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## MSc Motorsport Engineering

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# Contents Page

## Table of Contents

|                                             |    |
|---------------------------------------------|----|
| Contents Page.....                          | 1  |
| Table of Figures .....                      | 2  |
| Introduction.....                           | 3  |
| Task 1: Industrial Relevance.....           | 4  |
| Task 2: Literature Review.....              | 5  |
| Task 3: Proposed Methodology .....          | 9  |
| Task 4: Results Collection & Analysis ..... | 10 |
| 4.1 Design Techniques .....                 | 10 |
| 4.2 Heat Transfer Analysis.....             | 10 |
| 4.3 Manufacturing Process.....              | 11 |
| Task 5: Project Planning & Timescales ..... | 12 |
| Task 6: Evaluation .....                    | 13 |

## **Table of Figures**

|                             |    |
|-----------------------------|----|
| Figure 1: Gannt Chart ..... | 12 |
|-----------------------------|----|

## Introduction

Increased need for light, high-performance components in racing has driven the application of advanced computational design tools. Topology optimisation and generative design have been the most common types of structural optimisation among them. They enable the design of components with optimal strength-to-weight ratios without sacrificing manufacturability and regulatory compliance (Sigmund & Maute, 2013). This research contrasts density-based topology optimisation and generative design within the structural design of a suspension upright, one of the most critical structural elements of motorsport vehicles (Drummond, 2022). The research aims to compare the performance of both approaches against structural performance, weight minimisation, manufacturability, and computational efficiency. Generative design relies on AI-driven algorithms to create a sequence of iterations of the design, and thus it is most relevant to additive manufacturing (AM). Topology optimisation (TO), by contrast, employs a deterministic approach to optimise material distribution within a predetermined design space and therefore is more appropriate for traditional manufacturing processes such as CNC machining and casting. Aside from structural concerns, heat transfer phenomena will be analysed because motorsport components must operate under high-temperature conditions. Heat input from the braking system can influence material properties, which may change the durability and performance of lightweight optimised components. Through finite element analysis (FEA) simulation, manufacture process analysis, and real-world feasibility considerations, this research seeks to present a data-based comparison of the two optimisation methods. The findings will guide motorsport engineers in the best method to adopt during the creation of high-performance, regulation-limited components, which will ultimately result in better vehicle performance and track competitiveness.

## **Task 1: Industrial Relevance**

The evolution of computational design techniques has profoundly impacted engineering and manufacturing processes, particularly in high-performance industries such as motorsport. This research aims to investigate and compare generative design and topology optimisation, focusing on their application in the development of lightweight structural components (Sigmund & Maute, 2013). The study will assess the methodological differences between these optimisation strategies, their effectiveness in enhancing performance, and their implications for manufacturability. Furthermore, the influence of heat transfer considerations on the final design and production feasibility will be evaluated.

As the motorsport industry continues to advance, aerodynamic efficiency, structural integrity, and weight reduction remain key factors in performance enhancement. Computational design methods, such as generative design and topology optimisation, have become fundamental in achieving these objectives by minimising component weight while preserving strength and stiffness (Autodesk, 2023). The implementation of these techniques enables the development of highly optimised, lightweight structures, which can significantly influence race performance.

Generative design leverages AI-driven algorithms to explore a wide range of design alternatives, optimising weight distribution, stress paths, and manufacturability. This approach is extensively applied in Formula 1, Formula E, and endurance racing, where complex, organic geometries are developed beyond the scope of traditional engineering methods (Jabil, 2022). Generative design is particularly advantageous for additive manufacturing (AM), allowing the production of intricate, material-efficient components that would be impractical using conventional machining techniques.

In contrast, topology optimisation follows a deterministic approach, redistributing material within a defined design space to maximise the stiffness-to-weight ratio. This method is widely employed in the development of suspension uprights, brake callipers, wing mounts, and other structural reinforcements, ensuring durability while reducing material usage. Additionally, topology optimisation is more suited to CNC machining and casting, making it a preferred technique in conventional motorsport manufacturing due to its lower computational overhead and efficiency in rapid design iterations.

A critical consideration in motorsport engineering is regulatory compliance, particularly in adherence to FIA safety standards. Motorsport teams must carefully balance weight reduction with crashworthiness, durability, and load-bearing capacity. By integrating generative design and topology optimisation into the development of high-performance components, engineers can push the boundaries of lightweight design while ensuring compliance with industry regulations. Ultimately, this research aims to provide valuable insights into the advantages and limitations of these optimisation techniques, enabling motorsport teams to develop innovative, high-performance components that enhance on-track competitiveness and engineering efficiency.

## **Task 2: Literature Review**

Generative design is an advanced computational technique that employs iterative problem-solving approaches to search and iteratively optimise several design alternatives in an effective way. The procedure eliminates the need for manual optimisation of designs by allowing algorithms to generate, test, and optimise thousands of possible solutions against pre-defined conditions. By employing a parametric computational model, generative design mechanises the design process in such a way that only high-performing solutions are retained, while poor configurations are systematically discarded. This cumulative process often produces natural, non-learned geometries that may not have been imagined with traditional engineering techniques. Generative design has its roots in the early 1970s when rule-based computer-generated geometry formed the basis of its creation. The capabilities of artificial intelligence (AI) and cloud computing to advance this area even further have multiple times increased its use within engineering. Contemporary generative design software, such as Autodesk Fusion 360, utilizes AI-based algorithms and advanced optimisation techniques in order to solve complex, multi-objective design issues (Coulthard & Wang, 2022). The software enables simultaneous creation of multiple possible solutions that meet central performance criteria, including strength, weight, stiffness, and manufacturability, along with meeting some manufacturing limitations. One of the chief determinants of generative design adoption is computer capability as a lot of resources are needed to carry out high-fidelity simulations. Existing generative design tools often use cloud computing to allow parallel simulation and evolutionary runs to enhance efficiency. With these technologies, however, computational intensity is still a key issue. For example, General Motors stated it created over 150 viable seat bracket designs in a generative design process from one set of parameters (Autodesk, 2023). While this shows how strong the method is at being able to try an astronomical number of design space combinations, it also shows how computationally costly the cloud-based generative design processes can be, running for hours or even days to produce an optimal solution for very complicated structures. Generative design's computational burden is also demonstrated in motor sport applications. With a Formula SAE chassis project (Drummond, 2022), the processing time using Autodesk Fusion 360's generative design tool was significantly longer than anticipated for a high-level frame design, which shows the computationally heavy work required by high-resolution optimisation. Also, after the execution of generative design simulations, post-processing and analysis of the resulting solutions are needed to establish their feasibility and optimize the final design, again extending the development process.

Despite these restrictions, generative design is a powerful tool for engineering creativity in areas where light structures, advanced material efficiency, and aerodynamic optimisation are critical. With ever-increasing computing resources, generative design will be increasingly accessible, enabling engineers to spearhead the creation of high-performance components in car, aircraft, and motorsport engineering.

Below are some of the different types of generative design methods that could be used:

- **Computation model:** In generative design, the computational model serves as the foundation for design exploration and optimisation. It defines the design space, constraints, objectives, and performance criteria that guide the algorithm in generating multiple design alternatives.
- **Generator:** The generator method in generative design refers to the algorithmic process that creates multiple design alternatives based on the computational model. It systematically explores different configurations, optimising for predefined performance criteria such as weight, stiffness, and manufacturability.
- **Design Evaluation:** The design evaluation method in generative design is the process of assessing and ranking generated design alternatives based on predefined performance criteria. This step ensures that only the most optimised and feasible solutions are considered for further refinement or manufacturing.

Reducing the weight of a suspension upright is a crucial factor in decreasing unsprung mass, which significantly influences vehicle dynamics and handling characteristics. The unsprung mass affects ride comfort, road-holding ability, and overall performance, as it directly impacts body acceleration and tyre deflection ratios. An increase in unsprung mass can amplify vibrations, leading to a reduction in ride comfort, particularly within the 4-8 Hz frequency range, where human sensitivity to vibration is heightened. Therefore, optimising structural components such as suspension uprights is essential for improving both performance and driver experience.

Topology Optimisation (TO) is a computational method that is used to achieve optimum distribution of material in a given design space for maximum stiffness-to-weight ratio (Jensen, 2020). The density method employs a finite element discretisation of the design space, and each element is assigned a material density value between 0 and 1, indicating the absence or presence of material. The most widely used density-based method is Solid Isotropic Material with Penalisation (SIMP), where an interpolation function is used to eliminate intermediate densities, resulting in a binary solid-void material distribution (Dong et al., 2024). This ensures the design of structurally valid and manufacturable components. The iterative solver in topology optimisation reconfigures material in a systematic manner, reinforcing high-stress regions and eliminating non-effective material. This process generates extremely efficient, organic shapes with minimal excess mass while maintaining strength and stiffness. Originally

developed by Bendsøe and Sigmund in the 1980s and 1990s, the density method gained popularity due to its stability and simplicity to implement with finite element analysis (FEA). Although additional filtering and penalisation techniques have to be employed to prevent numerical instabilities such as checkerboarding and grey areas, the method is still widely applied across the fields of engineering. One of the key advantages of density-based topology optimisation is computational efficiency, with quicker convergence than generative design when producing a single optimised design. This aspect reduces the demand for high-performance computing hardware, which renders it an accessible choice for motorsport teams and structural engineers. Off-the-shelf software packages such as ANSYS and Abaqus have topology optimisation capabilities, enabling engineers to optimise designs within the framework of a typical engineering workstation. Although it takes multiple FEA iteration to converge, topology optimisation remains less computationally expensive than generative design, since it involves evaluating numerous various design possibilities. Motorsport teams are likely to employ topology optimisation early in the design process, leveraging its strength and lower computational burden to achieve optimised components rapidly. Generative design, on the other hand, may be employed for applications where the exploration of radically different geometries is required, even with the increased computational expense.

Generative design and topology optimisation both utilise finite element analysis (FEA) to analyse the response of components to structural loading, thermal loading, and vibration forces (Sigmund & Maute, 2013). Simulation reduces the quantity of physical prototyping so that engineers can predict stress distributions, strain rates, and deformation modes. Heat transfer analysis is a significant factor in suspension upright design in motorsport usage owing to exposure to hot temperatures from braking systems and aerodynamics. Heat absorption is accountable for altering the structural characteristics of material, so much so that it is necessary to study thermal expansion effects in detail. Steel, for instance, experiences a severe loss of mechanical properties when its temperature exceeds 482°C, with the yield strength and elasticity being decreased by 12-14% at the level of temperature. At temperatures higher than 600°C, the material undergoes extreme loss of structure. The dimensional stability of the part will be lost by the thermal expansion deformation and will lead to poor performance and eventual failure under dynamic load.

In a practical example, generative design and topology optimisation were both utilised to optimise a suspension upright with a focus on quantifying weight savings. A manually designed upright was initially analysed, with wasted material usage beyond structural requirements. Topology optimisation reduced the volume of the upright by 65%, resulting in a skeletal part that still maintained the necessary strength. In contrast to this, generative design achieved 88% volume reduction by integrating multi-load cases, considering combined turning and braking forces on the upright. In direct comparison of the two methods, the generative-designed upright was 66% lighter than its topology-optimised counterpart (Coulthard & Wang, 2022). Both designs were prototyped in ABS plastic via additive manufacture (3D printing) to enable structural testing. Testing showed that the topology-optimised upright possessed higher load-bearing capacity before failure, thanks to the more conservative material distribution.

Conversely, while the generative designed upright met all structural targets, it failed closer to safety factors as a result of the aggressive material reduction. This case study illustrates the intrinsic trade-offs of the two optimisation methods. Motorsport teams may prefer topology optimisation for manufacturability and robustness, especially when dealing with CNC machining or casting constraints. In applications where every gram of weight reduction is critical, however, and where large-scale validation of ultra-light parts is feasible, generative design can deliver greater performance advantages. The choice between the two approaches ultimately depends on manufacturing feasibility, structural safety considerations, and performance objectives.

### **Task 3: Proposed Methodology**

A density-based topology optimisation (TO) approach was implemented to design a lightweight front suspension upright, achieving a 21% reduction in weight compared to the original baseline design. Following this optimisation process, the finalised topology-optimised design will be prototyped and subjected to structural testing to evaluate its load-bearing capacity and mechanical performance under operational conditions. Subsequently, a generative design approach will be applied, starting from the same initial design parameters used for topology optimisation. Once an optimised generative design solution has been obtained, it will also be manufactured as a prototype and subjected to identical structural testing procedures. This comparative assessment will facilitate a direct evaluation of the performance, durability, and structural efficiency of both methodologies. The results will provide quantitative insights into the accuracy, strength, and manufacturability of each optimisation method, offering a data-driven basis for selecting the most effective approach for future applications. Furthermore, the repeatability of the methodology will be considered to ensure consistent results, time efficiency, and reliability. Ultimately, this research aims to determine the most suitable optimisation technique for developing high-performance, lightweight components that can be effectively manufactured and integrated into motorsport and automotive applications.

## **Task 4: Results Collection & Analysis**

### **4.1 Design Techniques**

#### ***Topology Optimisation***

To maintain simulation accuracy and uniformity, boundary conditions were made constant during analysis. The applied forces were a combination of braking and cornering loads, representing actual operational stresses encountered by the suspension upright. The research focused on examining the general deformation and stress pattern in the component under these forces. A factor of safety was employed to ensure structural integrity, preventing failure under maximum expected loads as well as for stress accumulation due to fatigue. Upon optimisation, the final topology-optimised model possessed 21% weight reduction compared to the original model without affecting the structural integrity and stiffness. The outcome confirms that topology optimisation can efficiently reduce mass while maintaining fundamental performance characteristics.

#### ***Generative Design***

The objective with the application of generative design is to compare its performance against topology optimisation under the same boundary conditions. To enable a fair and direct comparison, the same cornering and braking forces will be applied as with the topology-optimised simulations. The results will be collected and analysed using Computer-Aided Design (CAD) software to compare key performance parameters. In the generative design process, the objective is to achieve an optimum compromise between mass minimisation and structural performance such that the upright is sufficiently stiff and has a high enough load-carrying capacity while minimising mass as much as possible. A suitable factor of safety will be incorporated to ensure that it is durable and does not fail prematurely. The outcome of this comparative study will provide valuable insight into the most suitable optimisation technique for achieving lightweight, high-performance suspension components. A similar approach was utilised in the Project Chaos hypercar, where generative design enabled the development of ultra-lightweight brake callipers and engine components (New Atlas, 2023).

### **4.2 Heat Transfer Analysis**

Heat transfer calculations will be conducted to assess the thermal influence of surrounding components, such as the brake disc and calliper, on the suspension upright. The objective is to determine whether the heat generated by these components has a significant impact on the structural integrity and performance of the upright, necessitating design modifications. Additionally, the analysis will evaluate whether incorporating thermal effects into the design and simulation process is both practical and time efficient. This assessment will ensure that any required thermal considerations are integrated into the optimisation process without compromising computational efficiency or engineering feasibility.

### 4.3 Manufacturing Process

The selection of an appropriate production process itself depends upon the design complexity and the applicability of the chosen optimisation method. Economic viability and material availability are the prime concerns in the manufacturing stage so that the manufacturing process is also economically efficient along with being technologically possible. Material selection has already been made based on topology optimisation restrictions and legislative requirements, which restrict the use of certain materials to be cost-effective and legislated. This ensures that the final component meets performance, safety, and cost specifications while being producible within industry boundaries.

## Task 5: Project Planning & Timescales

A Gantt chart is drawn to make the project planning and monitoring of the progress easy. The chronological timeline is an easily readable format in which every step of the project is monitored so that all the activities are finished on schedule. The Gantt chart also includes contingency allowances for providing room for any unexpected problems or delays that may arise in the research process. This is a safety precaution that reduces potential setbacks, and the project runs smoothly and successfully completed by the end date in August.

Figure 1 below shows the Gantt chart representing the time scale of the project.

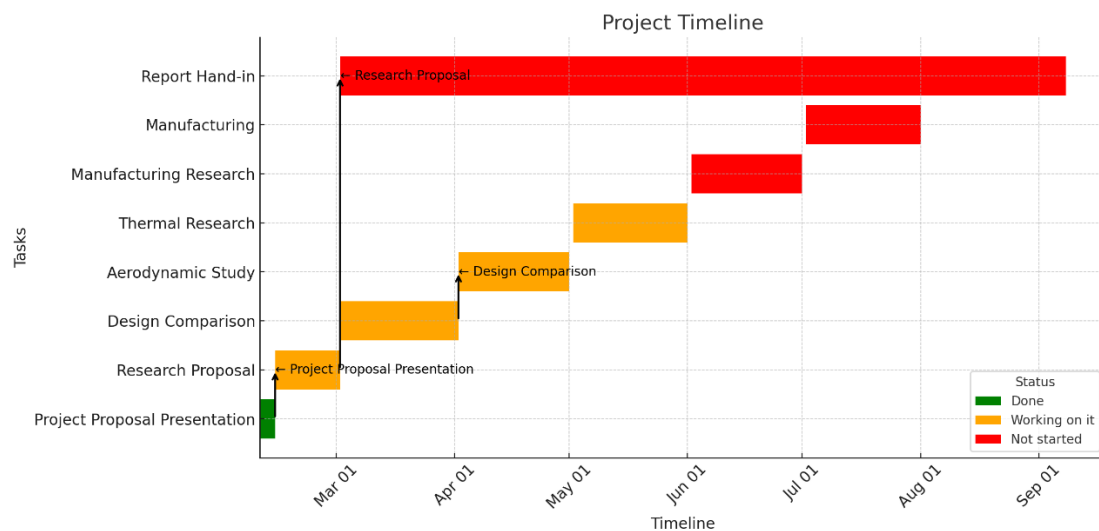


Figure 1: Gantt Chart

## **Task 6: Evaluation**

This work is industrially relevant, particularly for the automotive and motorsport industries, as light components are crucial to performance and fuel efficiency. Engineers are able to make informed decisions in choosing optimisation techniques by being aware of the advantages and limitations of each design approach. The difference between generative design and density-based topology optimisation in motorsport engineering offers significant distinctions in structural efficiency, computational efficiency, and manufacturability. Generative design, via AI-driven exploration, achieves up to 66% weight saving and excels in aerodynamic and lightweight structures but is ideal for additive manufacturing (AM) and not typically practical for CNC machining or traditional manufacturing (Sigmund & Maute, 2013). Topology optimization provides a more modest 30% weight saving with increased structural strength (Coulthard & Wang, 2022), which positions it as the go-to option for high-stress components like suspension uprights and brake callipers. Heat transfer considerations are also relevant in motorsport applications, where thermal degradation of materials by high temperatures from brake products can create a need for thermal-resistant coatings or specially optimised material choice. Generative design's complex, natural shapes require significant processing and cloud-based AI, which can take hours or days to offer up multiple solutions, whereas topology optimisation finds solution more rapidly and is more feasible for repeated design optimisation changes in motorsport. While generative design is optimum for weight reduction, it requires AM capabilities, but topology optimisation is more appropriate for conventional manufacturing and conformity. The optimal solution is a hybrid solution, using topology optimisation for structural performance and generative design for further lightweighting and aerodynamic fine-tuning, to deliver an optimum combination of performance, safety, and manufacturability for competitive advantages on the racetrack.

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