Multi-disciplinary Topology Optimization for Vehicle Bonnet Design

David Salway[1], Dr Tayeb Zeguer[2]

[1]GRM Consulting Ltd, [2]Jaguar Land Rover Ltd

1 Abstract

Bonnet Pedestrian Head Impact and Structural Stiffness and Strength targets have conflicting design requirements which currently result in design compromises, and the current CAE methods use different models and solvers. This paper highlights a new CAE capability to provide Multi-Disciplinary Optimization of bonnet geometry to achieve the conflicting Pedestrian Head Impact and structural stiffness/strength targets at lowest weight and cost. The aim has been to combine all bonnet load cases using one code "LS-DYNA®" and carry out trade-offs and optimize weight using LS-OPT®. A new developed topology process employing VR&D Genesis® for HIC optimization is presented and compared with LS-TASC® tools for a generic bonnet design.

2 Objective

The objective of this study is to establish a robust MDO process for bonnet design. Currently bonnet design is done in an empirical manner, by carrying over existing design features that are known to work in other vehicle programs.

Using Topology optimization for Head Impact applications has not been perfected before. A simple hypothesis was developed; that it was hoped would allow the problem to be solved:

*'The Head Impact properties of a bonnet are linked
to the linear characteristics of the bonnet structure when no secondary
impacts are considered'*

The motivation behind developing this process is to reduce the development cycle time of a 5* car, producing the lowest cost and mass design, whilst achieving the maximum category in consumer and legal testing for pedestrian head impacts.

To achieve the best results when using optimisation it is necessary to apply it to every stage of the development cycle. In the case of the bonnet it became apparent that this wasn't occurring. The current design route is shown in Figure 1
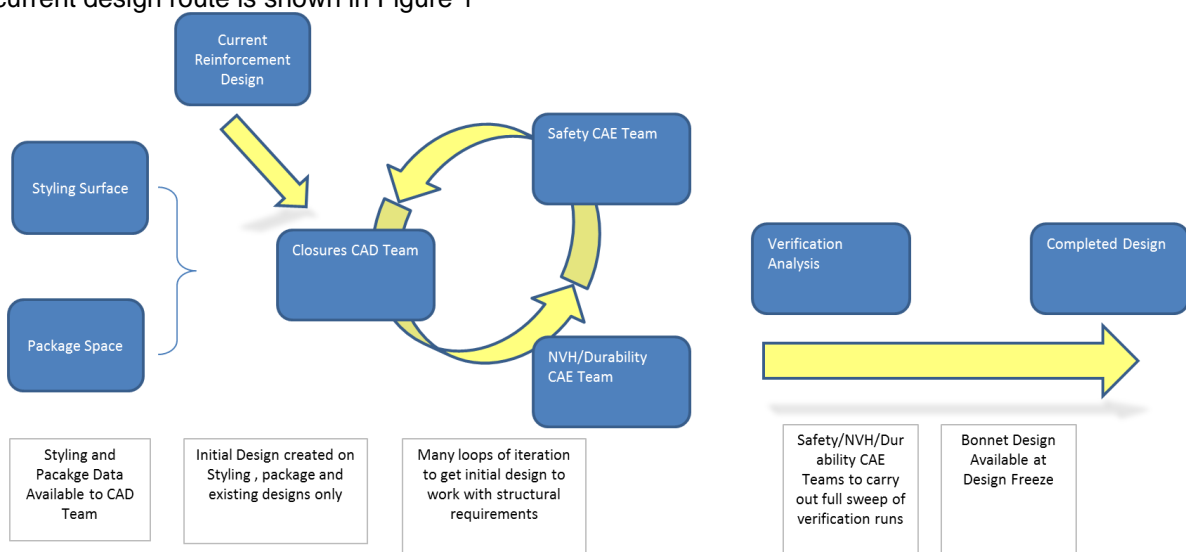

Figure 1 Current Bonnet Design Process

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By applying a more optimisation/CAE led approach it should be possible to reduce development time and improve design efficiency, the proposed work plan is as set out in Figure 2
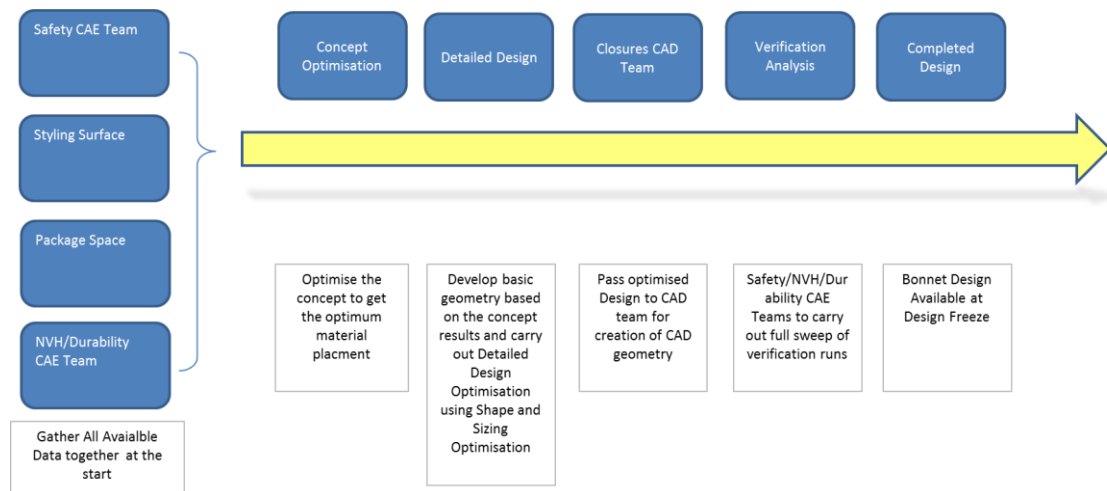

Figure 2 Proposed Bonnet Design Process

It is anticipated that the 'Concept Optimisation' phase will be carried out using a Topology optimiser, specifically VR&D Genesis®. An automated loop was proposed, such that the optimisation could be carried out, and then verification could be carried out using LS-DYNA for the head impact loads. The results of this verification would be used to modify the Topology constraints and hence guide the design.

Following this it is proposed that the analyst would create geometry based on the optimisation result. This would require the analyst to create a feasible solution, but this would be carried out in an FE pre-processor such as ANSA as opposed to full CAD at this stage of the process. This design could then be further developed through size and shape optimisation using LS-OPT. By coupling LS-OPT to ANSA it is possible to create complex morphing variables and then use LS-OPT to drive ANSA in batch mode and create the models for each design.

Currently the bonnet component analysis is carried out using LS-DYNA for the safety analysis (Head and Upper Leg) and Abaqus for the static load cases. It is proposed to use LS-DYNA implicit to replace Abaqus in the static analysis. This would then allow a common model approach to be employed, making the optimization set-up simpler.

3 Process Development

The whole process relies on being able to produce the concept design from the Topology optimisation. The later phases of the process are currently possible with the commercially available tools and as such do not need any significant research effort. The bulk of the effort was therefore put into developing a method to generate the concept design.

4 Model creation

Through discussion with the relevant CAE teams it became apparent which of the load cases were the most important to consider during the method development. Although in the application of the method it would be necessary to consider all of the requirements. The most important load cases considered in the method development were:

- Torsional Stiffness
- Rear Beam Stiffness
- Latch Over Bend

Analysis models of these load cases were gathered along with the requirements for each load. At this stage a baseline assessment was carried out to see how the current model compared to the

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requirements. The results of this analysis showed that for most of the requirements the bonnet exceeded the target, but did not comply with a small minority.

Currently the head impact models are run in LS-DYNA and feature the complete front-end of the vehicle, with powertrain and ancillaries. The run time of this model on 16 CPUs is approximately 8 hours, because of this a simplified model was produced. As stated in the hypothesis at this stage the effect of secondary impacts will not be considered, in light of this the under bonnet components were not required.

The model was setup with the hinges, latches and bump stops in position with the top half of the fenders and the front end carrier. The hinges and latches feature the kinematics of the full LS-DYNA model.

Two models were created, the first a Nastran linear model to be used to optimise in GENESIS and second an LS-DYNA model to be used for the Head Impacts and also the LS-TASC investigation. These can be seen in Figure 4.

To establish the constraints for the optimisation the models were run with the existing production bonnet. The static values were recorded, and used as constraint for the optimisation.

Further simple models were used during the process development to improve the turnaround time, an example of one of these models can be seen in Figure 3.
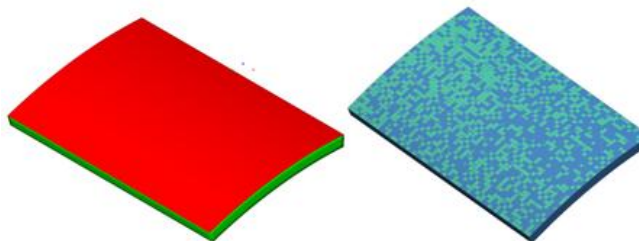

Figure 3 Quick Test Model

Figure 4 LS-DYNA and GENESIS Models

5 Concept Optimisation Method Development

The initial phase of the optimisation workflow is to complete a linear optimisation to determine the material placement considering both the static load cases and also an approximation of head impacts spread across the bonnet.

The total number of assessment points for this bonnet was approximately 180, it was decided that it wasn't practical to consider so many points. For the optimisation 20 points were considered spread across one side of the bonnet, and symmetry constraints were applied. The purpose of this was to try and minimise the number of active constraint that the optimiser would encounter, thereby improving solve time and convergence.

Two core methods were identified for optimising the reinforcement. Further variations on each method were considered. The first core method explored was a solid topology approach. By using sheet manufacturing constraints with this approach it was anticipated that the optimised part would require minimum interpretation to produce a manufacturable pressing.

An alternative approach was free solid topology without any manufacturing constraints, it was anticipated that this would provide a more straight forward problem for the optimiser than the constrained problem, but would require more interpretation to get to a design.

The second core method was to use shell Sizing and Shape optimisation. Various combinations of Sizing, Topometry, Topography, and Shape optimisation were tried. It was intended that shape optimisation would be used to provide the form to the inner, and then Sizing optimisation would be used to design the thickness.

When using the topology approach the connection between the bonnet skin and the inner is taken care of by the nature of the topology optimisation. For the shell based approach the connection between the Skin and inner needs to be controlled based upon the distance of the inner from the skin.

In addition to a variety of different optimisation design methods to consider, a number of different constraint/objective setups were considered as shown in Figure 5

Response Type	Minimise	Target	Constrain
Linear Head Impact Response		✓	✓
Mass Fraction	✓		
Static Constraints		✓	✓

Figure 5 Possible Constraint System Combinations

As the GENESIS models were being run it became apparent, that the method we would ultimately end up using had to achieve various requirements, it had to produce a converged solution, and it had to produce a coherent structure. Many times the optimisation would not converge, either by not meeting constraints, or in the case of Topology by not forcing elements to be 1 or 0.

6 Solid Topology Investigation

The solid Topology baseline model featured a large lump of solid material on the underside of the bonnet skin. The dimensions of this package space were based on the general depth of a current production bonnet. Due to the simple shape of this generic model the solids were created by offsetting the bonnet skin to create a hexa/penta mesh. The main sections of the particular production bonnet that was employed as a guide are all aluminium; as such this material choice was carried to the new mesh.

In other solid topology applications where a performance constraint or target is being employed we have found benefits to scaling the solid package space material properties. The logic to this is very simple; the solid topology result is never going to be as thin as the production panel, therefore by scaling the material properties, the mass and stiffness properties of the solid result will more closely match the eventual thin pressed sheet. This approach has been used with both the sheet metal and free Topology method.

Experience of using Genesis and advice from the developers suggest that the most effective way to use solid Topology is to constrain mass fraction and maximise stiffness. Unfortunately for this particular example that is not really feasible as we want to tune the stiffness to be stiff enough to achieve the static requirements, but compliant enough to give us the 5* HIC scores. From this it was apparent the less favoured approach of minimising mass fraction with either constrained or targeted performance as the best route forward.

7 Sheet Topology Method

This method is intended to give you a topology result that can be pressed from a single sheet. As the bonnet is made up of pressed parts, it was anticipated that this would provide an answer that would require the minimum interpretation into a feasible design. An example can be seen in Figure 6
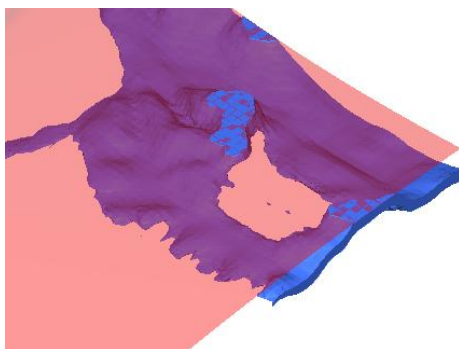
Figure 6 Example of Sheet Topology

The method is unique to VR&D Genesis and was developed with significant input from GRM. Because of past experience with this we were able to employ non-default parameters in a bid to improve convergence.

From running with the sheet Topology we encountered problems with convergence; generally the Topology should converge towards elements having a value of either 1 or 0. An example of this is shown in Figure 7 both models are identical apart from the one on the left having the sheet constraint activated.
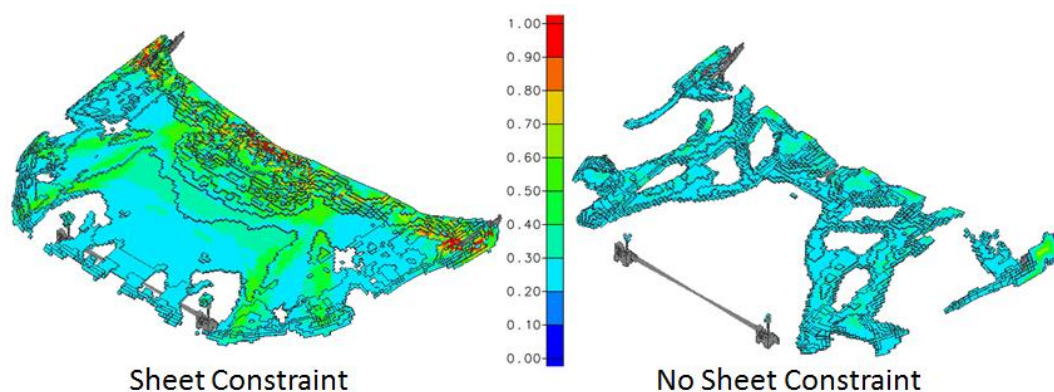

Figure 7 Effect of Sheet Constraint on Result

In addition to the convergence issue we found a problem with connections. Where the rear beam load was being applied into the structure via an RBE3(interpolation element), we discovered a feature of the method where the sensitivities and approximations were allowing the material to move away from the connection and then not being able to reconnect. An example of the disconnect is shown in Figure 8
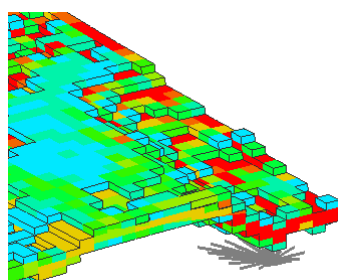

Figure 8 Loss of Connection on Rear Beam

By including the manufacturing constraints in the optimisation we are making life more difficult for the optimiser, as such this combination was sufficient to justify dropping the Sheet Constraints. It is, however, anticipated that the method will be further investigated in future.

8 Topology Method

Following the decision to drop the sheet constraints from the Topology further research was carried out using the solid topology method.

We explored the best problem formulation for the optimisation, trying various approaches. As previously discussed the most efficient method for solid Topology in Genesis is to use a fixed mass fraction. However, due to the nature of this problem this is not really appropriate as the objective is to achieve a specific stiffness and this will require material to be added and removed. The next approach considered, was to minimise the mass fraction whilst constraining the static and head impact cases. The optimiser prioritises the constraints, so it will increase the mass fraction to meet the constraints. Due to the large number of constraints this makes the optimisation quite slow, and also makes it uncertain if the optimiser will meet the constraints. It can also result in the optimiser going down a blind alley from which it cannot return.

The option that is currently favoured for the problem formulation is to constrain the static targets (torsion, bending, and rear beam stiffness) and then target the desired performance for the head impacts. This was achieved by subtracting the performance from the target, and then constraining the absolute result of this. At the target this gives a value of 0, to allow the optimiser some freedom this value was constrained to have an upper bound of 2.0 (due to the magnitude of the values we were using this equates to approximately 10%. The target value has no direct relationship to the HIC, as such experimentation was used to establish this value. The criteria were that the value had to provide sensible HIC scores, when the results were assessed in LS-DYNA, and that the value had to be such that the constraints in the linear solver were achievable. This target value was the value that would then be updated as the process loops and gets feedback from the LS-DYNA runs.

Various techniques have been discovered to encourage convergence. Through a number of tests it was concluded that control of the optimisation move limits and convergence parametrs should be changed from the default setting chosen for traditional linear analysis problems.

Another effect that was observed is that when an element gets to a density value of 1 it becomes trapped. In the same way as steadily reducing the move limits, trapping elements at 1 is done to encourage convergence in linear cases. To allow freedom in this case the value was reset from the deafult to cycle 100.

Following the first runs it was apparent the optimum mass fraction would be at a value 0.1 or lower, this is considered to be a low mass fraction, as such some non-default move limits were used to compensate. These non-default values alter the minimum move limit and also the fraction by which the move limit decreases each cycle.

9 Shell Shape and Gauge Method

As an alternative to the Topology method, a shell approach was also pursued. The inner was made as an offset shell with the intention of then using either Topography or free Shape optimisation to form the bonnet. As previously discussed this raises problems with controlling the connectivity of the inner and outer parts of the bonnet. As the inner moves away from the outer the connection between the two should detach, this effect is captured in the Topology method as the material is removed. To achieve the same using shape variables requires the connection element to be linked to the design variable.

Due to the nature of Topography where the individual design variables are generated internally it is not possible to create this link. Because of this a switch was made to using Shape Optimisation where each design variable is created by the user at the start. To speed up this process a script was created, which also generated the connections and created the design variable links. To achieve this, the connection was modelled using a CBAR element, with the stiffness of the CBAR linked to the shape change at the connection point. This approach was used right across the bonnet, with a separate CBAR property for each node to node connection. As the shape variable moved the inner away from the outer the connection stiffness would be reduced, using a power function, forcing it to decide between big sections or many connections. An example of the model setup is shown in Figure 9
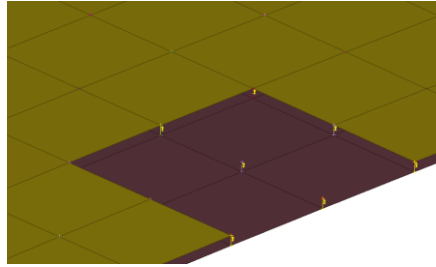
Figure 9 CBAR Connections to Link with Shape Variable

Various studies were carried out using this approach, to try and achieve a convincing shape. One of the advantages of Topography is that the method includes smoothing functions. By using the Shape approach a high level of noise was seen in the resulting structures. To try and smooth out the spikes a constraint was placed on the volume of the sheet, a spiky sheet has a much higher volume than the same basic shape with a smooth finish. The other issue that was identified was that the optimiser seemed to be struggling to converge on a definite shape. To overcome this various starting positions were considered; fully against the outer, fully away from the outer and at 50% of the potential move. We achieved some convincing results using this approach, but experienced convergence issue. It was therefore concluded that the Topology method provided a better solution and had more scope. However, there is definitely scope within this method and it warrants further investigation.

10 LS-TaSC comparison

Using LS-DYNA for the head impact analysis allowed us to test LS-TaSC with the problem. All of the models have been constructed to run in both GENESIS and LS-DYNA and as such it was very straight forward to setup the LS-TaSC optimisation. In LS-TaSC the individual load cases were run separately, and then combined. Individual results are shown in Figure 10

Figure 10 LS-TaSC Static Results

Something that was observed when comparing the results to the Genesis results in Figure 11 is that the LS-TaSC results have much more material. Investigation shows that whilst LS-TaSC had the constraints set for upper bounds on displacement, the optimised result exceeds the constraints by considerable margin. Results from the optimisation can be seen in Figure 12
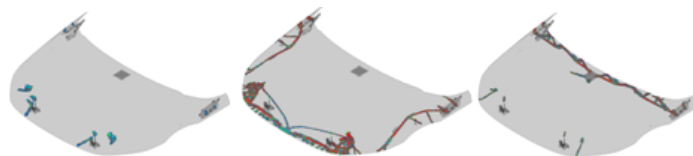
Figure 11 Genesis Static Results

	LS-TaSC			GENESIS		
	Torsion	**Latch**	**Beam**	**Torsion**	**Latch**	**Beam**
Constraint	1	1	1	1	1	1
Result	0.446	0.524	0.348	0.994	1.000	0.999

Figure 12 Comparison of Static Constraint

The comparable Genesis results exhibit displacements that are significantly larger than the size of the displacements in the LS-TaSC models, whilst still meeting the constraints. Discussing with LSTC about this has suggested that the constraints in LS-TaSC are still being developed.

The constraint method selected for the dynamic impacts was contact force, both peak and average were considered. The result of an average run is shown below in Figure 13 and the results are very encouraging. The next phase of the LS-TaSC study would be to incorporate a user defined HIC constraint and see how that effects the results.

Figure 13 LS-TaSC Head Impact Result

11 Detail Design using LS-OPT and morphing

The constraint values from the Topology optimisation are provided in Figure 14

	GENESIS Topology Result																						
	Torsion	Latch	Beam	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20
Constraint	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Result	1.00	0.99	1.00	0.97	0.98	0.96	0.92	1.00	0.92	0.92	0.99	0.97	0.98	0.95	0.95	0.92	0.92	0.98	0.92	0.93	0.94	0.95	0.94

Figure 14 Normalised Topology Results

Following the topology optimisation the penultimate stage of the process is interpreting the Topology density result into a pressed design. As previously discussed by removing the manufacturing constraints from the Topology optimisation a degree of interpretation was required to achieve a pressed design. Some features of the design are quite clear such as the deep drawn section at the rear, and the general layout of the material. The main fore/aft members in the result are not laid out in a classic pressed design; a section plot is shown in Figure 15
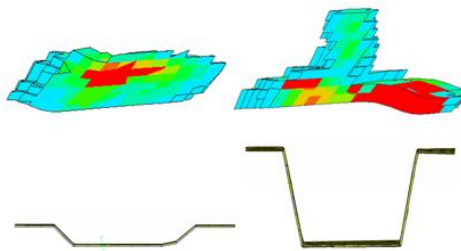

Figure 15 Section plot of Fore/Aft Members, showing Topology Result and Interpreted Pressed Design

In the pressed sheet some consideration has been given to both the pressing and assembly requirements and so extra material has been added around the outside to improve the feasibility. This is particularly evident around the hinges, latches and over the fender. The Topology result and interpreted design are shown in Figure 16
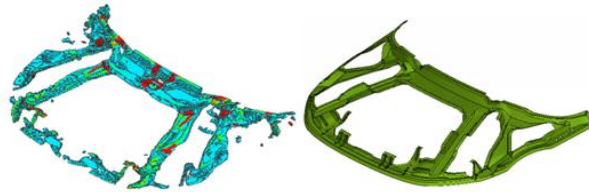
Figure 16 Topology Result and Interpreted Design

The outside of the whole pressing was attached to the outer using the same clinching approach as the original design. This is an area that has been identified as having potential for further optimisation. The connections between the inner and outer have long been considered to be important. The initial design has been developed so that there is a flange suitable to support an adhesive connection; the locations of these are based on where the Topology result has a connection between the inner and outer. A baseline run was carried out to verify the performance was close to the desired values. Some small detailed changes were made to the baseline model to improve the performance of the latch pull. The final stage of optimisation was to carry out a shape and gauge optimisation by coupling ANSA morphing to LS-OPT. The morphing was setup using direct morphing approach as recommended by Beta CAE. Variables were setup to vary the depth and width of the major sections and the thickness of the pressed inner. The connections were included in the morphing and then the adhesive was regenerated for each shape change and the mesh smoothed to improve the quality. When creating the shape variables special attention was paid to how they would combine and to ensure that the mesh remained viable. The design variables and morphing parameters are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Type	Name	Starting	Init. Range	Minimum	Maximum
Variable	Thick	1.		.5	2.5
Variable	OUTSIDE_DEPTH	0.		-8.	10.
Variable	REAR_ANGLE	0.		-25.	0.
Variable	REAR_CUTOUT_[	0.		-15.	5.
Variable	REAR_DEPTH	0.		-10.	10.
Variable	MID_DEPTH	0.		-10.	10.
Variable	OUTSIDE_REAR_	0.		-10.	10.
Variable	MID_INSIDE_TRA	0.		-10.	20.
Variable	MID_OUTSIDE_TF	0.		-10.	40.
Variable	REAR_INSIDE_AN	0.		-25.	5.
Variable	REAR_INSIDE_TF	0.		0.	35.
Variable	SWAGE_POS	0.		-10.	10.
Variable	SWAGE_DEPTH	0.		-4.	5.

Figure 17 Design variables and Morphing Parameters

The linking of LS-OPT to ANSA was carried out following the principles defined in the Beta Tutorial 'Optimisation with LS-OPT' [7]. A DOE study was carried out using a space filling approach to define the start points with a radial basis metamodel. The meta model was then used to carryout virtual optimisation to achieve different design objectives.

12 MDO Results

The DOE results have been used to explore the performance that can be achieved at different mass values. The first check was to verify the acuracy of the meta model, the accuracy plots, for each of the responses was checked. In this example a small number of points was used for each loadcase to keep the computation cost to a minimum for non-essential cost. To verify the results the chosen metamodel design should be verified using an LS-DYNA analysis. The metamodel accuracy was checked using LS-OPT, by plotting the predicted results against the analysis results.

The following optimisation schemes were tried:

- Minimise Mass, Static Constraints
- Minimise Mass and HIC for All Points, Static Constraints
- 4.0Kg Mass Constraint, minimise HIC, Static Constraint
- 4.5Kg Mass Constraint, minimise HIC, Static Constraint

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- 5.0Kg Mass Constraint, minimise HIC, Static Constraint

In the multi-objective cases the mass is dominated by the HIC scores due to the orders of magnitude involved, i.e the mass is in Kg and the HICs can be expected to be in a region from ~400-1700. By adjusting the weighting it was possible to overcome this, but this had the effect of causing the thickness variable to flip-flop between the upper and lower bounds. The results of the virtual optimisation and the thcikness variable dominating the mass can be clearly seen in Figure 18

Optimisation Scheme	Thickness	Outside_Depth	Rear_Angle	Rear_Cutout_Depth	Rear_Depth	Mid_Depth	Outside_Rear_Depth	Mid_Inside_Trans	Mid_Outside_Trans	Rear_Inside_Angle	Rear_Inside_Trans	Swage_Pos	Swage_Depth	Static Constraints Met	MASS(kg)	Torsion	Latch	Beam
Minimise Mass, Static Constraints	0.00	0.80	0.00	0.50	0.30	0.40	0.30	0.10	0.35	0.65	0.00	0.10	0.80		1.40	1.00	1.00	1.00
Minimise Mass & HIC, Static Constraints	0.00	0.80	0.15	0.50	0.45	0.30	0.30	0.10	0.50	0.55	0.00	0.00	1.00		1.40	1.00	1.00	1.00
Minimise Mass & HIC, Static Constraints	1.00	0.00	1.00	0.10	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00		7.00	0.50	0.50	1.00
4.0Kg Mass Constaint, Min HIC, Static Constraint	0.50	0.05	0.85	0.65	1.00	0.00	0.10	0.00	1.00	0.25	0.15	0.00	1.00		4.00	0.95	0.60	1.00
4.5Kg Mass Constaint, Min HIC, Static Constraint	0.55	0.00	0.90	0.60	1.00	0.00	0.10	0.00	1.00	0.25	0.10	0.00	1.00		4.50	0.90	0.50	1.00
5.0Kg Mass Constaint, Min HIC, Static Constraint	0.60	0.00	1.00	0.60	1.00	0.00	0.10	0.00	1.00	0.20	0.05	0.00	1.00		5.00	0.70	0.3	1.00

(Design Variables span the columns Thickness through Swage_Depth. Thickness/Mass Flip Flop Effect annotation points to the MASS/Torsion columns.)

Figure 18 Virtual Optimisation Results

The bonnet pedestrian scores have been postporcessed for the 5.0Kg reinforcement scheme and the scores are presented in Figure 20
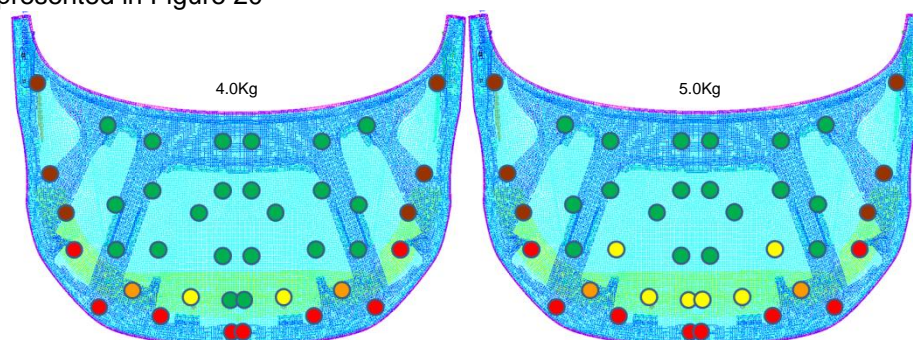

Figure 19 4.0Kg and 5.0Kg Optimisation Scheme Pedestrian Scores

13 Summary

As a method for improving the development time and costs of the bonnet reinforcement structure this process shows good potential. The correct use of Optimisation should reduce development time and produce a more efficient design. The post Topology phase is widely being used and available in commercial software application, some further exploration and adaptation to better suit the JLR HPC could be carried out, but really only to make it more user friendly.

The use of Topology to determine the material placement is unique and as such has presented a pretty big challenge. The development done in the Topology phase so far has shown that there is definitely some truth in the hypothesis. The work to develop this will continue. The ultimate goal is to make the Topology phase automated, and once the optimisation strategy has been fully refined, this will be the next goal.

14 References

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[2] Vanderplaats Research and Development: GENESIS Analysis Manual, Version 12.2, September 2012
[3] LSTC: LS-DYNA Keyword User's Manual, Version 971, May 2007
[4] LSTC: LS-TaSC Topolgy and Shape Computations for LS-DYNA, User's Manual, Version 2.0 April 2.0
[5] LSTC: LS-OPT User's Manual, Version 4.2, February 2012
[6] Beta CAE: ANSA V14.0.1 User's Guide, February 2013
[7] Beta CAE: Optimisation with LS-OPT, v 14.0.1, February 2013

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