investigated. Vemula *et al.* (2019), completed a topology optimisation case study on vehicle brake pedal (Figure 7), where the results revealed, 41.5% weight decrease, 29.4% less von mises stress, and 57% decrease on part deformation.

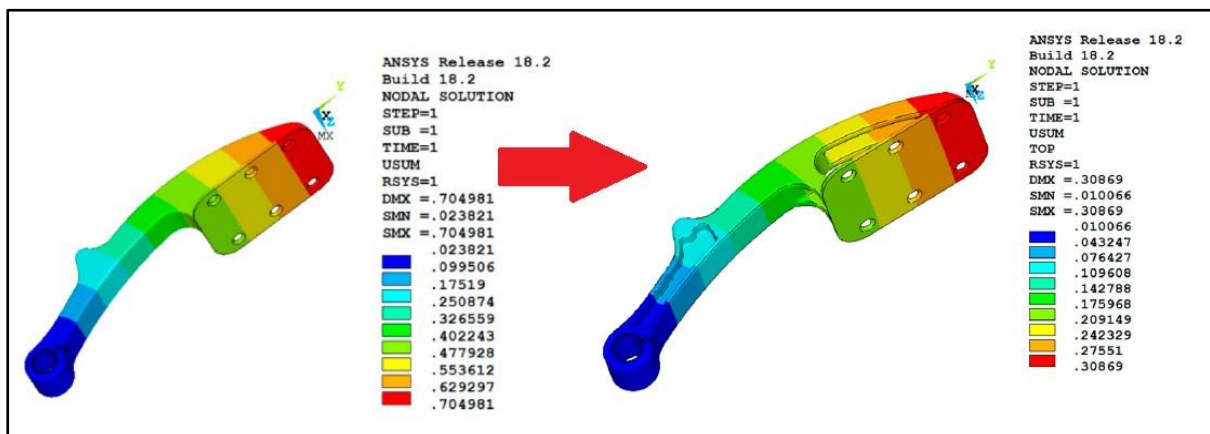


Figure 7: Topology optimisation case study on vehicle brake pedal (Vemula *et al.* 2019)

Stefano *et al.* (2019) optimisation approaches in design for additive manufacturing, which was applied on an ICE connecting rod, further proves the capabilities of TO and AM technologies in the automotive industry. The study results show that the optimised model is 37.33% lighter than the original rod part.

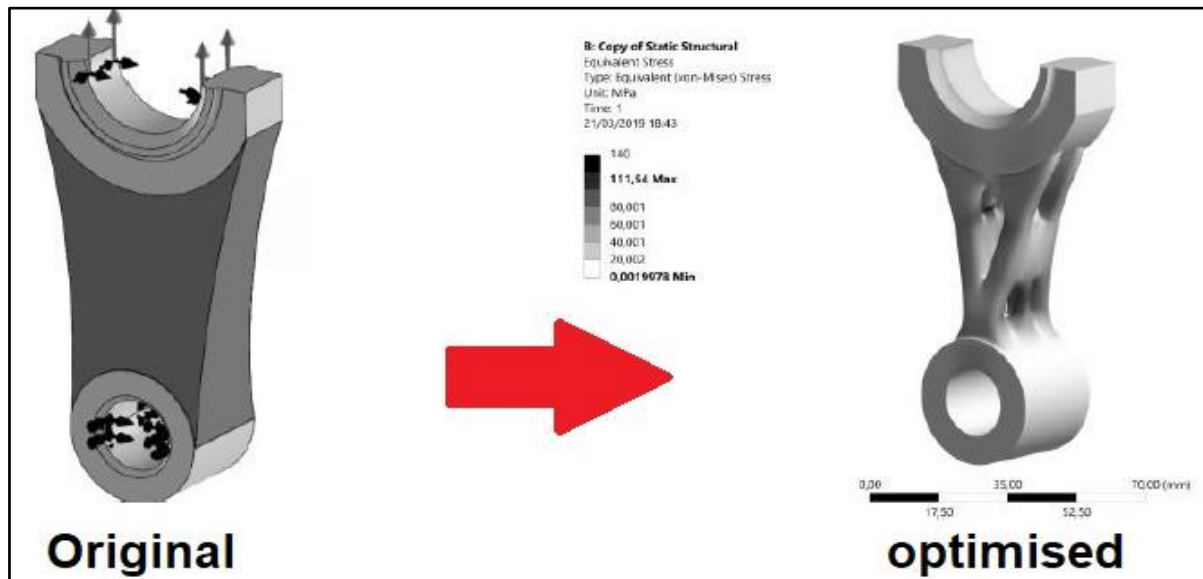


Figure 9: Topology optimisation for ICE connecting rod (Stefano et al. 2019)

A case study completed by Dalpadulo and colleagues (2020), also highlights outstanding results. This project further confirmed the effectiveness of topology optimisation, and DFAM techniques on the development and redesign of automotive structural parts. The case study addressed in this paper is similar to what this thesis is intended to investigate, which is the optimisation of steering upright, however, as previously mentioned the upright optimised in this research belongs to a Formula SAE race car. The results demonstrated a high level of design optimisation, generating a very complex structural shape with maximum stiffness, and minimum weight. Consequently, the part was successfully manufactured via AM, and specifically by selective laser melting (SLM) method, which is a powder bed fusion process as described previously.

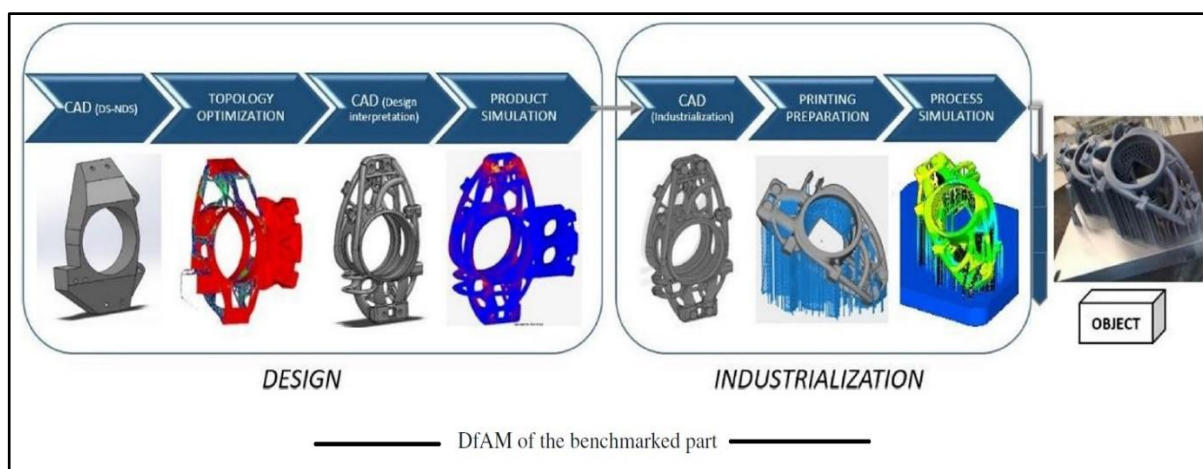


Figure 8: Topology optimisation for Formula SAE Upright (Dalpadulo, Pini and Leali. 2020)

Similarly, Mantovani *et al.* (2020) achieved high performance structural design for Formula SAE steering upright. The results accomplished in this study showed a 9% weight reduction over the original CNC component (Figure 10).

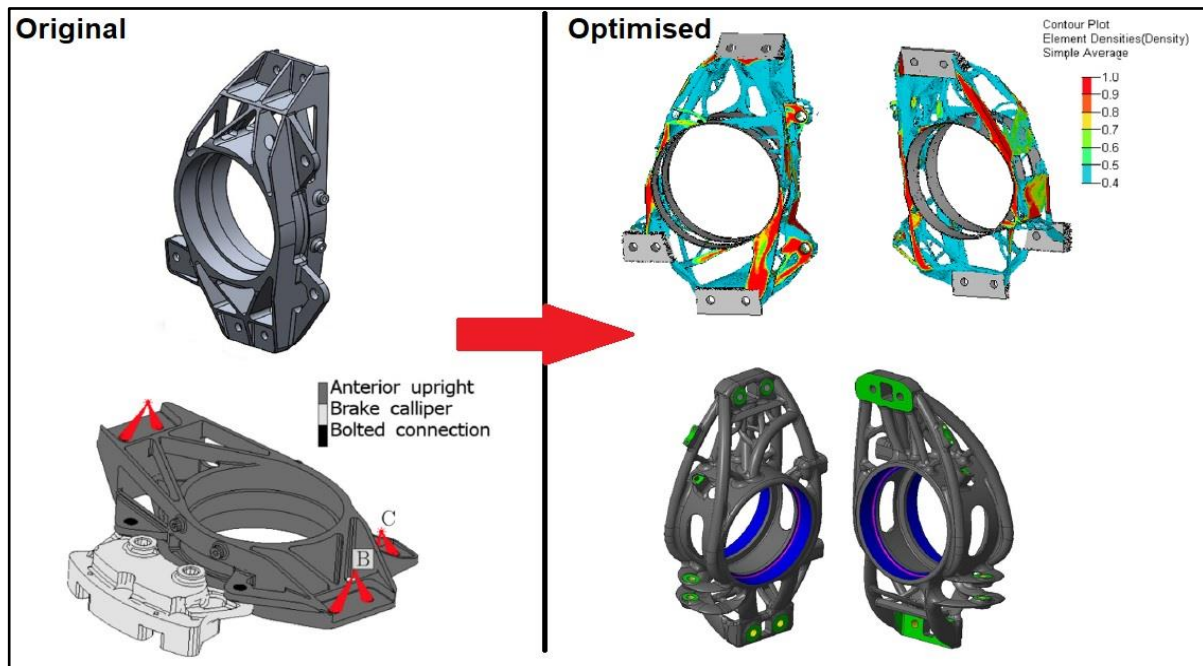


Figure 10: Topology optimisation on Formula SAE steering upright Mantovani *et al.* (2020)

After thoroughly studying and immersing myself in the available literature, and investigating the different structural optimisation cases performed on automotive/motorsport components, the aims and objectives of this project, were bench marked as follows:

The optimisation study will be carried-out with two different material selection, AM suited Aluminium alloy (AlSi10Mg), is first material which will be chosen as an economical and cost efficient material. Further, Titanium alloy Grade 5 (Ti6Al4V), will be chosen as the second material. Ti6Al4V, is identified amongst the high-end alloy grade and will be selected to unleash the potential of DFAM, pushing towards a maximum performance structural part, without any consideration of the costs.

The McLaren 720s upright, is originally manufactured with forged aluminium (Edmunds. 2020). With AlSi10Mg material, the aims will be to reduce the mass of the 720s steering upright by a minimum of 15%, while preserving the structural stiffness of the component if not optimising it further. However, with Ti6Al4V being the selected material, the aims will be set to challenging figures. The benchmark aims for titanium

alloy, includes a minimum of 30% weight reduction, and to further optimise the stiffness by at least 5% compared to original component.

5. Evaluation

It is anticipated that the proposed research project in this paper will produce robust evidence that in turn, will expand the related literature, and make a novel contribution by implementing topology optimisation design methodology with additive manufacturing, within a new context of an automotive case study (McLaren 720s Steering upright). The available literature is limited in the number of case studies completed on road vehicle, and the majority of papers have only touched the basics of TO with minimal simulation time. It is aimed that this project will invest intensively on the simulation time related to the topology optimisation, in order to accomplish the most optimum developed structure.

It must be noted that this type of research requires significant computational resources with high end hardware technology, and the researcher has already secured this to run the intensive simulation work planed, with access to the software mentioned previously, for both Solidworks and Altair engineering programs being an academic student version, and Geomagic Wrap as a free version from 3D Systems. Also, the researcher has not received any parts, data, or any form of support from the McLaren Automotive team. The McLaren parts investigated in this project are self-sourced via personal funds. The associated expenses include the purchase of a used McLaren 720s steering upright (i.e., £349.99) and the rental of a 3D scanner (i.e., £300), that will be rented for 2 days to scan the original component.

Importantly, the project is not without limitations. For instance, a limitation of this research relates to the feasibility of manufacturing the optimised design at the end of the project. Specifically, AM costs are very expensive, and are only available at high level industries. However, this project will discuss the complete procedure and method intended to be used for 3-D printing (AM), if the study has an opportunity to develop further to this stage.

REFERENCES

- Joost, Will. (2012) 'Technology Area Development Manager Lightweight Materials Vehicle Technologies Program', *US Department of Energy*.
- Dumbre, P., Mishra, A., Asher, V. and Kulkarni, S. (2014) 'Structural analysis of steering knuckle for weight reduction', *International Journal of Advanced Engineering Research and Studies*.
- Gebler, M., Schoot Uiterkamp, J. and Visser, C. (2014) 'A global sustainability perspective on 3D printing technologies', *Elsevier, Journal of Energy Policy*.
- Victoria, M., Martí, P. and Querin, O. (2009) 'Topology design of two-dimensional continuum structures using isolines.', *Elsevier, Journal of Computer and Structures*.
- Ford, S and Despeisse, M. (2016) 'Additive manufacturing and sustainability: an exploratory study of the advantages and challenges', *Elsevier, Journal of Cleaner Production*.
- Clausen, A., Aage, N. and Sigmund, O. (2016) 'Exploiting Additive Manufacturing Infill in Topology Optimization for Improved Buckling Load', *Elsevier, Journal of Engineering*.
- Lewandowski, J and Seifi, M. (2016) 'Metal Additive Manufacturing: A Review of Mechanical Properties', *Reviews In Advance Journal*.
- Xia, L. (2016) *Multiscale Structural Topology Optimization*, Oxford: ISTE Press Ltd & Elsevier Ltd.
- Nana, A., Cuillière, J. and Francois, V. (2016) 'Towards adaptive topology optimization', *Elsevier, Journal of Advances in Engineering Software*.
- Zhang, Y., Wu, L., Guo, X., Kane, S., Deng, Y., Jung, Y., Lee, J. and Zhang, J. (2017) 'Additive Manufacturing of Metallic Materials: A Review', *Journal of Materials Engineering and Performance*.
- Walton, D and Moztarzadeh, H. (2017) 'Design and development of an additive manufactured component by topology optimisation', *Elsevier, IRP Journal*.
- E.Ormer, M., Gschweidl, M., Ferrari, M., Madera, I. and Mouriaux, F. (2017) 'Designing for Additive Manufacturing: Lightweighting Through Topology Optimization Enables Lunar Spacecraft', *ASME Journal of Mechanical Design*.
- Dutta, B. and Froes, F.H. (2017) 'The Additive Manufacturing (AM) of titanium alloys', *Elsevier Journal & Metal-powder.net*.
- Hallgren, S., Pejryd, L. and Ekengren, J. (2018) '(Re)Design for Additive Manufacturing', *Elsevier, IRP Journal*.
- Bhardwaj, S., Umashankar, A. and Agarwal, A. (2018) 'Design and Optimization of Steering Upright to Reduce the Weight Using FEA', *SAE International Journal*.

Abdi, M. (2018) 'Design optimisation for an additively manufactured automotive component', Inderscience, *International Journal of Powertrain*.

Sehmi, M., Christensen, J., Bastien, C. and Kanarachos, S. (2018) 'Review of topology optimisation refinement processes for sheet metal manufacturing in the automotive industry', *Springer-Verlag GmbH Germany*.

Panesara, A., Abdia, M., Hickmana, d. Ashcrofta, I. (2018) 'Strategies for functionally graded lattice structures derived using topology optimisation for Additive Manufacturing', *Elsevier, Journal of Additive Manufacturing*.

Jankovics, D and Barari, A. (2019) 'Customization of Automotive Structural Components using Additive Manufacturing and Topology Optimization', *Elsevier, IFAC*.

Wiberg, A., Persson, J. and Olvander, J. (2019) 'Design for additive manufacturing – a review of available design methods and software', *Linkopings Universitet Tekniska Hogskolan*.

Taub, A., De Moor, E., Luo, A., K. Matlock, D., G. Speer, J. and Vaidya, U. (2019) 'Materials for Automotive Lightweighting', *Annual Review of Materials Research*.

Stefano, R., Gianpaolo, S., Federico, U., Roberto, M. and Gianmaria, C. (2019) 'Optimization approaches in design for additive manufacturing', *International Conference on Engineering Design*.

Vemula, A., Naidu, B., Chandrasheker, B., Mylapalli, K., Mondal, P. and Shareef, L. (2019) 'Topology Optimized Design Methodology to Suit Additive Manufacturing Process', *SAE International Journal*.

Wang, W., Chen, X. and Wang, J. (2019) 'Unsprung Mass Effects on Electric Vehicle Dynamics based on Coordinated Control Scheme', *American Control Conference*.

Haghdadi, N., Laleh, M., Moyle, M. and Primig, S. (2020) 'Additive manufacturing of steels: a review of achievements and challenges', *Journal of Mater Science*.

Aktiengesellschaft, P. (2020) 'Innovative pistons from a 3D printer for increased power and efficiency'. *Porsche Press Release*.

Dalpadulo, E., Pini, F. and Leali, F. (2020) 'Integrated CAD platform approach for Design for Additive Manufacturing of high performance automotive components', *International Journal on Interactive Design and Manufacturing*.

Bonera, E., Gadola, M., Chindamo, D., Morbioli, S. and Magri, P. (2020) 'On the Influence of Suspension Geometry on Steering Feedback', *MDPI, Journal of Applied Sciences*.

Mantovani, S., Babieri, SG., Giacomini, M., Groce, A., Sola, A. and Bassoli, E. (2020) 'Synergy between topology optimization and additive manufacturing in the automotive field', *IMechE, Journal of Engineering Manufacturing*.

Schuh, G., Bergweiler, G., Lichtenthaler, K., Fiedler, F. and De la Puente Rebollo, S. (2020) 'Topology Optimisation and Metal Based Additive Manufacturing of Welding Jig Elements', *Elsevier, IRP Journal*.

Chaudhari, P and Khairnar, R. (2020) 'Weight Optimization of Hub and Knuckle Using Topology Optimization', *SSRG International Journal of Mechanical Engineering*.

Cao, J., Huang, Y., Reddy, N., Malhotra, R. and Wang, Y. (2020) 'Incremental sheet metal forming: Advances and challenges', Northampton University, *Mechanical Engineering, Civil and Environmental Engineering*.

Pawsey, C. 2018. *Lightweight materials reducing weight of suspension systems*. [Online] Available at: <https://www.automotive-iq.com/chassis-systems/articles/lightweight-materials-reducing-weight-suspension-systems> [Accessed 19 March 2021].

Bugatti Automobiles. 2018. *WORLD PREMIERE: BRAKE CALIPER FROM 3-D PRINTER*. [Online] Available at: <https://www.bugatti.com/media/news/2018/world-premiere-brake-caliper-from-3-d-printer/> [Accessed 15 January 2021].

3DEO. 2018. *Overview of Powder Bed Fusion – Metal 3D Printing*. [Online] Available at: <https://www.3deo.co/manufacturing/intro-to-metal-3d-printing-processes-powder-bed-fusion-dmls-sls-slm-lmf-dmp-ebm/> [Accessed 14 February 2021].

Edmunds, D. 2020. *2020 McLaren GT Suspension Deep Dive | A grand tour underneath*. [Online] Available at: <https://www.autoblog.com/2020/10/28/mclaren-gt-suspension-deep-dive/> [Accessed 03 March 2021].

Metal-Am. 2020. *Metal Additive Manufacturing processes*. [Online] Available at: <https://www.metal-am.com/introduction-to-metal-additive-manufacturing-and-3d-printing/metal-additive-manufacturing-processes/> [Accessed 16 March 2021].