

William Davies

Module: Structural & Fluid
Analysis

Module Code: ACMA6010

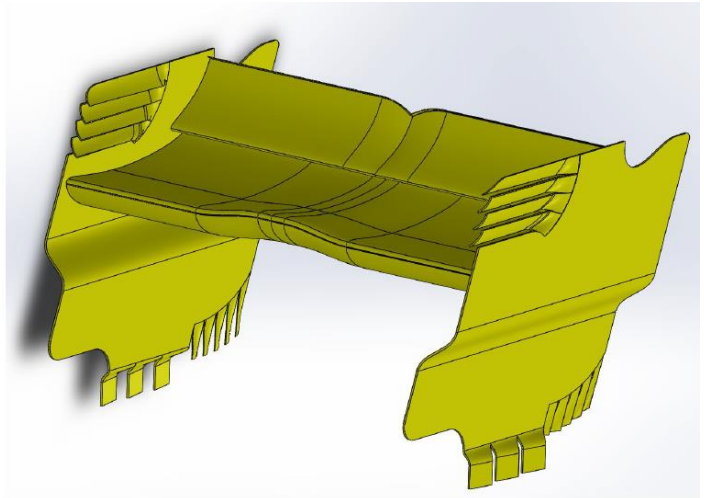
Assignment Title: Designing a
race car rear wing: Fluid flow
assessment

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Introduction

The understanding of fluid flow around an object is critical within the engineering world. If the fluid flow is taken into consideration during the design phase of any project it can have huge benefits, including; enhances performance of the object; improved safety and durability/longevity, whilst minimising the environmental impact of the equipment being produced. Throughout this topic we have critically analysed many different objects to understand exactly how fluid flow can effect different aspects of equipment, whilst under different environmental pressures. One of the fields in which the understanding of fluid flow through huge investment is very strong is in the Formula 1 car racing circuit. This is due to the extreme lengths these teams are willing to go to in order to make improvements to their vehicles to give them a competitive edge over their competition. These vehicles are also subject to a huge amount of environmental factors which require them to be extremely well engineered. (Lake, 2023)



1) Reynolds Number

Reynolds number is a critical quantity used in fluid dynamics which is dimensionless. This number characterises the flow of fluid around a given object. The Reynolds number is named after Osborne Reynold who was a British engineer and physicist. Reynolds number can be defined as 'The ratio of inertial forces to viscous forces in a fluid flow,' shown by the equation:

$$Re = \frac{(\rho * V * L)}{\mu}$$

Whereby:

ρ = Density of the fluid.

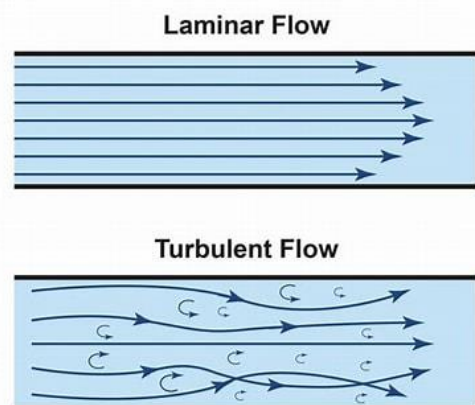
V = Velocity of the fluid, relative to the object.

L = Characteristic length scale of an object.

μ = Dynamic viscosity of the fluid.

Calculating the Reynolds number in a given scenario gives the ability to determine the type of flow around the object. The types of flow around an object are broken down into 2; Laminar and Turbulent. The type of flow can be determined by the Reynolds number value. If the flow was Laminar, you would see a low Reynolds number value, due to the fact that the fluid runs has the ability to flow smoothly in parallel layers, which in turn creates minimal mixing. Whereas, the Turbulent flow would occur at a high Reynold number, due to the flow of fluid becoming more chaotic, exhibiting a swirling/mixing motion. (Rogers, 2023)

Reynolds number has huge significance in aerodynamics, particularly in 'wing flow,' as this will have a huge influence on The Boundary Layer. The Boundary Layer is a thin layer of fluid un parallel with the wings surface where its viscosity plays a dominant role. How the boundary layer behaves, be it Laminar or Turbulent flow, has a huge effect on the overall flow characteristics which in turn will affect the aerodynamic performance of the wing. When a low Reynolds number is calculated, the flow around a wing tends to be Laminar. With this being the case, the airflow is very smooth and predictable. Although, when the there is an increase in the Reynolds number, airflow my change into a turbulent regime. When the airflow is Turbulent, more drag can be created, whilst air mixing is enhanced. This had the potential to delay flow separation, whilst improving lift characteristics. There is no exact point in which the airflow will transition from Laminar to Turbulent, as it is heavily dependent on several external factors, (Raman, N/A) which include; the angle of attack, the surface finish of the wing, and even down to the temperature and viscosity of the air. (Azami, 2017)



In order to estimate the Reynolds number for the airflow around the wing, several assumptions must be made, these include:

- The air density
- The dynamic viscosity
- The velocity at which the wing is travelling at a given time through the air
- A characteristic length scale (chord length)

Calculated Reynolds Number for the Racing Car Wing:

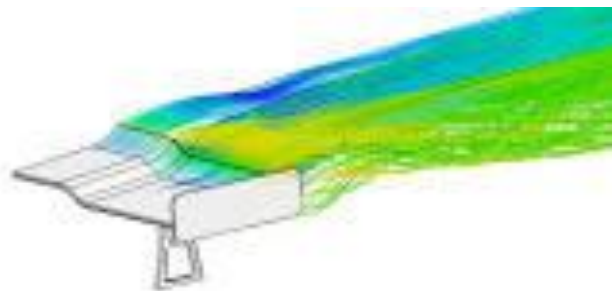
In order to fully understand the wings capabilities, it is essential to test it at the racing car limits. The calculation below is based off of a formula 1 racing car driving around Silverstone track within the UK at its maximum speed, giving the maximum wing (chord) length of 1.1m allowed by the FIA. (Hasanovic, 2018)



(N/A, 2023)

$$Re = \frac{(1.225 \times 85 \times 1.1)}{1.81 \times 10^{-5}}$$
$$Re = 6328038.674$$

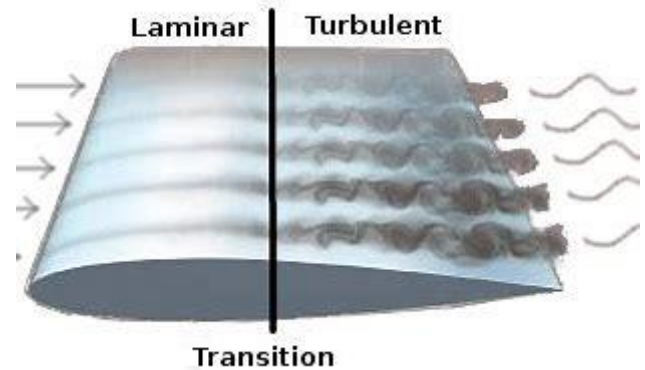
As can be expected with the conditions described. The fluid flow around the wing would be very turbulent whilst the car is at its max speed, this would cause some instability within the car and mean that these speeds could only be maintained for a short period of time whilst travelling along a straight within Silverstones race track. Any attempt of cornering at this speed would result in the car losing control and crashing.



(N/A, 2023)

2) Boundary Flow Around The Wing

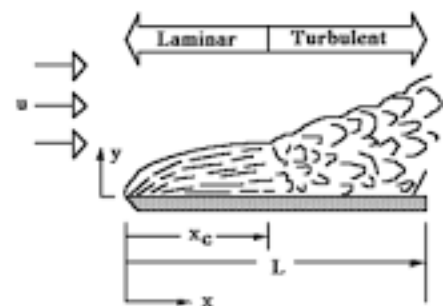
When Boundary flow around a wing is discussed, it is in reference to the airflow near the surface of the wing. Even more so in the racing car industry, this plays a huge part in determining the aerodynamic characteristics of the wing. When the boundary flow changes (through many factors), it can dramatically effect the drag, lift and even introduce flow separation and turbulence around the wing in motion. The Boundary layer can also be described as the thin layer of fluid (air in this context) that is developed around the surface area of the wing as its travelling through the air. This is due to non-slip conditions, whereby the velocity of the air at the surface of the wing is zero. As touched on previously, the boundary layer is classified into 2 main types; Laminar and Turbulent.



(Ekhert, 2023)

When analysing the race cars wing, it can be seen that its leading edge is very soft /streamlined and this would mean that the flow would be laminar. This design would mean that at the leading edge of the edge of the wing, there would be very little drag at this point allowing the laminar boundary layer to develop before transitioning into turbulence as you work your way back to the rear of the wing. This leading edge of the wing is the portion that would promote the lift.

Moving backwards to the rear and to the side of the wings, airfoil profiles can be observed. These would be carefully designed to promote drag which is then converted into down force at the rear of the car in order to balance out the lift at the front of the wing. These airfoils, in combination with the rear portion of the wing at an extreme angle ensure that the rear of the vehicle has sufficient force in order to maintain extremely accurate handling by maintaining its contact with the road surface. The turbulence also allows attached flow to be retained for a longer period of time and reduces the chances of flow separation. It can also be seen that the surface area of the wing in contact with the airflow is far greater on the top due to the additional airfoils than the underside in order to reduce lift as much as possible and promote down force.



(Azami, 2017)

The end plates of the wing with cut outs also provide a large amount of control over the vortices created which also promotes better control of the airflow. (Urlings, 2016)

The shape of the wing is designed in such a way that it has exact control of the transition for laminar to turbulent flow. This design allows for increased mixing and delayed flow separation. In simple terms, the front of the wing is designed not to hinder/block the flow of air around the wing, which would cause increased air resistance and ultimately have a negative effect on the vehicles ability to perform, whilst the rear of the wing harnesses the smooth flowing air and retains it by having a

controlled transition, improving the vehicles ability to maintain contact with the racing surface. (N/A, 2021)

3) Building A Racing Car Wing from Carbon Fibre Reinforced Plastic

When analysing the proposition to manufacture this racing wing from Carbon Fibre Reinforced plastic, it is extremely important to take several factors into account, as these can have major implications on the overall wings performance. This material is a composite, known for the extremely high strength to weight ratio, fatigue resistance and stiffness, all of which are crucial factors in the materials required to build a racing car wing. There are several different factors that must be taken into consideration when deciding to manufacture the wing from this material, these include:

(Fatawa, 2023)



Historical Materials Utilised for Racing Car Wings

In the very early racing car days, the rear wings were non-existent as the primary focuses of the race teams were on the cars stability. In around the 1970's wings then began to be introduced. At this time they were usually constructed from lightweight aluminium or steel tubing with fabric, glass fibre or aluminium sheet acting as the wing surface.

(Mowbray, 2014)

As the understanding around aerodynamics improved over time and material advancements, in the 1980's carbon fibre composites acting as wing endplates and main plates in combination with aluminium or other metals started to become the material of choice for the racing teams. This was due to it having a much higher strength to weight ratio than the historical materials, alongside its ability to be shaped into the intricate designs.



(Smith, 2018)

As further advancements in materials and racing investment improved, we are now using fully moulded carbon fibre reinforced polymers for all structural elements of the wings, as described.

The Historical Development of Carbon Fibre Reinforced Plastic

The knowledge and techniques now available around the use of carbon fibre reinforced plastics has dramatically improved over the years. This technique has been extensively used throughout the motorsport world for many years. Even more so in the high performance car racing space, particularly in Formula 1 racing due to the large investment and financial backing. The utilisation of this material has evolved alongside the technological advancements in material technology. Throughout the years, there has been a strong drive to improve the manufacturing techniques of this material, such as the utilisation of an autoclave, curing, resin infusion and pre-pregnation techniques in order to create precision layers of the carbon fibre orientation, which in turn maximises the materials performance.



(Edelstein, 2020)

The Wings Aerodynamic Efficiency

The design and construction materials used to manufacture a racing cars wing has a significant impact on its aerodynamic efficiency. If the wing were to be manufactured using carbon



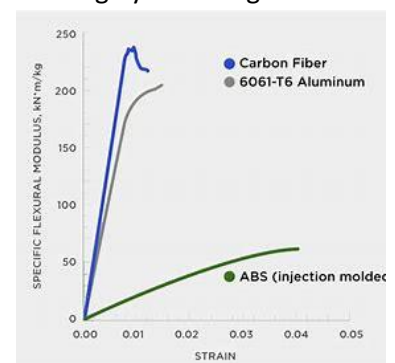
fibre reinforced plastic, it would allow the team to create complex and precision forms. By giving them the ability to do this, it will create optimised and streamlined wing profiles. By having the ability to easily create this, the team will have an increased element of control when generating down force, the reduction of drag, whilst enhancing the vehicles performance around the track. (Smith, 2007)

The Performance Benefits of Using This Material

There are several reason why this material is more highly favoured over traditional materials, such as, steel or aluminium. These can be broken down into several factors, which are:

Weight of the wing – due to the fact that this material has a much higher stiffness to weight ratio than these traditional materials, it is much for effective during racing. This means that the desired shape and size of the wing can be created at a fraction of the overall part weight, whilst maintaining, or even outperforming traditional materials for a fraction of the weight. This is hugely advantageous during racing due to the criticality of each component, where weight reduction wherever possible is prioritised in order to give even a fractional advantage over the competition. Some of the advantages of reducing weight wherever possible are; improved acceleration, fuel efficiency and overall handling of the car.

The high strength properties – this materials high strength properties due to the knitted fibres in a cross-hatch pattern means that it has a high resistance to high stresses/aerodynamic loads. This would enable the wing to maintain its shape at high speeds, resulting in better control and overall stability of the car.



(Sharma, 2023)

Fatigue resistance – due to the nature of the car constantly accelerating and decelerating, the wing has huge potential to fatigue and fail under stress. Utilising this material would mean that the wing could cope with these harsh racing conditions, by resisting fatigue and therefore ensuring longevity and durability of the overall car.

Surface finish – with the overall surface finish of the wing being incredibly good, this encourages good fluid flow and means that there would be no turbulent flow behaviours at the front of the wing do to pitting or other manufacturing techniques which would've been present when utilising the historical materials.

Current Developments in Carbon Fibre Reinforced Plastics

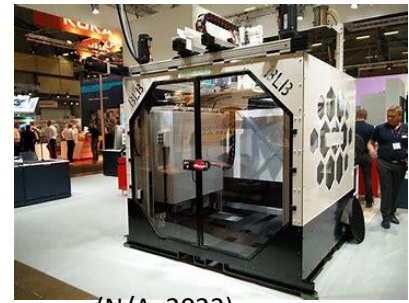
With technology ever advancing, there is a continuous drive to utilise new methods in order to improve race car wings performance alongside heavily focussing on weigh reduction wherever possible, whilst maintaining critical structural and performance attributes. Some areas that are being heavily invested into at the moment in order to improve design flexibility, reduce manufacturing cost and lead times are:

Automated Fibre placement – this technique is where a robotic arm accurately lays the carbon fibre sheets exactly where programmed. This manufacturing technique is ever advancing and will allow highly complex shapes to be produced at extreme levels of accuracy.

(N/A, 2022)



3D printing of critical parts – this technique has been becoming increasingly popular in many industries as the technology has advanced and the use of different materials have become more sophisticated.



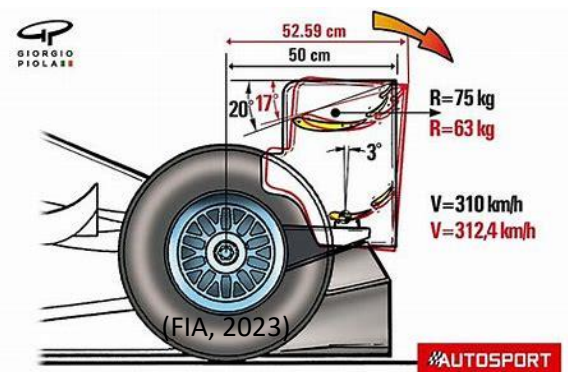
(N/A, 2023)

Alongside the physical developments in the manufacturing techniques, the way in which the materials are designed and tested prior to manufacture, through the use of computational modelling and optimisation techniques are becoming well used. This technological advancement gives the designers an accurate picture of how the material will perform through the utilisation of software and saves huge amounts of time and money during the development phases as it reduces the need for tangible models to be manufactured and tested which comes at a huge cost. This ensures that the structural and aerodynamic characteristics of the wing are as near to perfect as possible prior to going into production.

Industry Standards and Racing Constraints

Although there is heavy investment into the development of rear racing wings. Formula 1 governing bodies (FIA) have introduced several rules and regulations to ensure that the racing remains fair and safe. (FIA, 2023) These rules and regulations include:

- There are limits to the amount of downforce a racing car wing can generate in order to prevent the vehicle reaching excessive speeds as they want to minimise the amount of close racing as much as possible.
- Regulations may specify maximum height/width of the wing to prevent them from restricting visibility to the other cars whilst racing.
- Sharp edges and easily detachable components must be at a minimum to prevent causing extra injury to the drivers in the event of a crash.
- Budgetary constraints play a huge part of wing design as each formula one teams spending is closely monitored and regulated.
- There is a strict amount of time allowed for all aspects of testing i.e wing tunnel testing to ensure that all teams have a fair playing field and the teams with more investment cannot get an unfair advantage over others.



(FIA, 2023)

4) Potential Modelling Techniques to Simulate Fluid Flow Around The Wing

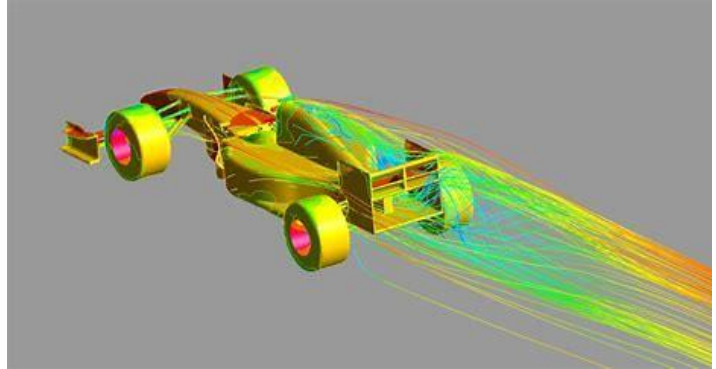
There are several different modelling techniques used within the racing car industry to simulate fluid flow around the vehicle in general.

The quickest and most simplistic way of modelling fluid flow around this wing would be utilising analytical methods. Utilising these methods would mean focusing on simplified mathematical models that provide rough solutions for specific flow solutions. This type of method would more often be used in the very early stages of design development and testing to give quick estimations of certain design aspects. Some examples of this method would be simplified boundary layer models or potential flow theory.

Although this method is relatively quick and easy, giving an insight into overall flow behaviours, there is very limited accuracy and limited ability to capture all fluid flow phenomena.

The most common method of evaluating this is through Computational Fluid Dynamics (CFD).

CFD is the use of a combination of mathematics, physics and computer software to visualise and analyse how a gas or liquid flows and the effect it has on an object. It utilises computational power to solve the governing equations, in order to predict how the fluid will flow over/around an object. In this particular application, CFD would be utilised to divide the whole wing into small control volumes and solve a number of equations at their discrete points. (Richardson, 2022)



There are many advantages to using this tool

when simulating the wing performance, these include:

(Richardson, 2022)

- CFD gives a highly detailed insight into how the wing would perform under different conditions. There would be extensive information provided around the flow field, which could also include the overall air pressure distribution along the wing, velocity profiles and each difference force acting upon the wing in exact points.
- When having this exact details it would give the team a good idea of how the wing would act under different conditions and allow different design ideas to be trialled relatively quickly and with ease. This would allow the team to effectively optimise the design within a timely manner, saving huge costs on the manufacture of any prototypes.
- Having the ability to virtually test the wing in different scenarios saves a huge amount of time and resource. Especially if the race team are travelling globally, a huge variation of different scenarios can be tested within a very short period of time. This would give the team confidence going into all racing scenarios globally.

Although there are many advantages to CFD, it also has some draw-backs that must be taken into consideration prior to investing time and money into this software, these include:

- There can often be a level of inaccuracy when utilising CFD. This is due to the fact that often times assumptions and simplifications of the design and external factors are made within the equations, turbulence modelling and boundary conditions. Often times this will introduce uncertainties which may skew the overall result.
- Although significantly less than other industry standard methods, CFD requires a level of investment into the correct hardware. An overall ide of how the wing can perform can be done using a relatively cheap system, but when going in depth into complex geometries (which racing car wings often are) and high-resolution simulations, an increased level of computational power from an industrial PC may be required, which will often cost large sums of money.
- There are many constraints into the level of testing that can be performed based on the users computational ability. In order to accurately generate a high quality mesh that replicates the exact wing designed can be hugely time consuming and sometimes unachievable if not correctly trained.

5) Experimental Methods Used On The Wing

The most commonly used laboratory technique throughout the car racing industry is wind tunnel testing, for this specific application would require a full scale model of the cars rear wing to constructed from the desired material, once constructed it would then be placed in a wind tunnel where it would be subjected to controlled airflow. Specific measurement sensors and instruments would be strategically placed around the wing in the wind tunnel, which would give outputs of the forces and flow characteristics of the shape created under different conditions.



(N/A, 2022)

In order to accurately test and compare the laboratory results to that generated through the simulation software, the following considerations must be undertaken:

The Wind Tunnel Set-up

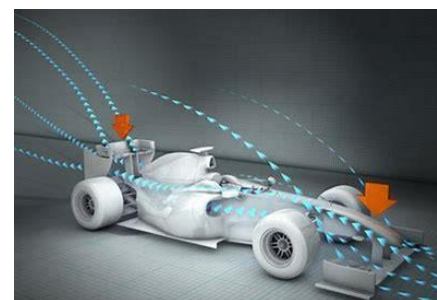
It is crucial that the correct set-up is able to be achieved within the wind tunnel. There are many different factors that must be taken into consideration when selecting the correct wind tunnel capable of achieving the desired results, the key things that must be taken into consideration are:

- The wind tunnel must be large enough to fit the rear wing prototype in, with spare room for the necessary adjustments to be made.
- Adjustable parameters are required in order to control the airspeed, turbulence intensity and angle of attack on the test wing.
- It is crucial that the wing is mounted securely and in the correct orientation within the wind tunnel to replicate the desired conditions.
- The wing must have strategically placed sensors to measure the desired testing outputs, such as; the lift and drag as well as other critical parameters such as pressure distribution of the surface of the wing.
- Ensure all load cells or force transducers are calibrated and have the appropriate levels of accuracy to measure the desired results.

Defined Testing Conditions

In order to achieve repeatable and accurate results from the wind tunnel testing, it is essential that several testing conditions are applied, these include:

- Define the angles of attack.
- Test a range of airflow velocities.
- Cover a large range of different scenarios in order to fully understand how the wing will behave under real world conditions.
- Ensure that the maximum amount of tests are repeated in order to have accurate and repeatable results.

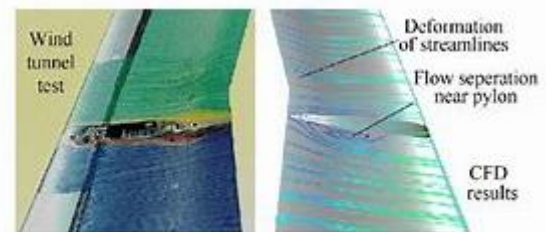


(N/A, 2022)

Comparing the Wind Tunnel to the Simulation Results

In order to validate the simulation results, a direct comparison to the experimental data must be undertaken. In order to maintain accuracy and repeatability between the two, it is essential that the simulation set-up is extremely close to the wind tunnel experiment, in terms of the wing geometry, boundary conditions and overall wing accuracy.

When comparing the test results, visual representations are best to understand the correlation between the 2. Taking a large level of readings across the spectrum and plotting them on the same graph would allow a direct comparison to be made around statistical metrics such as; the coefficient of lift and drag or the root mean square error. (Stump, 2018)



(b) Lower view of wing

(Xi, 2019)

Through both testing methods visual representations of flow patterns are generated/obtained and these can be compared to the simulations predicted flow patterns.

Throughout this comparison, discrepancies will be identified. It is critical that these discrepancies are analysed. Once analysed, it would give the team the ability to understand the differences such as the limitations within the experiment or the setup inaccuracies. Once understood it is critical that the testing is refined and replicated and all of the step repeated, ensuring that the next result is more accurate and repeatable.

Conclusion

To conclude, throughout this report there has been a critical analysis of the proposed rear car racing wing. An in depth discussion has taken place referencing rear world Formula one car racing rules and regulations in order to gain a further understanding into the design and manufacturing methodology behind the racing cars rear wing. Potential design, simulation and real world testing techniques have been analyse and informed recommendations have been made. We have also looked into the development of materials utilised during the manufacturing process, giving opinions on where the next technological advancements may be made. Overall, this report has been very insightful and a much greater understanding of the whole process has been achieved.

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