Florian Kimmerlin

# Powertrain component topology optimization

Master of Automotive Engineering – CVUT in Prague

Master Thesis
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# Acknowledgment

The work on which this paper is based couldn't have taken shape without the help of a few inspiring people.

I would like first to thank my tutor Mr. Drinkwater, for answering patiently all my questions and giving me the opportunity to lead the project as I wanted to. Mr. Drinkwater offered me a precious backing on every aspect of the project, alongside with a true recognition of my work.

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I would like then to thank my manager Mr. Tunc for his infallible support, and for the trust he placed in me. Mr. Tunc did his best to make my work easy, in a relaxed and friendly atmosphere, conducive to the successful completion of the project.

On another note, I thank the whole Design Team, and more generally Jaguar Land Rover's Powertrain Research Team, for the warm and sincere welcome I received during this internship.

Finally, I thank my placement supervisor Mr. Hořenín, for his kindness and his availability.

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

# MASTER'S THESIS ASSIGNMENT

## I. Personal and study details

Student's name: **Kimmerlin Florian** Personal ID number: **472617**
Faculty / Institute: **Faculty of Mechanical Engineering**
Department / Institute: **Department of Automotive, Combustion Engine and Railway Engineering**
Study program: **Master of Automotive Engineering**
Branch of study: **Advanced Powertrains**

## II. Master's thesis details

Master's thesis title in English:

**Powertrain Component Topology Optimisation**

Master's thesis title in Czech:

**Optimalizace topologie komponent pohonné jednotky**

Guidelines:

This project aims to expand component topology optimisation capability within Jaguar Land Rover and deliver an example component design. We'll look to you to analyse existing engine top end components with regard to structural design and the efficient use of materials. You'll then use the range of tools already available within Jaguar Land Rover to propose an optimised design, working from the ground up and using a blue sky approach to considering fundamental load paths, alternative materials, and processes.

Bibliography / sources:

Name and workplace of master's thesis supervisor:

**Ing. Jindřich Hořenín, Dpt. of Autom., Comb.Eng. & Railway, FS**

Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **01.03.2018** Deadline for master's thesis submission: **20.08.2018**

Assignment valid until: ___________

Ing. Jindřich Hořenín
Supervisor's signature

doc. Ing. Oldřich Vítek, Ph.D.
Head of department's signature

prof. Ing. Michael Valášek, DrSc.
Dean's signature

## III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

17/03/18
Date of assignment receipt

Kimmerlin Florian
Student's signature

CVUT-CZ-ZDP-2015.1

Because of confidentiality issues, and accordingly to Jaguar Land Rover's confidentiality policy, no numerical values or specific names will be included in this paper. Similarly, certain concepts might be slightly evaded.

# Table of contents

# List of acronyms and abbreviations

Like each and every company, Jaguar Land Rover uses a lot of acronyms and abbreviations in the everyday work. You can find below the list of those which will be used in this paper.

| | |
|---|---|
| JLR | Jaguar Land Rover |
| FE | Finite Elements |
| P6 | In line 6 cylinders petrol engine |
| D6 | In line 6 cylinders diesel engine |
| DOHC | Double Overhead Camshaft |
| In. | Inlet |
| Ex. | Exhaust |
| CVVL unit | Continuously Variable Valve Lift unit |
| DS | Design Space |
| NDS | Non - Design Space |
| DRCO | Design Variables, Responses, Constraints, Objectives |
| IE | Interacting Element |
| RBE | Rigid Body Element |
| Tet element | Tetrahedral element |
| Tria element | Triangular element |
| UTS | Ultimate Tensile Strength |

# Introduction

Because of the urgent need to protect the environment, and because of the scarcity of the natural resources, reducing the weight of vehicles has become an overriding objective for the automotive industry. Companies track every single undesired gram down, as a weight reduction of 1Kg represents an average emission reduction of 8 $g_{CO2}$ per 100 Km [1].

For this purpose, many different tools have been developed by the industry, among which is topology optimization. Automotive companies need thus to develop new component optimization processes within existing processes, which are working fine on their own. That was precisely the reason for my 6-month internship at JLR. My mission was to implement an optimization process in the Design Team of the Powertrain Research Department, without disrupting the business. This optimization process was mine to create, through the delivery of an example component.

My work was consequently divided in three parts. First, I learnt about optimization, from its base principles to how it works and what its objectives are. I looked at the different solutions available in terms of software and methods, before defining the scope and the planning of the project. I also went on a training about topology optimization with Altair Engineering. Then, as a second step, I used my newly acquired knowledge to optimize the example component I was asked to work on: the cam-carrier mounted on JLR's P6 engines. I had to set up the whole model, in order to get in the end a part that could be sent to production. Once this optimization was done, the last step of the project was to implement a new process within JLR's Powertrain Research Design Team, so that everybody in that team could easily run a component optimization afterwards.

Since this paper is based on the work I did during my internship at JLR, it will answer the same question: how do you implement an optimization process in an automotive Design Team, by delivering an example component and without disrupting the existing processes?

As a whole, this paper will also logically follow the same three axis as my internship. I will first talk about optimization in general, before explaining how I optimized the cam-carrier, and then looking at the process I implemented in JLR's Powertrain Research Design Team.

# Jaguar Land Rover

JLR is a British multinational automotive company, subsidiary of the Indian automotive company Tata Motors. The company is composed of two brands, *Jaguar Cars Limited* and *Land Rover*, both of them having a complex and long history in car making.

*Jaguar* was created in 1922 by Sir William Lyons as a company originally producing motorcycles (the first cars were not produced before 1931). First named *Swallow Sidecar Company* and then *SS Cars Limited* (*SS* was standing for *Standard Swallow*), it got renamed as *Jaguar Cars Limited* after WWII for obvious reasons. *Jaguar Cars Limited* has produced many outstanding cars through its history, such as the *E-type* (1961-1975) or the *Jaguar XJ* (1968-today).

The first *Land Rover* vehicles were built in 1947. They were cheap vehicles aiming to meet the needs of the post-war period. Closely related to the *Jeep* cars, they were designed to be simple and robust, in order to withstand demanding environments. From these first adventurers to the last *Range Rover Velar*, *Land Rover* has produced only all-terrain vehicles (4*4) and sport utility vehicles (SUV), slowly evolving from a grassroots brand to the premium brand we know.

*Jaguar Cars Limited* and *Land Rover* were merged together in 2008 when Tata Motors bought them from Ford. Even if they now work side by side, the two brands both keep their own spirit and customers. They only share knowledge and technologies, as they do in the Powertrain Research Department, where this project was led.

JLR employs more than 40.000 people all over the world and sells more than 650.000 vehicles a year, mainly in Europe. Described as a premium brand, it produces cars at the leading edge of the technology, such as the new all-electric I-pace.

# About Topology Optimization

## What is component optimization?

Component optimization has many different definitions. In engineering design, it is "finding the best compromise among several often conflicting requirements.[2]“ Thus, component optimization has an important role in today's industry and is used in several ways. There a six different types of component optimization:

*Picture 1: the different types of optimization*

*Courtesy of Altair Engineering*

Topology, free size and topography optimization enable the user to create new designs from scratch, in a blue-sky approach, whereas free shape, shape and size optimization work on existing designs, in order to refine them.

***Topology optimization*** – As a starting point, topology optimization works with a design envelope. It is used to find the best material placement inside that envelope, which respects all the constraints and objectives.

***Free Size optimization*** – As a starting point, free size optimization works with a shell FE structure. It enables engineers to determine the optimum thickness of that structure, element by element, which respects all the constraints and objectives.

***Topography optimization*** – As a starting point, topography optimization works with a shell FE structure. It will add bead patterns to that structure, from the elements, in order to respect the different constraints and objectives.

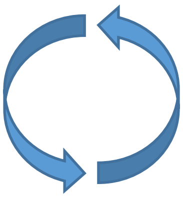
***Free Shape optimization*** – As a starting point, free shape optimization works with a geometry. It aims to find the optimum component thickness that respects all the constraints and objectives. Contrary to free size optimization where the thickness is worked out element by element, the thickness, in the case of free shape optimization, is the same for the whole component.

***Shape optimization*** – As a starting point, shape optimization works with a geometry and a number of shapes defined by the user. It enables engineers to find the best fractional summation of the shapes previously defined which respects all the constraints and objectives.

***Size optimization*** – As a starting point, size optimization works with a geometry with some features on the boundaries. It will modify the position of the nodes on the boundaries to find a more optimal geometry that meets all the constraints and objectives.

These different types of optimization have had a real impact on the design processes of the automotive industry. Over the past few decades, there has been a huge evolution of these design processes in the companies.

The original design process integrating some manual optimization was the following:

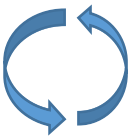


- Creation of a first design
- Analysis of the design
- Evaluation of the analysis results
- Summation of all the limiting factors (requirements, cost, time…)
- Update of the design into a new design
- Return to the analysis

The induced loop was broken by the engineers as soon as the design was satisfying enough. Naturally, this kind of process was truly laborious to follow and resources consuming when dealing with all the computational work.

The new design process using an optimization software is much faster and simpler from the engineer’s point of view (◌ = computer-based steps):

- Creation of a FE model
- Definition of the design variables, the objectives and the constraints



  - Computer-based evaluation of the design space
  - Evaluation of the analysis results
  - Update of the design for a new improved design
  - Return to the analysis

We clearly observe that the input from engineers has been dramatically reduced thanks to this new process, which enables companies to save time and money.

The project I worked on in JLR was based on topology optimization. As a consequence, this paper will focus on that particular kind of work.

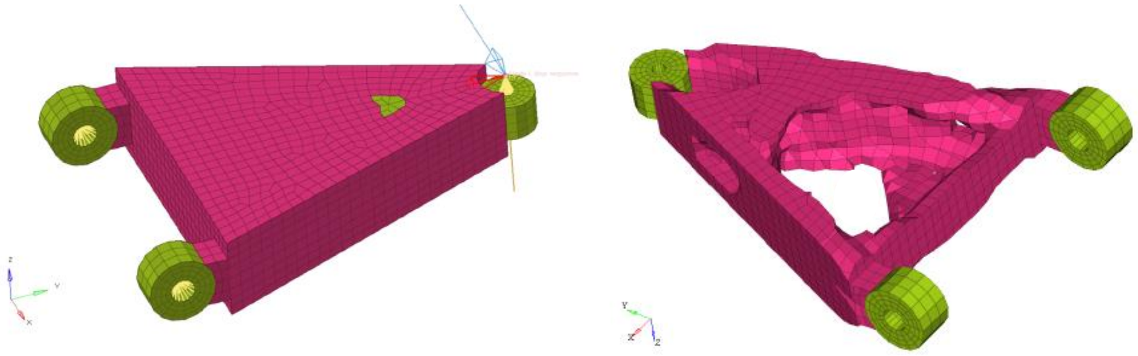
## How does topology optimization work?

There are 3 main steps when running a topology optimization:

1. **The user creates the geometry (DS and a NDS), and meshes it.**

The DS is the design envelope, the place where the software will define the optimum material placement. It must be as large as possible to enable the software not to be restricted in its work.

The NDS is the space where there must be material in all cases. It gathers the sealing surfaces, the pipes inner surfaces, the bolts clamping surfaces,…



*Picture 2: illustration of the DS (left picture, violet) and the NDS (left picture, green) and the corresponding topology optimization result (right picture)*

*Courtesy of Altair Engineering*

2. **The user defines the DRCO model.**

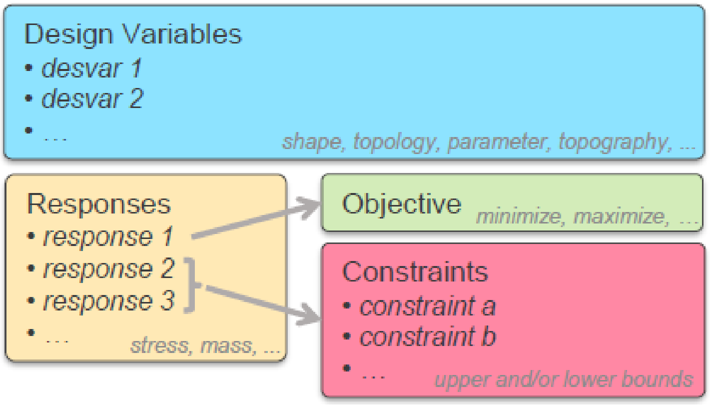
DRCO stands for Design Variables – Responses – Constraints – Objectives. It defines what work the software has to do when running the optimization.

- The design variables are the parameters the software can change to reach the objectives set for the optimization. It is typically the design envelope in the case of a topology optimization.

- The responses are output characteristics of the model that will be measured and monitored while the optimization is running. It can be stress, mass, displacement, strain,…

- The constraints are numerical limits applied to the different responses. For example, a constraint could be set for the stress not to be higher than 150MPa in the design.

- The objectives define what the software will work towards. It can be minimizing the mass, increasing the stiffness of the design, …



*Picture 3: description of the DRCO model*

*Courtesy of Altair Engineering*

### 3. The software runs the optimization.

During the optimization, the software works with the FE model.

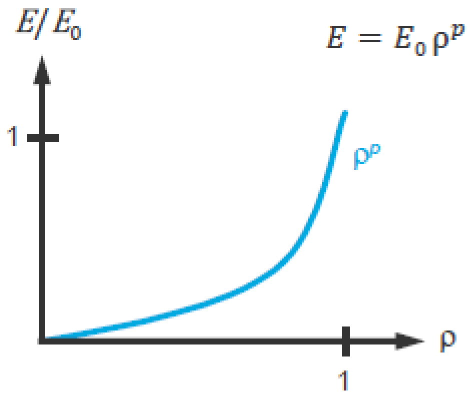
For each element, the software sets a density. That density is typically a scale between 0 and 1, and has no link with the weight of the element. A density of 0 means that the element is void whereas a density of 1 means that the element is solid. Intermediate values of density represents fictitious material, which is meaningless.

For each loop of the optimization run, the software will update the density of each and every single element, depending on how the latter violates the constraints set by the user. The more an element violates the constraints, the bigger density it will have.

At the end of the optimization run, the software will delete all the elements with a density under a given threshold: the optimized design is now created.

In case most of the elements have a density close from the threshold, a penalization technique may be used to help the software force the elements of the design to be represented only by densities of 0 or 1. In this case, the stiffness of the material is changed in order to be linearly non-dependent with respect to the density.

For all the elements, Young's modulus is set to $E = E_0 * \rho^p$ where $p$ is defined by the user and $\rho$ is the density. This method has a direct impact on how the elements violate the constraints, thus on how fast the elements density converge towards 0 or 1.



*Picture 4: illustration of the penalization technique*

*Courtesy of Altair Engineering*

## 2 different algorithms

When running a topology optimization, the user has to decide what algorithm the software will use to solve the problem. There are 2 different sorts of algorithms:

- The mathematical programming methods
- The evolutionary algorithms

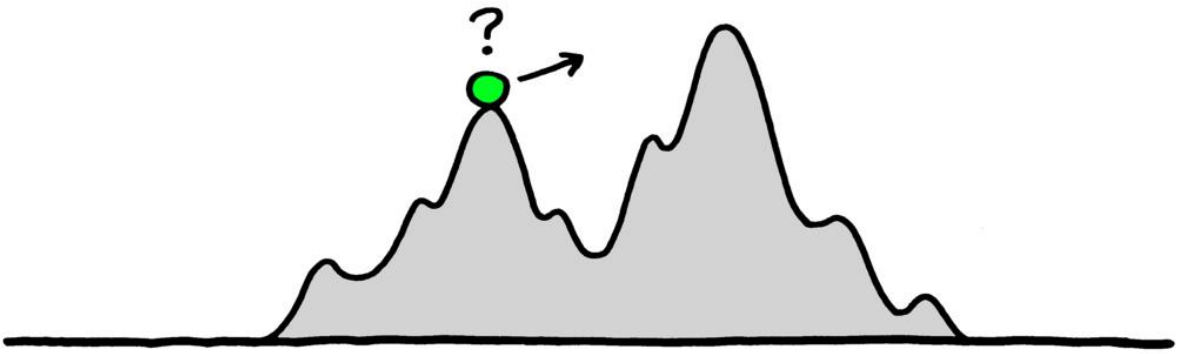
### The mathematical programming methods

The mathematical programing methods are gradient-based algorithms. They solve the problems by using a “steepest descent” fashion and mathematical logic. There are very few function evaluations, which is good if the evaluation is time-consuming, as it is the case in a FE analysis for instance. However, there is a high risk that the algorithm finds a local optimum instead of a global one.

The most common mathematical programming methods are the Sequential Quadratic Programming and the Method of Feasible Directions.

Let f be the function to optimize and $\gamma$ the step between each function evaluation.

| In case of a search for a minimum | In case of a search for a maximum |
|---|---|
| Start from a point ($X_0$, $f(X_0)$) | Start from a point ($X_0$, $f(X_0)$) |
| Evaluate the function and its gradient at the point ($X_i$, $f(X_i)$) | Evaluate the function and its gradient at the point ($X_i$, $f(X_i)$) |
| Determine the next point ($X_{i+1}$, $f(X_{i+1})$) by using the negative direction of the gradient:<br>$X_{i+1} = X_i \pm \gamma$<br>$f(X_{i+1}) = f(X_i) + \gamma * f'(X_i)$ | Determine the next point ($X_{i+1}$, $f(X_{i+1})$) by using the positive direction of the gradient:<br>$X_{i+1} = X_i \pm \gamma$<br>$f(X_{i+1}) = f(X_i) + \gamma * f'(X_i)$ |
| Repeat the 2 previous steps until the function has converged to a minimum (no more negative direction during the gradient evaluation) | Repeat the 2 previous steps until the function has converged to a maximum (no more positive direction during the gradient evaluation) |



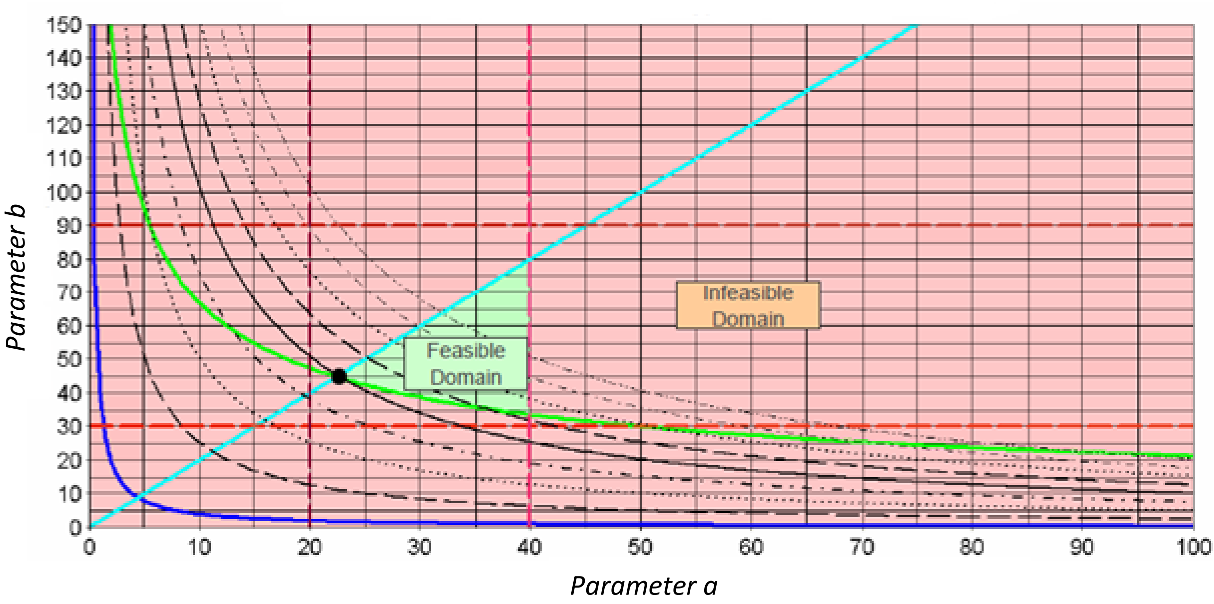
*Picture 5: illustration of the local optimum issue faced while using the gradient-based algorithms*

*Courtesy of Altair Engineering*

In the case of a search for a maximum, if the algorithm gets to a local maximum, it won't find any positive direction during the gradient evaluation. The algorithm will stop even if the maximum is local, not global. In the case of a search for a minimum, the logic is the same, but with negative directions. Thus, there is a high risk for the algorithm not to find the global optimum.

### The evolutionary algorithms

The evolutionary algorithms mimic the natural human behavior when facing an optimization problem. It requires a lot of function evaluations given that it tries most of the different possibilities to find the optimum. Thus, it is advised to use this kind of algorithms for small models or simple analysis.



*Picture 6: illustration of the mathematical design space*

*Courtesy of Altair Engineering*

As shown on the picture above, the software first determines what values the function to optimize can take. For this purpose, it considers all the physical constraints set by the user on the different parameters the software will change to run the optimization. Theses constraints define a mathematical design space in which the software will work. Given a different step for each parameter, the software will try all the possible solutions within this design space. There are ways to reduce the number of evaluations needed to perform the optimization, but those methods are kept secret by the companies producing the software.

Of course, this method is really time and resource-consuming.

## The usual process for a topology optimization

Designing a new part with topology optimization usually follows a simple process:

1. **Optimization setup and run**

The first optimization is based on stiffness. Its aim is to reduce the volume of the part while increasing its stiffness. As much as possible, it is good to shift the part's natural frequencies as high as possible to avoid any overlap with the engine frequencies. Once the compromise between low volume, high stiffness and high frequencies is found, the results can be interpreted.

2. **Results interpretation**

The aim of the results interpretation is to turn the software output into a machinable part. It is the user's role to determine how to do it, and how close to the output the new design should be.

3. **Stress analysis**

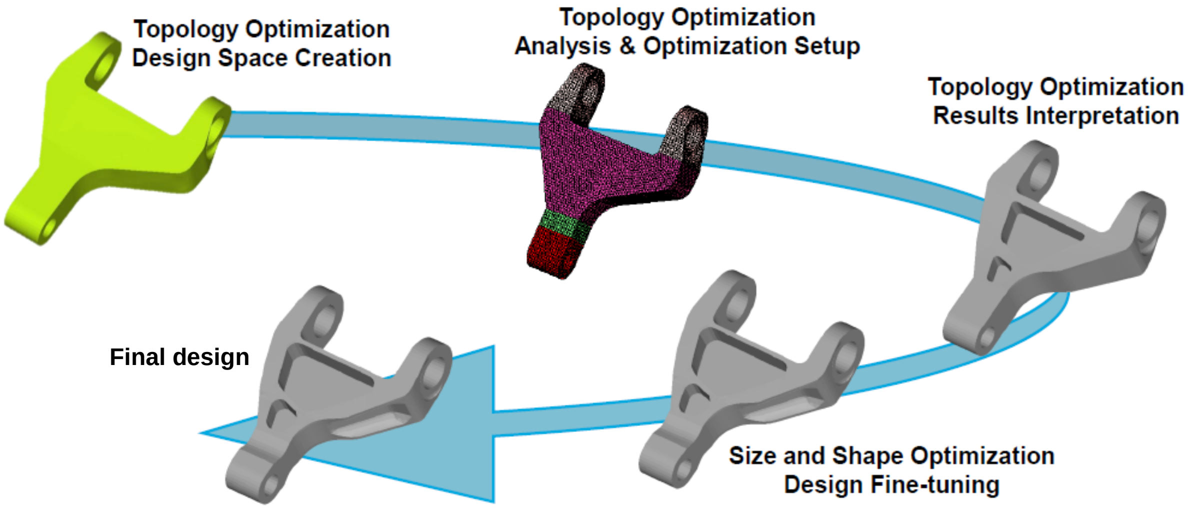
For the first time in the optimization process, a stress analysis is run. It enables the user to spot all the places of the part where the stress is higher than what is admitted.

4. **Shape optimization**

Based on the results of the stress analysis, the shape optimization removes all undesired stresses from the part by slightly changing its shape.

5. **Final stress and frequency analysis**

Finally, a last stress and frequency analysis is run to validate the design. At this step, the natural frequencies of the part should be high enough and no undesired stress should appear.



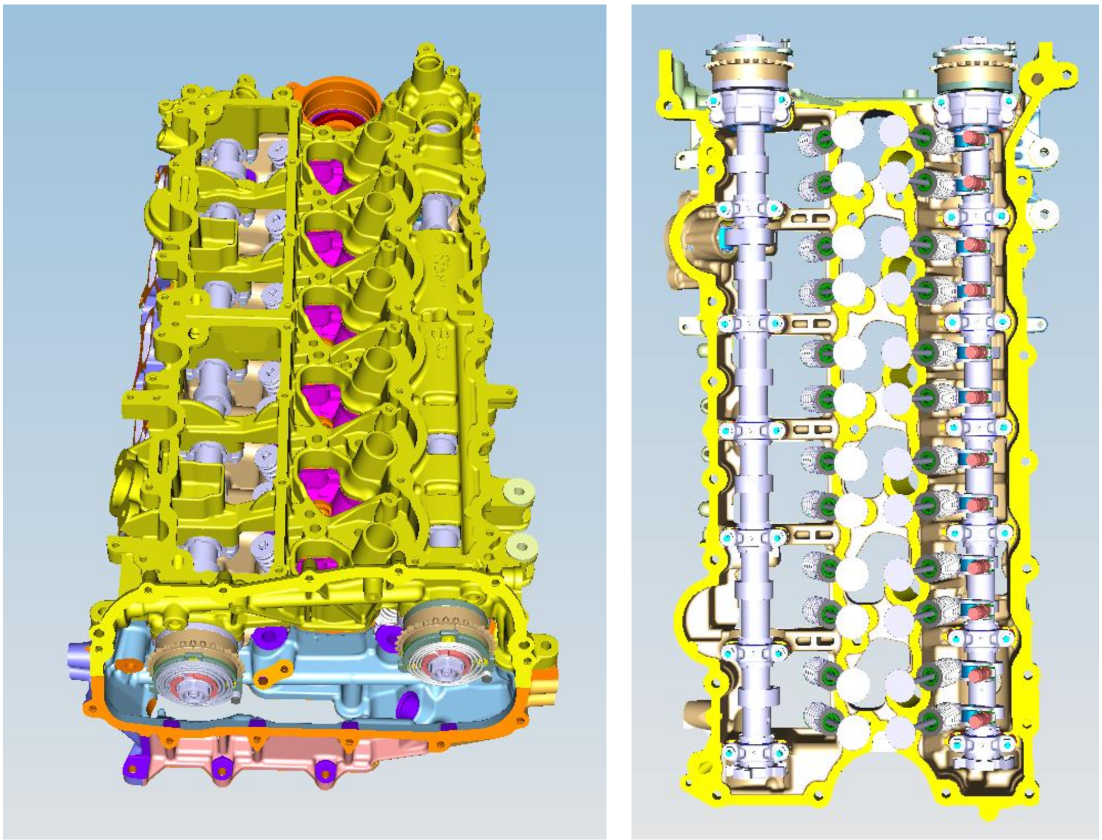
*Picture 7: illustration of the usual topology optimization process*

*Courtesy of Altair Engineering*

## The P6 cam-carrier

The aim of my 6-month placement in JLR was to implement a new topology optimization process within the Design Team of the Powertrain Research Department, by delivering an example component. This component was a P6 cam-carrier.

Contrary to many car-makers, JLR made the choice to install cam-carriers on its DOHC engines. This means that the camshafts are held by the cam-carrier instead of the cylinder head.

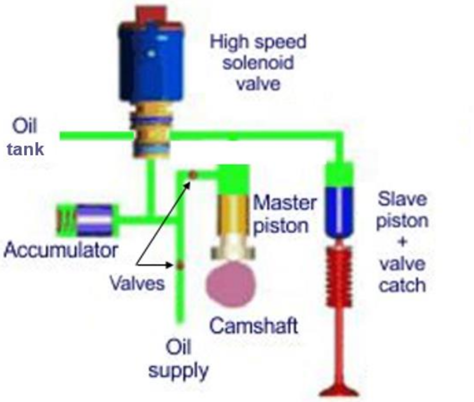


*Pictures 8 & 9: illustration of a cam-carrier (yellow) mounted on a cylinder-head with the two camshafts (left) and bottom view of a cam-carrier carrying the camshafts (right)*

*Courtesy of JLR*

This disposition has 2 main advantages. First, it allows the design of a simplified cylinder head. Then, it allows engineers to easily mount different elements on it, such as the CVVL units, an oil breather or the fuel pump.

The CVVL units enable an electric control of the valve timing and lift. The camshaft pushes a piston which acts as a pump and pressurizes some oil in a pressure accumulator within the CVVL unit. Then, an electronic solenoid valve controls the opening of the valves by controlling how the oil is released.

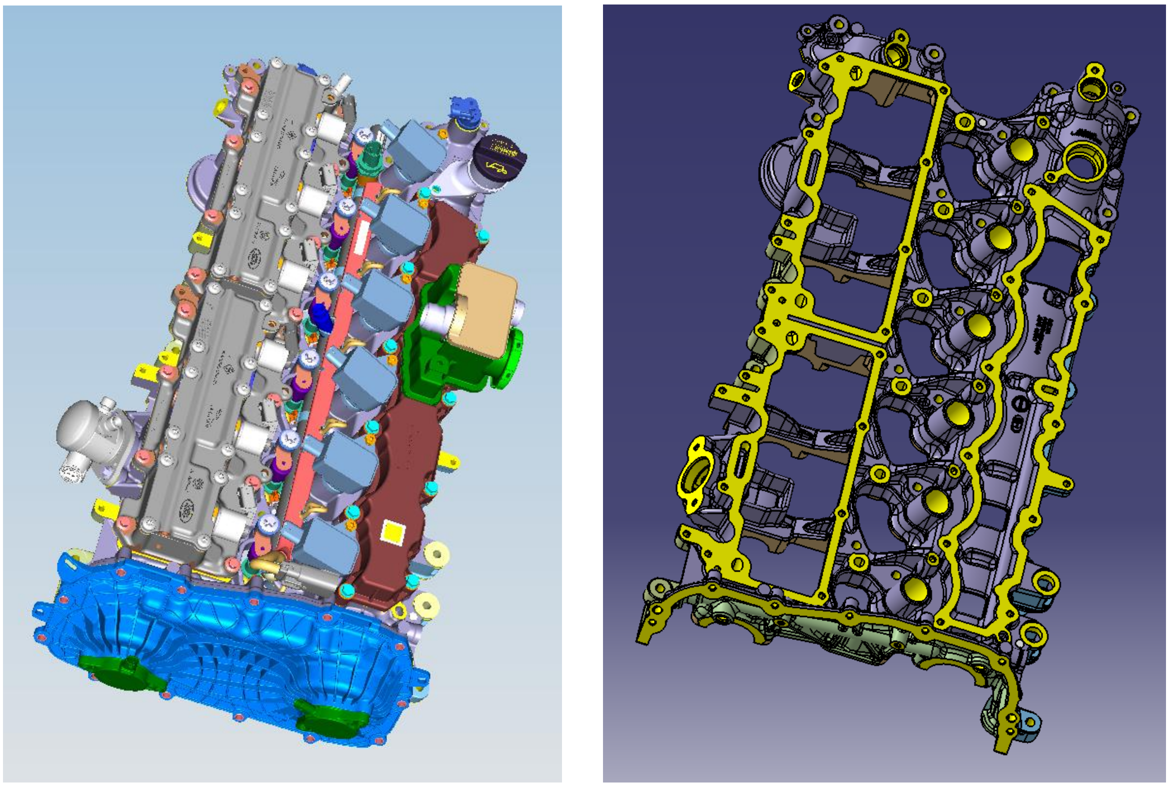


*Picture 10: illustration of how a CVVL unit works*

The oil breather is designed to release the pressure from the inside of the crankcase. Indeed, due to small leaks at the piston rings, at the gaskets, or because of the mechanical clearances, some pressurized gases get out of the combustion chamber inside the crankcase. To avoid damaging the latter, it is necessary to relieve its internal pressure while keeping the oil inside the engine.

Basically, an oil breather is simply a pipe going from the crankcase to an oil separator, where the gases are cleaned before being reinjected in the intake manifold. Another pipe brings the oil back from the oil separator to the engine.

The cam-carrier I worked on was a P6 cam-carrier. It is mounted on petrol 6 cylinders engines. In addition to the camshafts, it carries two CVVL units, the oil breather, the fuel pump, the filler neck, the fuel system, the spark plugs and different sensors.



*Pictures 11 & 12: illustration of the cam-carrier I worked on with the IE mounted on it (left), and without (right)*

*Courtesy of JLR*

After a discussion with my tutor and the Design Team's management, decision was made to target a 15% reduction of the weight of the cam-carrier while not increasing the price by more than 10%.

## The choice of the software

The first step of the optimization of the cam-carrier was to decide was software I would use for it. A short literature review enabled me to select a few possible software:

Hyperworks, Abaqus, Catia V5, SolidThinking Inspire, Genesis, Tosca, Solidworks,…

Three constraints were set on the choice of the piece of software:

- available licenses in JLR
- facility for the members of the Design Team to be trained on this particular piece of software
- facility to run a topology optimization

Because of those constraints, only three pieces of software were shortlisted: Hyperworks, Catia V5 and SolidThinking Inspire.

Catia V5's optimization tool is parametric. It means that the software will optimize only given parameters. Each single distance, angle or radius of the geometry must be parametrized for Catia V5 to run the optimization. Thus, since it would be far too much work to parametrize a model as complex as the cam-carrier, Catia V5 was abandoned.

On another note, Hyperworks and SolidThinking Inspire share the same solver, the same file types (the models can be loaded in both interchangeably) and are developed by the same company: Altair Engineering.

Hyperworks is more powerful and presents more options, but requires more time and skills to set up a model. On the other hand, SolidThinking Inspire is really intuitive and presents a nice graphic interface. Thus, decision was made to use both pieces of software in the Design Team in the future. The simple and small models would be optimized with SolidThinking Inspire whereas the complex models would be optimized with Hyperworks. Of course, it was decided to optimize the cam-carrier on Hyperworks.

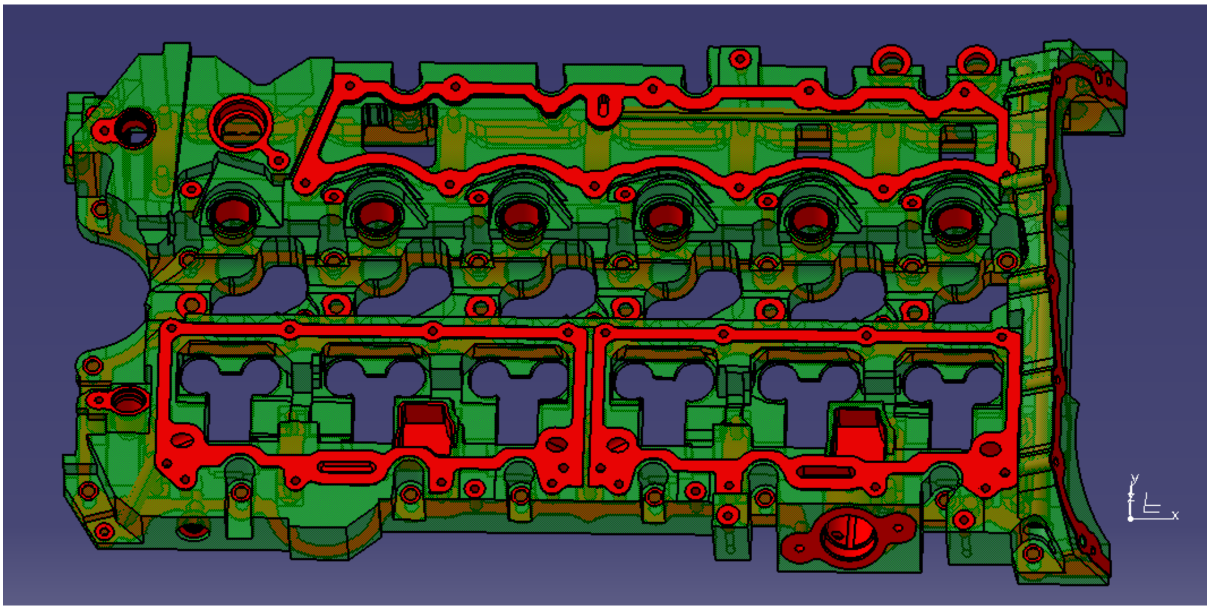
Among others, Hyperworks is composed of a mesher, Hypermesh, a solver, Optistruct, and a viewer, Hyperview.

## Creating the geometry

The second task of the optimization of the cam-carrier was to create the DS and the NDS. This was done with Catia V5, the piece of software used for the design work in JLR.

The NDS gathers all the sealing surfaces from the elements mounted on the cam-carrier, the oil pipes and the bolts under-head surfaces.

The DS is the biggest possible space that includes the original cam-carrier without clashing any other element of the engine.



*Picture 13: illustration of the DS (green) and NDS (red)*

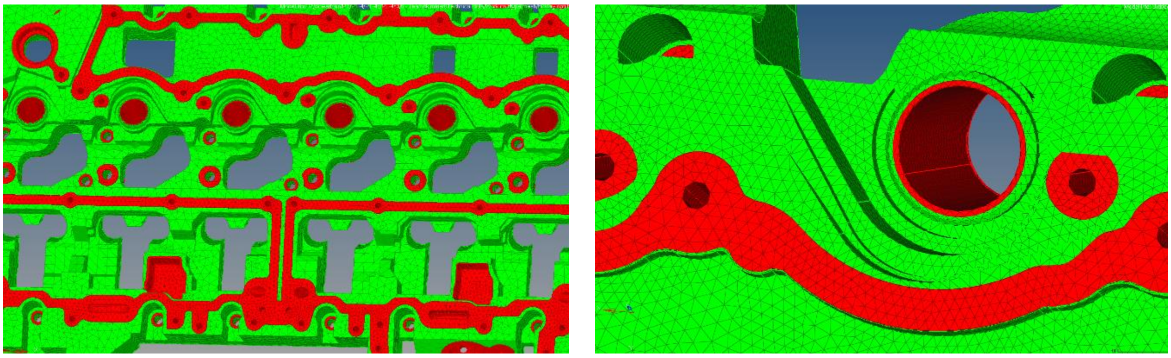
*Courtesy of JLR*

## The meshing

Once the two spaces were created, the next logical step was to mesh them. Indeed, Optistruct doesn't work with geometries but with FE models, since the optimization relies on different analysis, such as stiffness, stress or modal analysis…

A first attempt was made to mesh the two spaces directly with Hypermesh. However, the software interface is truly user-unfriendly, which caused the meshing to take far more time than expected. As a result, the choice was made to mesh the two spaces in Abaqus instead of Hypermesh.

Indeed, there was already an existing capability in the Powertrain Department to mesh parts with Abaqus, but not with Hyperworks. Thus, it was easier to get some guidance on how to do the meshing with Abaqus.

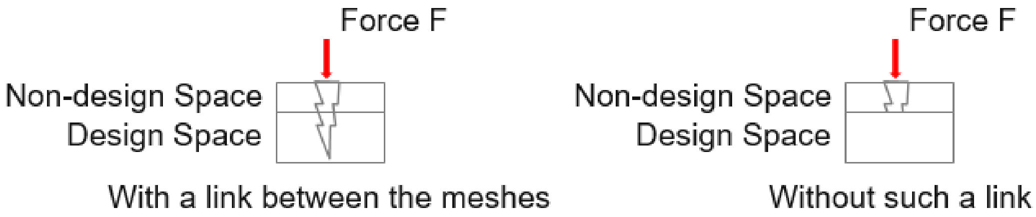


*Pictures 14 & 15: illustrations of the meshes of the DS and NDS*

*Courtesy of JLR*

Because of the complex geometry of the part, tet elements were used, with an average size of 0.8 cm. The resulting mesh was composed of 1,200,000 elements.

Once the meshing was done, a tight contact was implemented in Hyperworks between the two FE spaces in order to be sure the two spaces would act as one. Indeed, the delimitation between the DS and the NDS is purely fictional.



*Picture 16: illustration of the need to link the DS and the NDS*

*Courtesy of JLR*

## Setting up the optimization model

Setting up the optimization model was the last step before running the optimization. There were 3 different things to do:

### 1. Defining the material and the type of elements

The material was chosen to be the same as the one of the original cam-carrier for different reasons. First, the optimized design should withstand the same loads as the original model. Besides, the casting process would be the same, some high pressure die casting. Thus, since we didn't want the price to increase at this early step of the project, selecting the same material appeared as the right choice to make.

The chosen material was the aluminium LM24 ALSi9Cu3(Fe)(Zn), with the following characteristics:

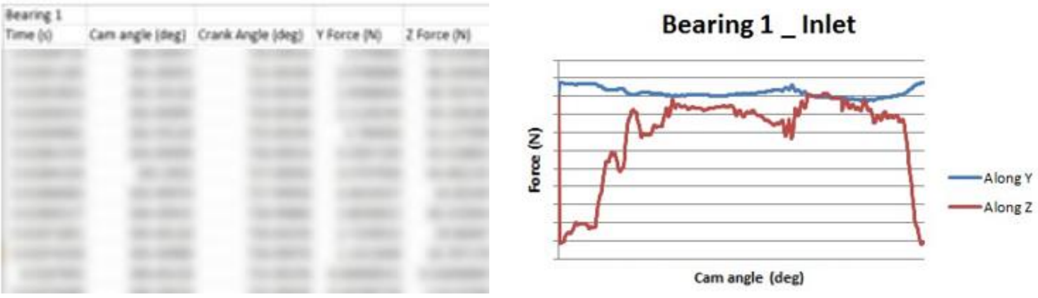
- Young's Modulus: 70 GPa
- Poisson's ratio: 0,33
- Density: 2,79 g/cm$^3$
- Thermal expansion coefficient at 20°C: $2,1.10^{-06}$ /°C

The type of elements was chosen as SOLID Elements. It helps Optistruct to know whether the model is made of shell elements, 3D elements, circular elements (for pipes and tubes…) SOLID elements are basically 3D elements.

### 2. Defining the load case and the load step

Creating the load case was one of the biggest steps of the project. There were 6 different types of loads to take into account:

- the loads coming from the camshafts
- the loads coming from the IEs mounted on the cam-carrier
- the bolts loads
- the G-loads coming from the engine vibrations
- the temperatures
- the boundary conditions



Bearing 1

| Time (s) | Cam angle (deg) | Crank Angle (deg) | Y Force (N) | Z Force (N) |
|---|---|---|---|---|

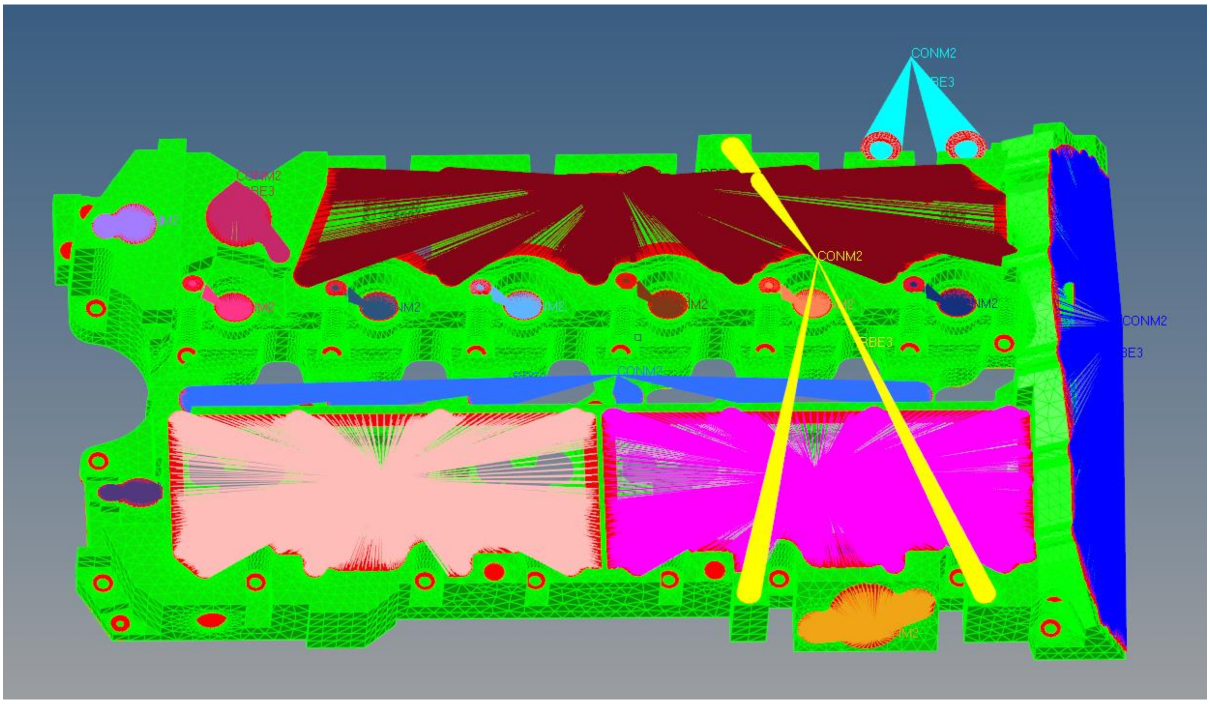
*Pictures 17 & 18: illustrations of the load case for the 1st bearing of the in. camshaft*

*Courtesy of JLR*

There were two major issues that needed to be worked on: how to implement the dynamic loads of the camshaft into the model, since the solver only accepts static loads, and how to model the IEs mounted on the cam-carrier?

There were 2 options to address the first issue. The first one was to implement only the peak loads of the cam-shaft as static loads. The second one was to turn the dynamic loads into static loads by using the Equivalent Static Load Method. However, this method required the whole camshaft mechanism to be modelled into Optistruct, which would have taken too much time. Thus, the choice was made to model the dynamic loads by their peak loads.

The second issue was addressed thanks to kind pieces of advice from JLR employees. The way the IEs mounted on the cam-carrier would be modelled in Optistruct is by linking mass points to the cam-carrier through rigid body elements. Each mass point would be positioned to the center of gravity of an element, its mass being the total mass of the element. Thus, the loads created by the element on the cam-carrier, due to the gravity and the G-loads, would be well spread over the contact surface on the cam-carrier, as if the complete element had been modelled.

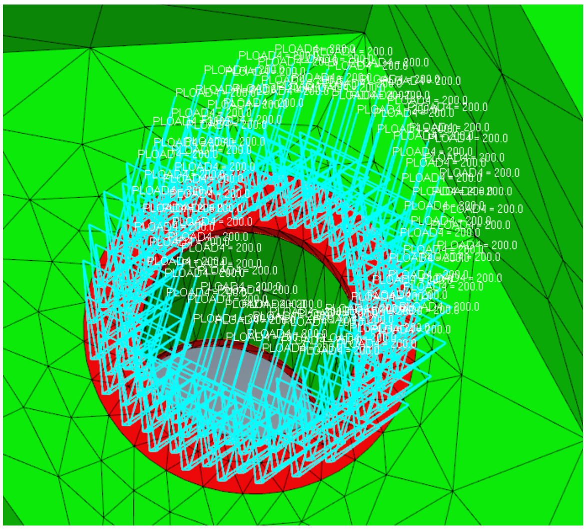


*Picture 19: illustration of how the IEs mounted on the cam-carrier have been modelled*

*Courtesy of JLR*

From the bolts point of view, there were two different cases.

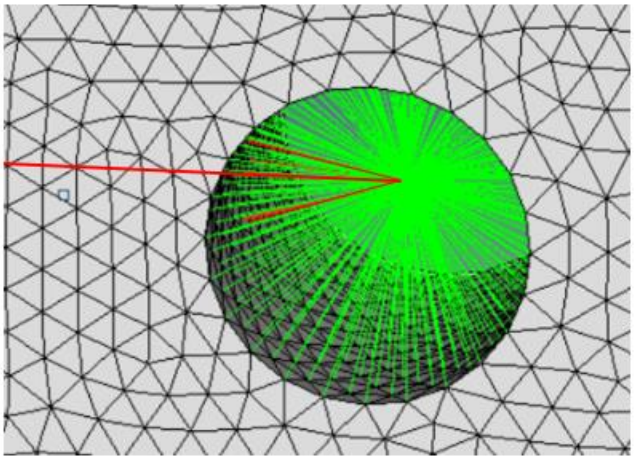
For the non-threaded holes first, the clamping force was applied as a pressure on a washer around the hole. This pressure has been worked out for each bolt by dividing the clamping force by the area of the washer, which is equal to the area of the bolts underhead surface.



*Picture 20: illustration of the pressure applied on the washers of the non-threaded holes*

*Courtesy of JLR*

Then, the threaded holes were represented by a tight contact between the cam-carrier and a rigid body element figuring the bolt, on which the clamping force is applied.



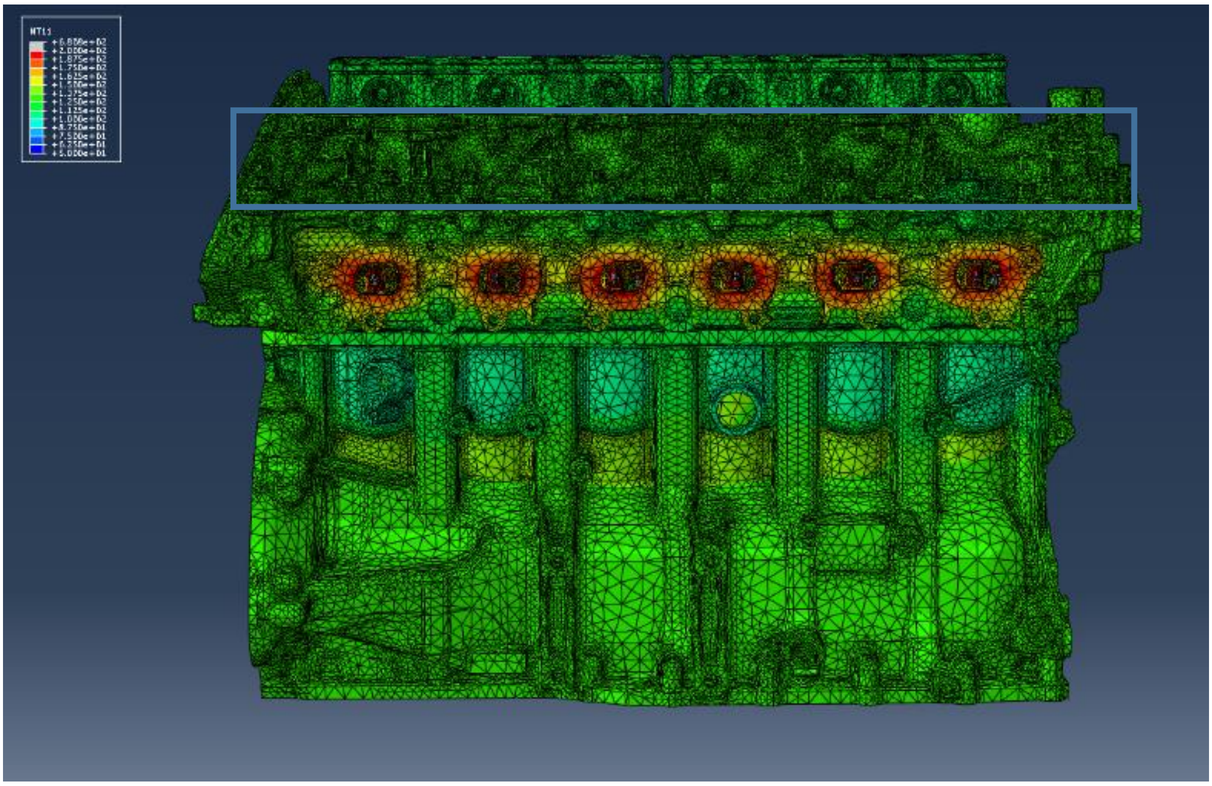
*Picture 21: illustration of the rigid body element figuring the bolt*
*(the red arrow figures the force applied)*

*Courtesy of JLR*

For each element mounted on the cam-carrier, the pressure resulting from the bolt clamping forces on the contact surfaces was computed by dividing the sum of all those clamping forces by the area of the contact surface.

As for the temperatures, how to implement them was quite simple.

The production team sent the temperatures map for the whole engine. From there, a closer look has been given at the particular temperatures of the original cam-carrier; we observed that they were all between 140°C and 160°C (approx.). As a result, the choice has been made to work with a uniform temperature of 150°C for the model.



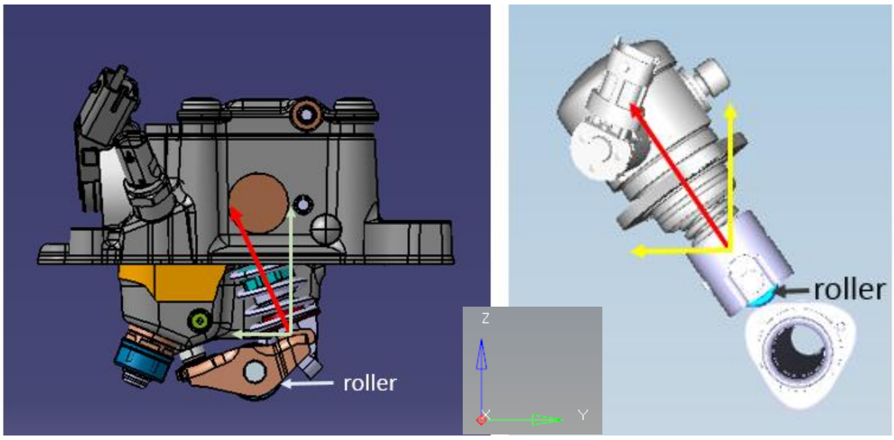
*Picture 22: illustration of the temperatures map for the whole engine*
*(the blue rectangle locates the cam-carrier)*

*Courtesy of JLR*

The G-loads were modelled by applying an acceleration of 3G in each direction to the whole model, since this method is the one the production team applies to come up with their first designs. Gravity has also been applied.

On another note, the sealing surface in contact with the cylinder head is constrained not to move. All 6 degrees of freedom are constrained, to mimic how the cam-carrier is linked to the cylinder head by the bolts.

Finally, some of the IEs also produce loads while they are working. It is the case of the CVVL units and the fuel pump. When the camshaft pushes the roller, on each of those elements, the opposed spring creates a reaction force, which needs to be taken into account as two axis loads.

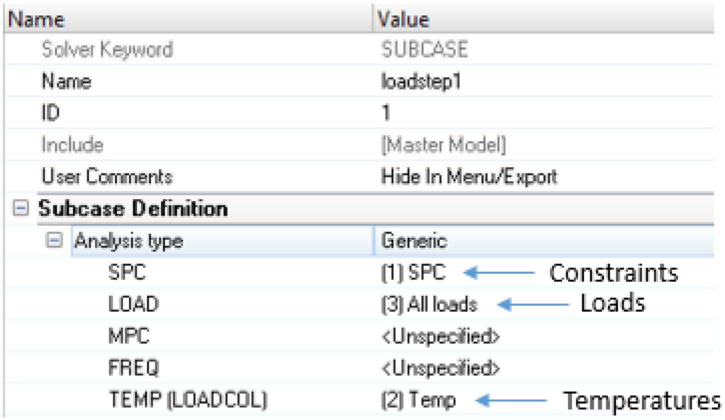


*Pictures 23 & 24: illustration of the loads induced by the CVVL units (left) and the fuel pump (right)*

*Courtesy of JLR*

As a whole, the load case was composed by 8 different types of loads.

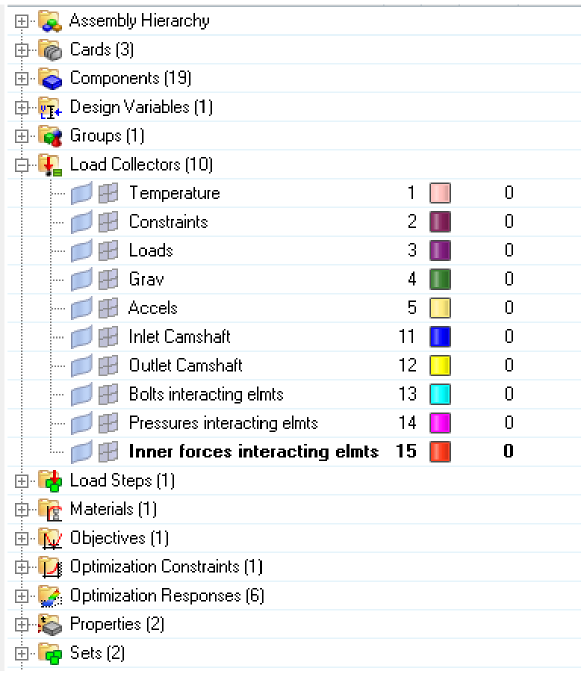
All those loads were gathered in a loadstep, to define the types of load in Optistruct (load, constraint or thermal load).



| Name | Value |
|---|---|
| Solver Keyword | SUBCASE |
| Name | loadstep1 |
| ID | 1 |
| Include | [Master Model] |
| User Comments | Hide In Menu/Export |
| ⊟ **Subcase Definition** | |
| ⊟ Analysis type | Generic |
| SPC | [1] SPC ← Constraints |
| LOAD | [3] All loads ← Loads |
| MPC | <Unspecified> |
| FREQ | <Unspecified> |
| TEMP (LOADCOL) | [2] Temp ← Temperatures |

*Picture 25: illustration of the loadstep*

*Courtesy of JLR*



⊞ Assembly Hierarchy
⊞ Cards (3)
⊞ Components (19)
⊞ Design Variables (1)
⊞ Groups (1)
⊟ Load Collectors (10)

| | | | |
|---|---|---|---|
| Temperature | 1 | 🟥 | 0 |
| Constraints | 2 | 🟥 | 0 |
| Loads | 3 | 🟪 | 0 |
| Grav | 4 | 🟩 | 0 |
| Accels | 5 | 🟨 | 0 |
| Inlet Camshaft | 11 | 🟦 | 0 |
| Outlet Camshaft | 12 | 🟨 | 0 |
| Bolts interacting elmts | 13 | 🟦 | 0 |
| Pressures interacting elmts | 14 | 🟪 | 0 |
| **Inner forces interacting elmts** | **15** | 🟥 | **0** |

⊞ Load Steps (1)
⊞ Materials (1)
⊞ Objectives (1)
⊞ Optimization Constraints (1)
⊞ Optimization Responses (6)
⊞ Properties (2)
⊞ Sets (2)

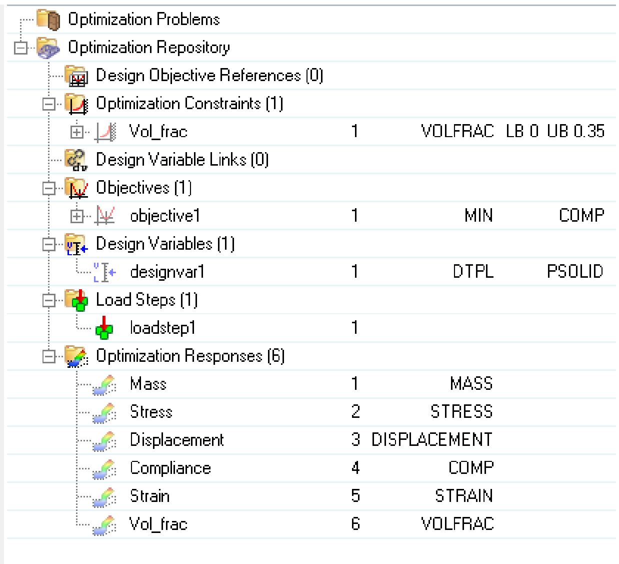
*Picture 26: illustration of the load case in Optistruct*

*Courtesy of JLR*

### 3. Defining the DRCO model

The last step before running the optimization was to define the DRCO model, the type of optimization that would be run. In accordance with the theoretical process of a topology optimization, the DRCO model was set as follow:

**D**esign variable: DS
**R**esponses: total mass, total volume, compliance
**C**onstraints: final volume = 35% initial volume
**O**bjective: minimize the compliance



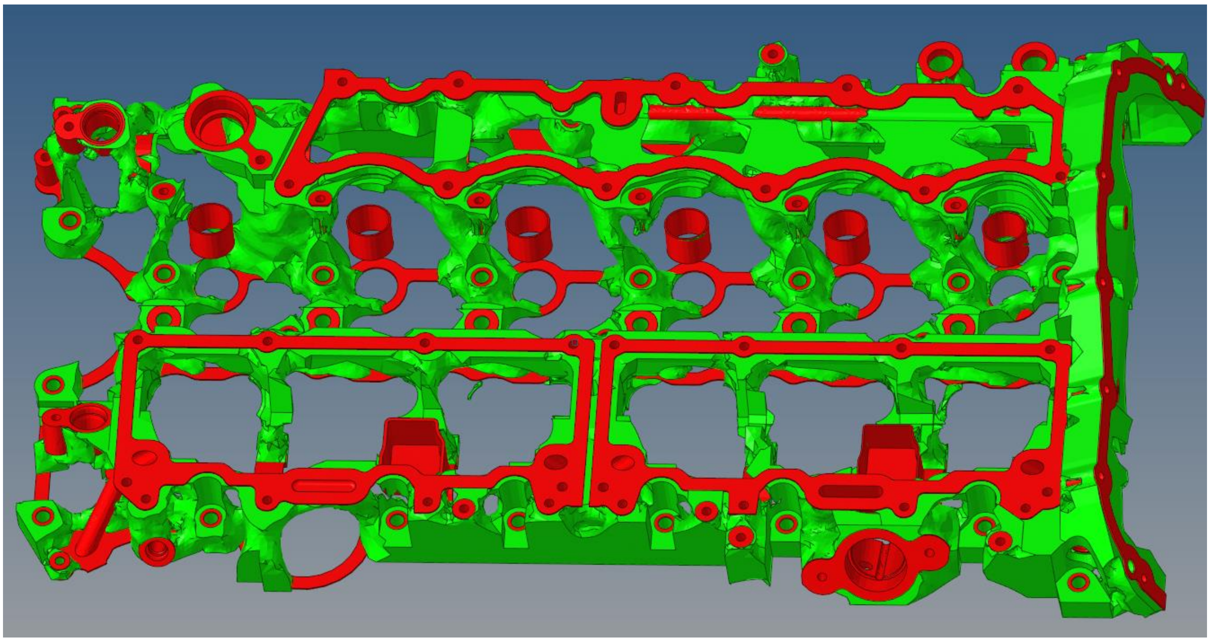
| | | | |
|---|---|---|---|
| Optimization Problems | | | |
| Optimization Repository | | | |
| Design Objective References (0) | | | |
| Optimization Constraints (1) | | | |
| Vol_frac | 1 | VOLFRAC | LB 0 UB 0.35 |
| Design Variable Links (0) | | | |
| Objectives (1) | | | |
| objective1 | 1 | MIN | COMP |
| Design Variables (1) | | | |
| designvar1 | 1 | DTPL | PSOLID |
| Load Steps (1) | | | |
| loadstep1 | 1 | | |
| Optimization Responses (6) | | | |
| Mass | 1 | MASS | |
| Stress | 2 | STRESS | |
| Displacement | 3 | DISPLACEMENT | |
| Compliance | 4 | COMP | |
| Strain | 5 | STRAIN | |
| Vol_frac | 6 | VOLFRAC | |

*Picture 27: illustration of the DRCO model*

*Courtesy of JLR*

## Running the optimization

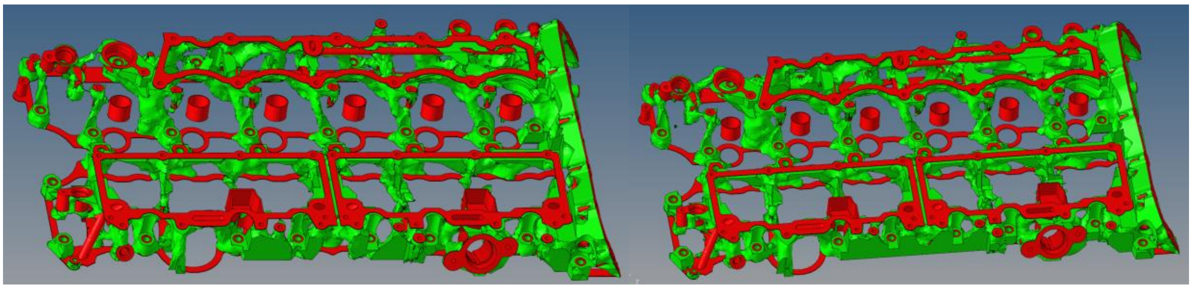
Once the optimization model was set up, it could be run on JLR’s cluster. After a few hours, we got the following first results:



*Picture 28: illustration of the first results from Optistruct*

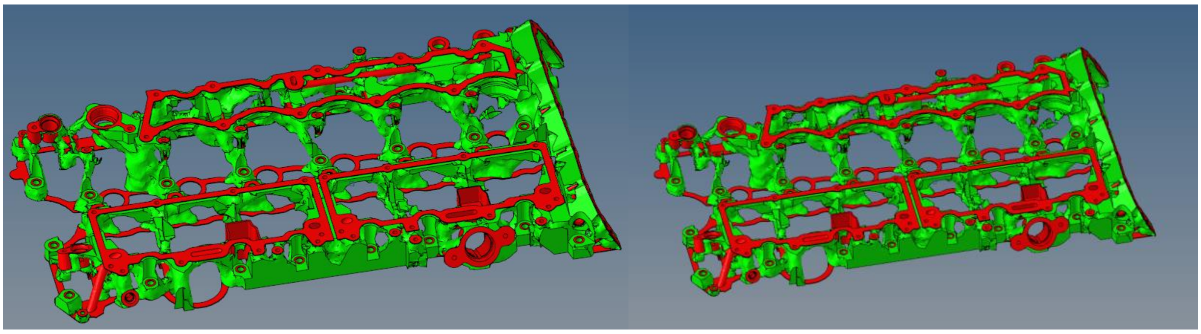
*Courtesy of JLR*

Later on, more optimizations were run, with different targets in terms of volume. They all returned similar results in terms of shape of the optimized design. Only the local thickness was different.



*Pictures 29 & 30: Optistruct results, 20% (left) and 25% (right) of the initial volume*

*Courtesy of JLR*



*Pictures 31 & 32: Optistruct results, 30% (left) and 35% (right) of the initial volume*

*Courtesy of JLR*

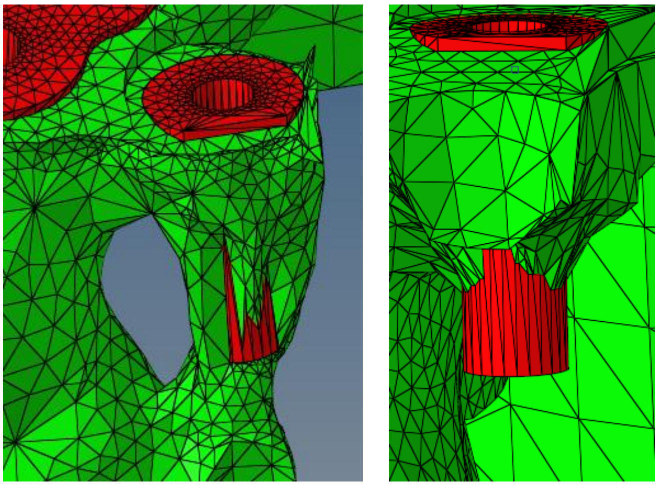
More optimizations were also run with different manufacturing constraints. There are 6 different possible constraints in Optistruct:

- **Mindim** → The geometry should not be thinner than a given dimension in any place
- **Maxdim** → The geometry should not be thicker than a given dimension in any place
- **Extrusion** → The cross-section of a profile should always be the same
- **Draw direction** → The geometry should be castable in the case the molds slide in the given direction (no inaccessible holes for example)
- **Pattern grouping** → The geometry should include the given patterns (most often symmetries)
- **Pattern repetition** → The geometry should include repetitions of the given pattern

*Picture 33: illustration of the effect of the maxdim constraint on a small part*

*Courtesy of Altair Engineering*

However, the cam-carrier was a too complex part to notice any sensible difference. In fact, those manufacturing constraints were impacting the design on a too small scale for us to take them into account.



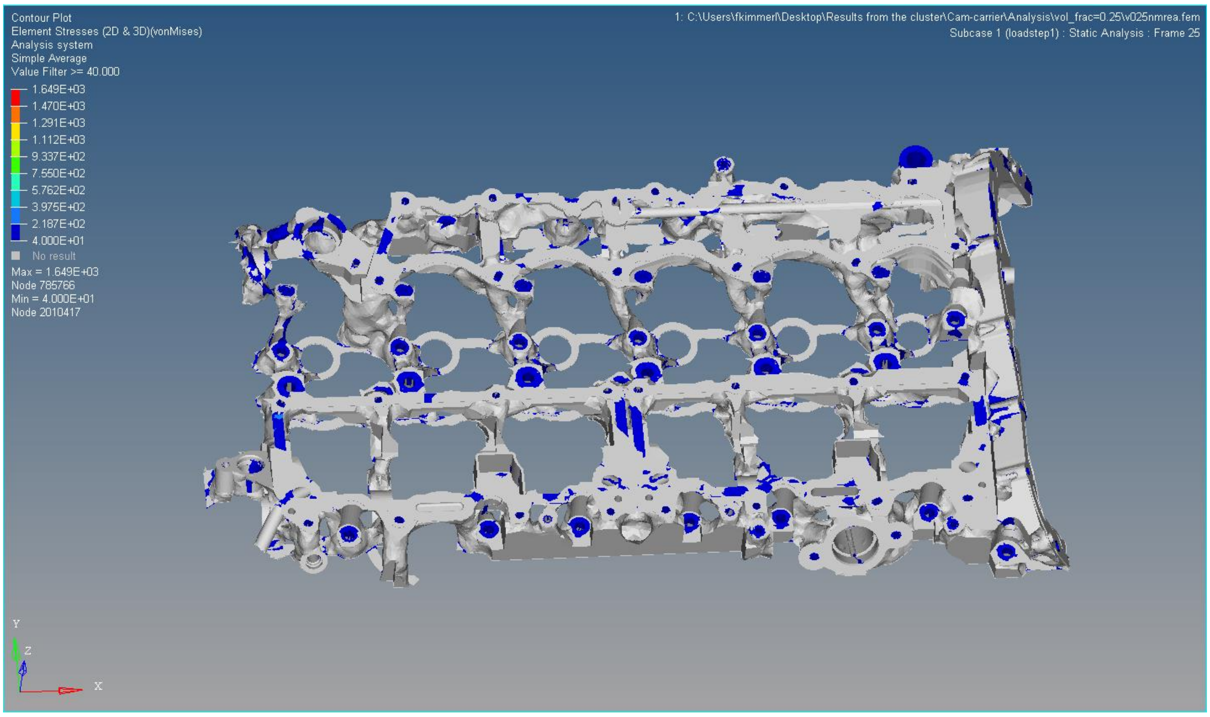
*Pictures 34 & 35: illustration of the effect of the manufacturing constraints on the cam-carrier design (without maxdim on the left, with maxdim on the right)*

*Courtesy of JLR*

## Analyzing the results

### Stress analysis

As explained above, since the stresses were left untouched during the optimization process, we could come up with plenty of different feasible designs. To know which one we could use as a base for our further work, a stress analysis was run on them. The target was to find the design with the smallest volume possible but with not too much undesired stress, even if we could get rid of them through the shape optimization. For this purpose, we chose 1/3 of the UTS of the aluminium as a safety factor (UTS: 255 MPa, Safety factor: 85 MPa)



*Picture 36: illustration of the stress analysis of the "30% of the initial volume" design*

*Courtesy of JLR*

## Frequency analysis

In parallel with the stress analysis, a frequency analysis has been run on the optimized designs. Its aim was to know if the natural frequencies of the latters were high enough, not to overlap the ones of the engine. The threshold not to go under has been hand calculated with the formula below.

$$Threshold\ (order) = \frac{RPM_{max}}{60} * order * \frac{\sqrt{2}}{2}\ Hz$$

where $RPM_{max}$ is the maximum engine speed and the order is the mode order

Thus, the threshold frequency to reach for the first mode of the optimized design was 212 Hz.

However, another frequency analysis was run on the original cam-carrier. Its first mode was 402 Hz. This gap between our threshold frequency and the original cam-carrier's frequency could be explained by the fact that the production engineers look at the frequencies of the whole engine in addition to a component-by-component approach. That is the reason why the cam-carrier may have higher frequencies than needed just for its own safety. Moreover, it is also possible that the frequencies got high because of casting requirements that added material to the first design the engineers came up with. In any case, the design would be validated since the 1st mode frequencies are higher than 212 Hz.

Anyway, since the previous approach was out of the scope of the project, we chose that for a design to be valid in terms of frequency, its 1st mode frequency should simply be over 212 Hz.

As a result of the stress and frequency analysis, the design with 25% of the initial volume was chosen. Indeed, this was the best compromise in terms of stress, volume and frequencies. It was the design with the smallest volume that presented a 1st mode frequency of 286 Hz (>212 Hz) and had a reasonably low number of high stress regions.

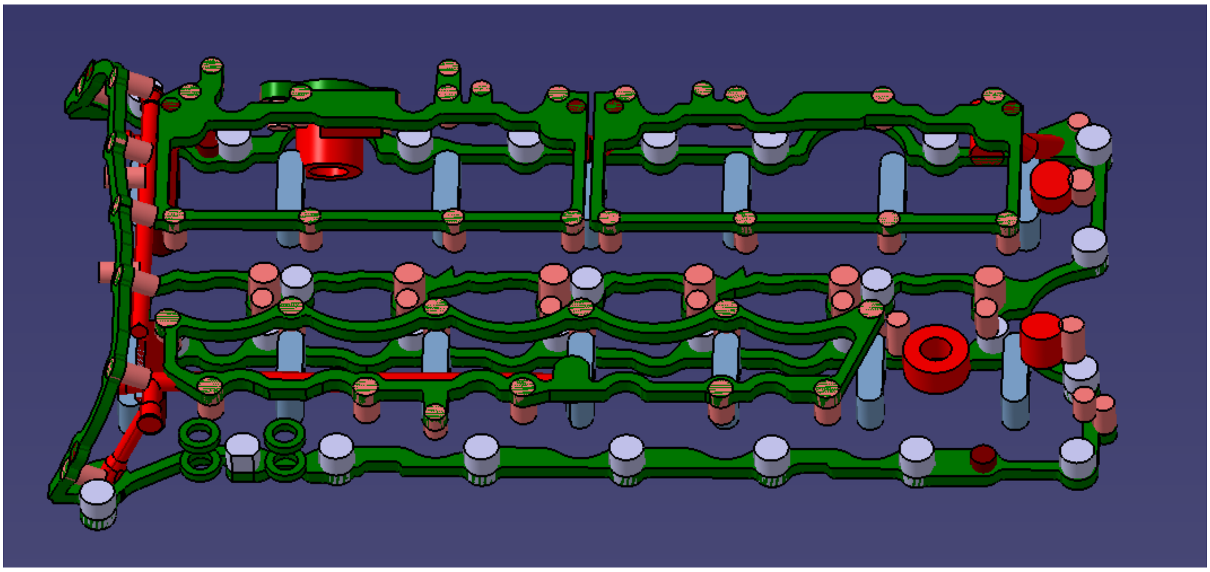
From this Optistruct output, a new machinable design now needed to be worked on.

## Creating the new design

The new design was created in accordance with JLR's design rules. It needed to be castable (High pressure die casting) at no extra cost and with the existing tools in JLR.

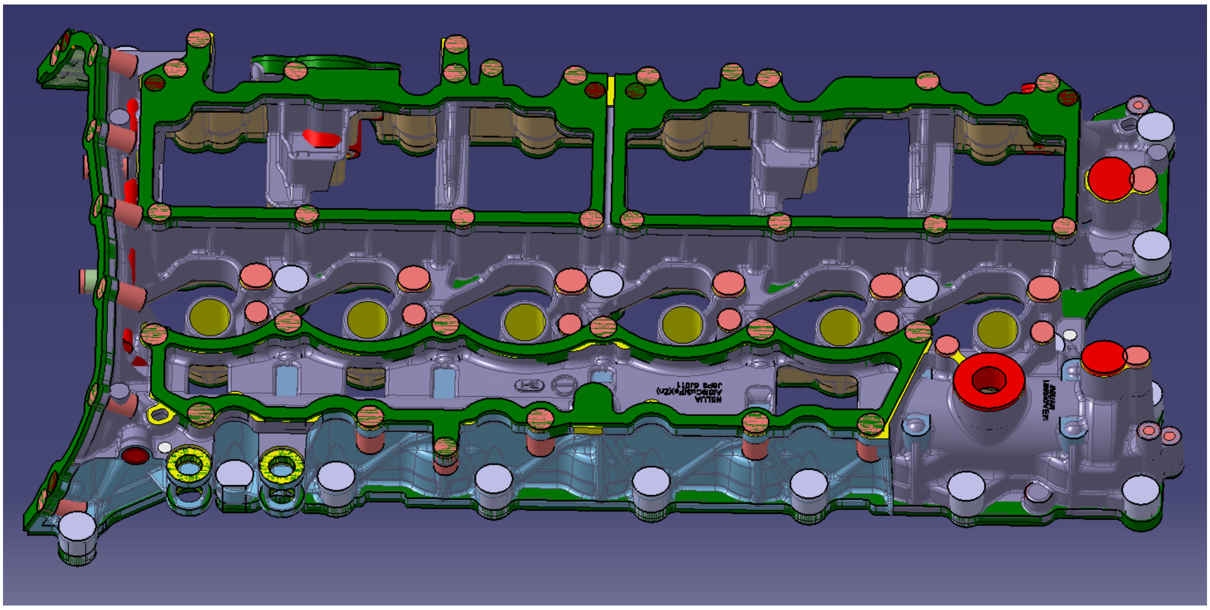
First, all the flanges (later turned into sealing surfaces), bolt placements and pipes were created, in order to be sure there would be some material where it is necessary. A 2 millimeters margin was taken everywhere, from the radii of the pipes to the lengths of the bolts. All this work was based on the original cam-carrier, to ensure that the new design would perfectly fulfill his duty without changing anything in the design of the IEs.

Broadly speaking, a 2 millimeters machining allowance (in addition to the 2 millimeters margin) and 1,5° drafts were taken into account in the design. Shrinkage and sagging were also strictly monitored during the whole process of creating this new design.



*Picture 37: illustration of the bolt placements, pipes and flanges*

*Courtesy of JLR*



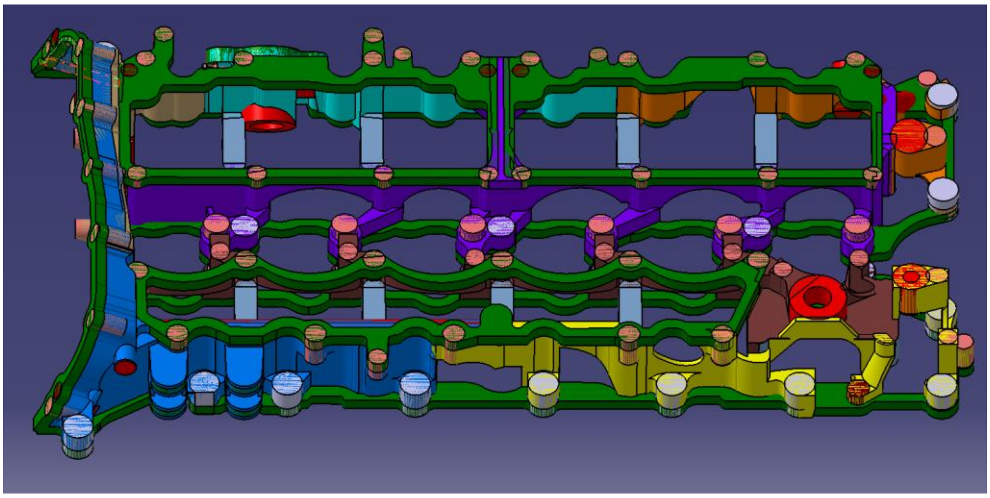
*Picture 38: illustration of the bolt placements, pipes and flanges in the original design*

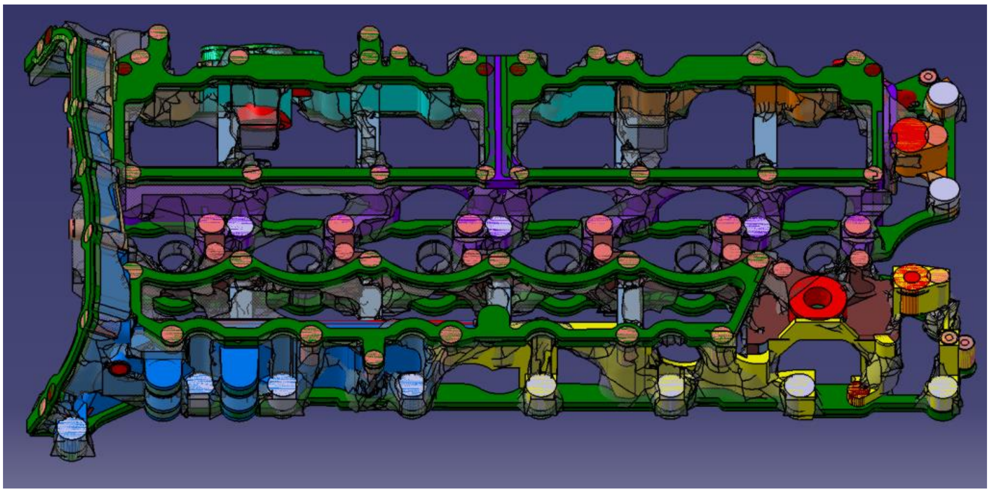
*Courtesy of JLR*

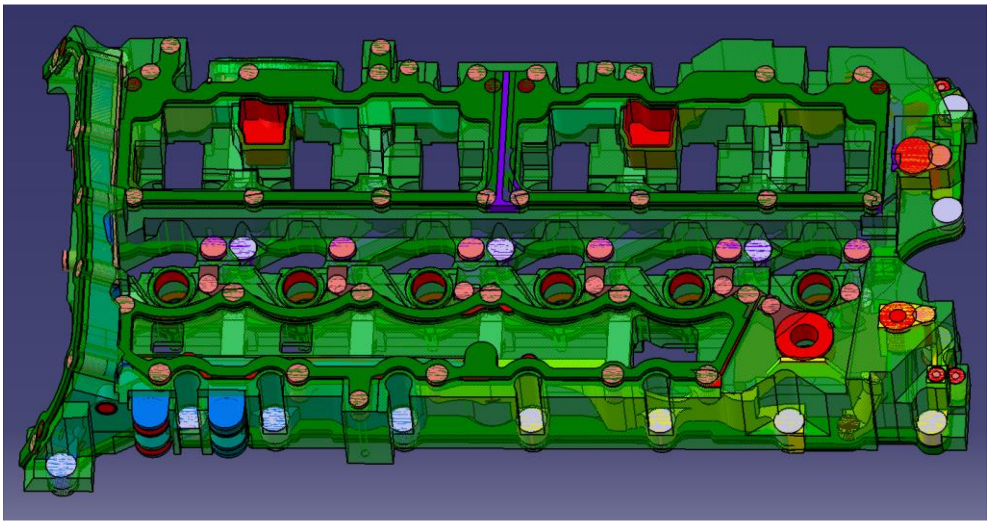
Then, the walls were created by linking all the flanges, bolt placements and pipes together.

There were a few constraints on those walls:

- They should be as light as possible
- They should mimic the output from Optistruct
- They should be created inside the DS

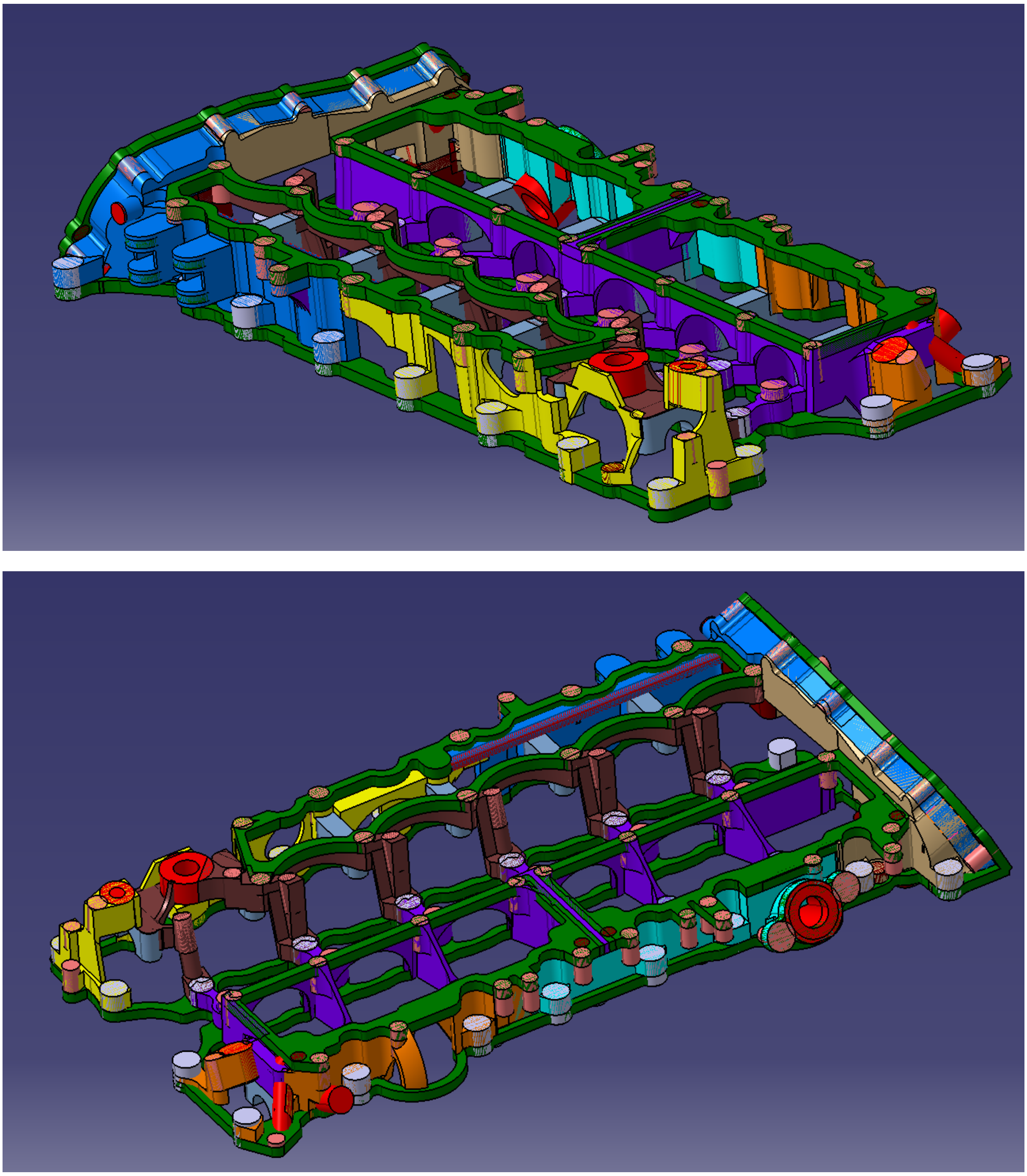






*Picture 39 & 40 & 41: illustration of the creation of the walls (top), mimicking the Optistruct output (middle), and inside the DS (bottom)*

*Courtesy of JLR*



*Picture 42 & 43: general views of the new design*

*Courtesy of JLR*

Three more steps have been covered before to get to the final design. First, all the machining allowances have been removed. Then, a stress and frequency analysis has been run to check if the design was satisfying enough (a few ribs were added at this stage). Finally, some plastic covers were created to seal the cam-carrier.

Sadly, those three steps won't be illustrated in this paper. Indeed, the new design and the plastic covers are on track to be patented, which is the reason why those steps will be evaded.

# A new process in JLR’s Powertrain Research Design Team

As previously explained, the aim of the project was to create and implement a new process within JLR Powertrain Research Design Team, in order to expand its capability in terms of topology optimization.

The creation of this process has naturally been divided in two distinct steps: a technical part about the optimization itself, and a part more business-related on how this process was shaped to JLR’s needs.

## The technical process

For years, the Powertrain Research Design Team has always worked with external suppliers to run its topology optimizations. The Design Team was then only the buyer of the service provided by the supplier. Because of this relation, there was no topology optimization capability within the team; nobody knew how to run one.

Thus, the project needed to address two different issues:

- Creating a simple process that any member of the team could follow to run a topology optimization.
- Creating a self-contained process, which would enable the team to run a topology optimization after the end of the project without any external input.

As a result, the process needed to include:

- A short guide of where to find help about the software used to run the optimization and about the general process of topology optimization.
- A precise description of what to do to run a topology optimization
- The possibility for the user to run different types of optimization (topology, shape, free-size…) by following the same single process. Thus, there should be a possibility for the user to navigate through different options within the process.

On another note, another choice was to be made concerning the format to give to this process for the Design Team. Different possibilities were considered: a Powerpoint presentation, a PDF document, a video or a long excel sheet.

The choice was made to work with a Powerpoint presentation for different reasons:

- Possibility to navigate in the presentation through hypertext links
- Possibility to edit the document at any time
- Facility to work with, while running a topology optimization
- Possibility to add comments
- Attractive design

Of course, this presentation should be as detailed as possible, for it to be self-contained. The idea was to make a kind of tutorial out of it.

## Shaping the technical process to JLR’s needs

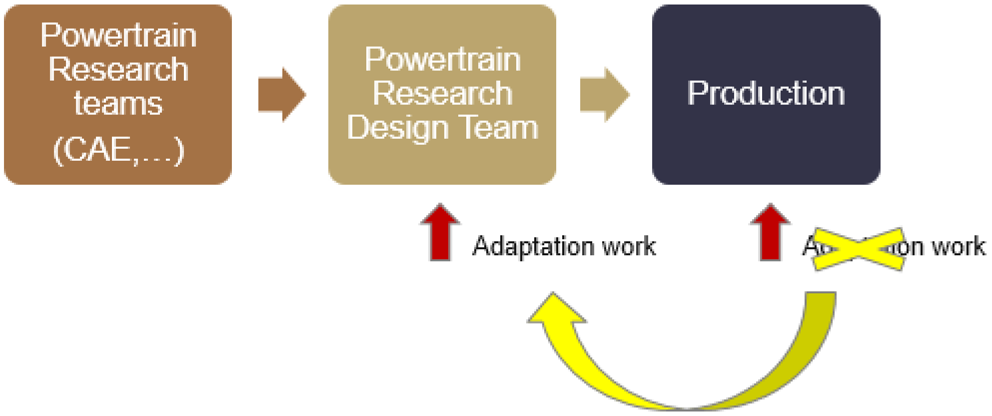
Once the technical process of how to run a topology optimization was ready, the next step was to determine how to shape the general process to JLR’s needs.

The Powertrain Research department has no real link with the Production Department. Indeed, it is more like a showroom of what JLR is able to do, in which the Production Department can select some interesting projects to adapt on the new engines.

Thus, a gap exists between the research projects and the production projects. Most of the research projects must be adapted and modified before to be accepted into production.

This work is usually done by the Concept Team that adapts the research projects to the production’s needs.

The idea behind this project was to include part of this adaptation work in the optimization process to try reducing the gap between Research and Production.



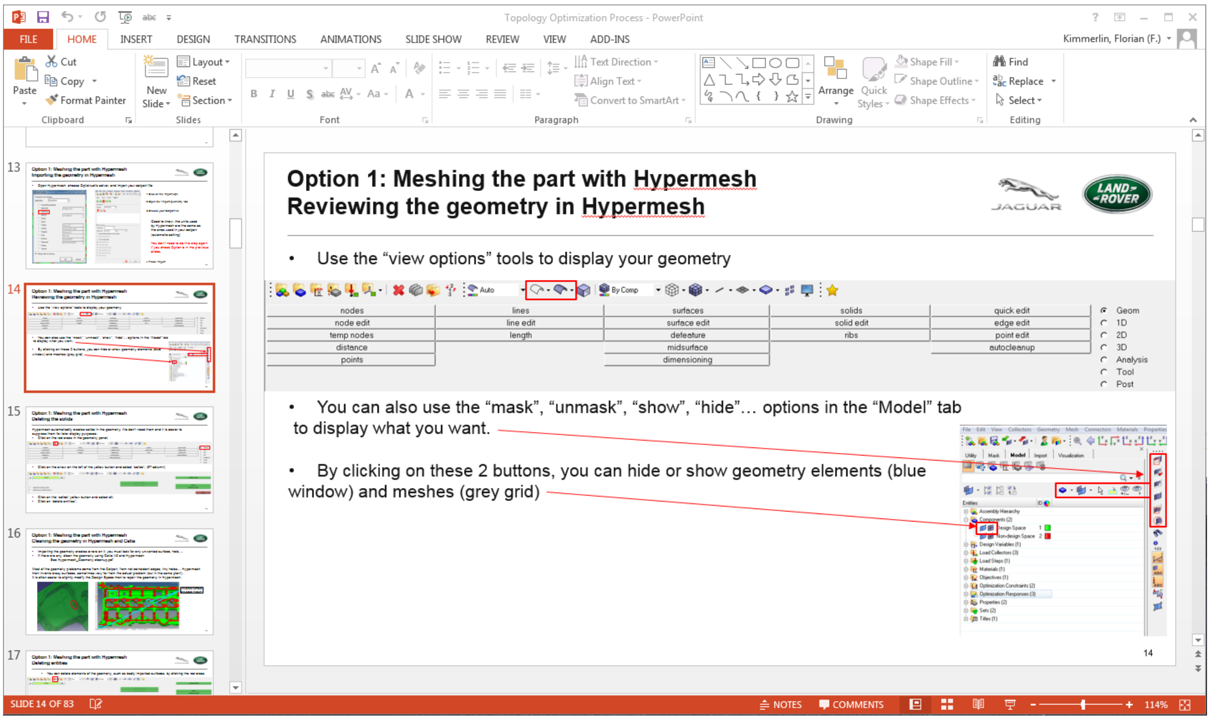
*Picture 44: illustration of how the process would be shaped to JLR’s needs*

*Courtesy of JLR*

As a result, the process should find a balance between Research and Production: it should reduce the gap between the two, but not completely erase it, since in this case, the Powertrain Research Department wouldn’t have any reasons left to exist.

Thus, meetings were set with the Production, Concepts and CAE Team for them to tell us their requirements and standards that should be included in our work in terms of design, methods, materials, projects selection… and include them into the process.

In the end, the result was a self-contained Powerpoint presentation of 120 slides. This presentation explains how to run a topology optimization with the tools already existing within JLR, and what to do to shape your work to JLR’s needs. It is designed for everybody to be able to use it, from the experts to the novices.

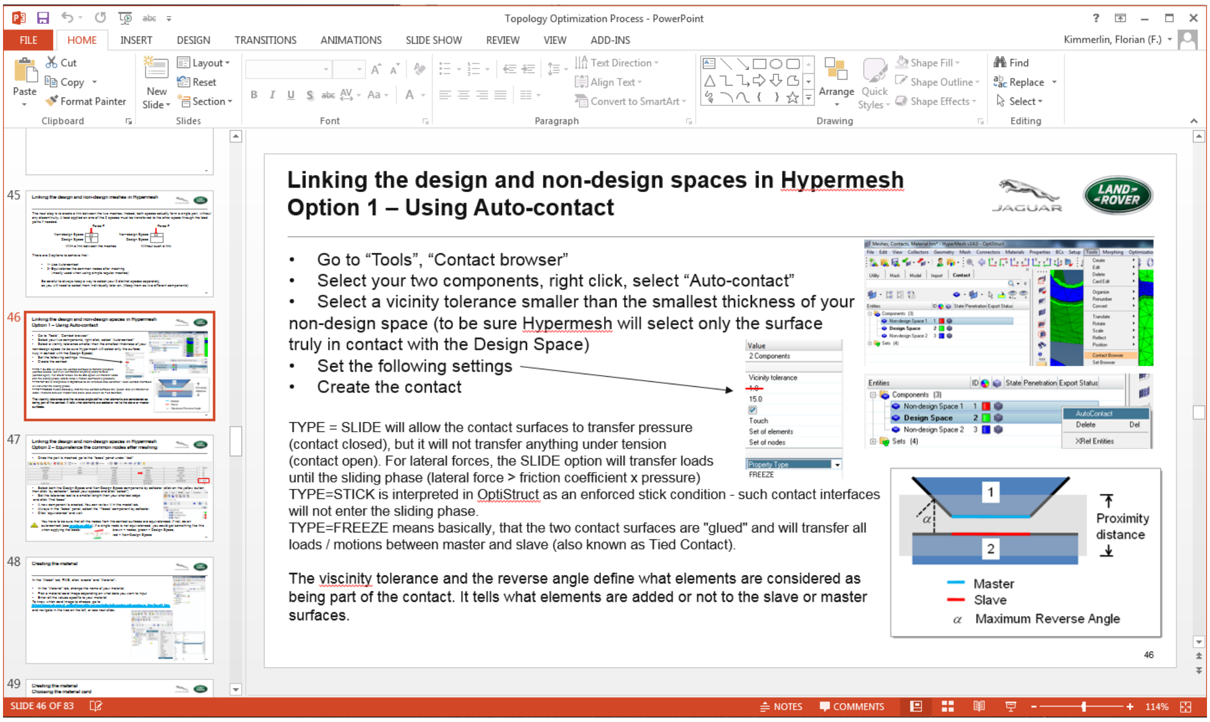


**Option 1: Meshing the part with Hypermesh**
**Reviewing the geometry in Hypermesh**

- Use the “view options” tools to display your geometry

- You can also use the “mask”, “unmask”, “show”, “hide”… options in the “Model” tab to display what you want.

- By clicking on these 2 buttons, you can hide or show geometry elements (blue window) and meshes (grey grid)



**Linking the design and non-design spaces in Hypermesh**
**Option 1 – Using Auto-contact**

- Go to “Tools”, “Contact browser”
- Select your two components, right click, select “Auto-contact”
- Select a vicinity tolerance smaller than the smallest thickness of your non-design space (to be sure Hypermesh will select only the surface truly in contact with the Design Space)
- Set the following settings
- Create the contact

TYPE = SLIDE will allow the contact surfaces to transfer pressure (contact closed), but it will not transfer anything under tension (contact open). For lateral forces, the SLIDE option will transfer loads until the sliding phase (lateral force > friction coefficient x pressure)
TYPE=STICK is interpreted in OptiStruct as an enforced stick condition - such contact interfaces will not enter the sliding phase.
TYPE=FREEZE means basically, that the two contact surfaces are "glued" and will transfer all loads / motions between master and slave (also known as Tied Contact).

The viscinity tolerance and the reverse angle define what elements are considered as being part of the contact. It tells what elements are added or not to the slave or master surfaces.

*Pictures 45 & 46: Illustration of the type of slides created for the process on Powerpoint*

*Courtesy of JLR*

# Conclusion

Topology optimization, and optimization in a more general way, are very vast engineering fields and this project has explored only a few of the possibilities they offer. However, this placement enabled me to learn a great deal about different subjects.

First, I learned a lot of course about optimization. From the training I did with Altair Engineering to the tutorials I read on the internet, I could fully understand all the theory behind the concepts, and the processes used when running an optimization. Then, I also learned a lot about the casting. Creating the new design from scratch was a great experience for my engineering background. I had to take into account all the different constraints that apply when working on a part that will be high pressure die cast. I know how the material flow behaves inside the die, how the material cools down, or what the cores should look like. Then, I learned a lot on the software I used during my placement, mostly Abaqus, Hyperworks and Catia V5. I got some useful help from my colleagues which enabled me to progress quickly. Finally, I improved a lot my presentation skills and my soft skills, through the numerous regular presentations I did, and the many meetings I took part in.

Besides, this project has also enabled me to learn how to act as an engineer, how to behave as a working professional. I could turn from a student into an engineer, thanks to the trust the team and my manager placed in me.

On another note, the project met the requirements the team had about it, since the optimization process has been delivered on time into the team, and the example component met the objective of a 15% weight reduction.

Still, 6 months was too short to go really deep into detail. A few other improvements could be made to the part. First, we could have a look at the choice of the material. For this project, the material used was the same as for the original cam-carrier, but there could be a better choice to make. In addition, we could have a look at the type of casting performed to create the part. Here again, the choice was made to keep the same one as for the original cam-carrier, but changing it could reduce the number of design constraints on the part, and thus enable the designer to save some more weight. Then, we could go further in the optimization if we could slightly modify the elements interacting with the cam-carrier. The choice was made not to change them during the project, but we could have saved some more weight if we had. Finally, we could have a look at how to implement dynamic loads into the models. Indeed, even if the Equivalent Static Load Method already works towards it, the software only works with static loads, which is a truly limiting factor.

As a whole, the placement was very beneficial to me, for my engineering background as for my personal skills. I met interesting and truly involved people, who turned this placement into a real pleasure.

# Bibliography

Please find below the references of the two documents used at the beginning of this paper.

[1] http://www.lepoint.fr/automobile/innovations/des-idees-pour-alleger-de-20-le-poids-des-voitures-12-03-2013-1638936_652.php

[2] World English Dictionary, Optimization