# The Application of FEA in the Optimisation of Die Cast Components & the Consequent Reduction in Development Costs & Time

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## 1. Abstract
This paper details applications of FEA techniques in the optimisation of large, thin-walled, high-pressure, die cast magnesium alloy components for the automotive industry. Initially the processes of topology, topometry and shape optimisation are discussed before detailing good practice in the use of these techniques in the automotive industry by a first and second tier supplier to automotive OEMs. Finally, the way in which CAE led design fits into the product lifecycle, successfully reducing development times and costs, is discussed and demonstrated.
**2. Keywords:** Structural Optimisation, Automotive, FEA, GENESIS

## 3. Introduction
Despite optimisation techniques being well understood, readily available and relatively cheap to implement, they are still underutilised in industry. In 2004 Vanderplaats stated that “In engineering, while development [of optimisation techniques] has been underway for over forty years, applications have lagged far behind. The time has come for that to change” and that “optimization technology has matured to the point where it can and should be used routinely for engineering design”[1]. In a 2004 paper, he reminded us that in 1978 he “predicted that optimization would be commonplace by 1985”, but then went on to say, “Clearly, that did not happen and predictions are no longer made”[2].
With increasing focus on the environment and the cost of engineering design, it is imperative that designs are as efficient as possible. This efficiency can be improved by using CAE to lead design, rather than simply using it as a verification tool. In particular, this can be achieved by using optimisation techniques which “can be used with minimal added cost or effort to significantly reduce energy consumption”[3]. For example, “a ten percent mass reduction will increase fuel economy by about seven percent”[1], and given the current economic climate there are also significant benefits to the economy since a “one percent economy improvement [in fuel consumption] will save nearly three billion dollars per year in the U.S. at the pump”[1].
However, “despite the widespread availability of this technology, it is seldom taught as a design tool by universities and remarkably underutilised by industry”[1]. This is now starting to change, for example, in February 2009 Swansea Metropolitan University became the first university in the U.K. to include the practical application of optimisation tools in GENESIS into one of its courses.
There are however, examples where optimisation is used successfully. This paper summarises some of the FEA techniques that are available and then details the applications of these techniques in the optimisation of large, thin-walled, high-pressure, die cast magnesium alloy components for the automotive industry by a first and second tier supplier to automotive manufacturers. Finally, the way in which CAE led design fits into the product lifecycle, successfully reducing development times and costs, is discussed and demonstrated using this example.

## 4. FEA Optimisation Processes
In order that the examples given in this paper can be clearly understood, the optimisation techniques that are used in the examples will now be discussed.

### 4.1. Topology
Topology is used to define where the most efficient structural loadpaths are within a structure, and is a “specialization of material optimization, forcing zero/one answers”[4]. A package volume is needed within which the part must fit and then loadcases are applied to the package volume to determine these loadpaths. This

is achieved by varying the modulus of elasticity and density. As described by Leiva, “In Topology optimization, the design variables correspond to the element volume fractions. The volume fraction designs simultaneously the material properties E (modulus of elasticity) and $\rho$ (density) with the purpose of getting a 0-1 answer to identify the key elements to keep and the rest to discard”[5].

Topology can successfully be used to design the a-surface of a part (i.e. what the main shape of the part needs to be), as well as being used to determine how an existing part needs to be reinforced to be as efficient as possible, for example in a casting, by the use of ribbing.

The results of a topology optimisation are mathematically correct, but are not final solutions, and these need to be interpreted into a manufacturable engineering design. In many ways this is a limitation of topology. As described in 2005 by Schramm “the interpretation of the results is still a mostly manual process”[6].

Topology is generally used as the first step in optimising a design, “topology optimization seldom produces a final part, even though manufacturing constraints are used. This is because topology optimization normally does not include stress and other constraints. However, it does identify load paths and provides a very good starting point for shape and sizing optimization”[1].

### 4.2. Shape Optimisation

Once the major structural members have been defined, the cross sectional size of those members can be determined by using shape optimisation. Loads are applied to the structure and the physical dimensions of these members are altered to meet the set criteria by using “scale factors of perturbation vectors”[5] as the design variables.

### 4.3. Topometry

Once the position and size of the major structural members has been established, topometry can then be used to determine how much material is needed throughout the structure to ensure that specific loadcases are met.

Size optimisation is well established where a physical property (for example the thickness of a group of shell elements) is varied. “Sizing optimization has traditionally been the entry point to the use of optimization technology in design. Especially in designs that use a lot of sheet metal this is a useful tool. It is well established and implemented”[6].

However, topometry is significantly different to traditional size optimisation, “Topometry optimization is a generalization of sizing optimization. Unlike size optimization, where all elements associated to a property data entry are designed with the same values, in topometry optimization each element is designed independently”[5]. This can have significant advantages. Size optimisation can work well, for example, as stated above in a fabricated structure. However, in order to run a size optimisation the analyst must group the elements together that will be optimised thus influencing and limiting the results. Topometry “allows performing sizing optimization on each element individually”[5] thus resulting in a more efficient structure. Castings have the huge benefit that a varying wallstock can be applied throughout the structure (as long as certain manufacturing constraints are met), ensuring that extra material need only be added where it is required. Thus topometry results can be integrated well into a cast design.

## 5. Examples of use by an Automotive Supplier

Structural optimisation in the automotive industry is not a new idea. In 1923, Henry Ford said “Saving even a few pounds of a vehicle’s weight means it could go faster and consume less fuel. Reducing weight involves reducing materials, which in turn, means reducing cost as well”[7]. However, as already stated, optimisation techniques are underutilised. In reality it is difficult to determine the real extent to which optimisation techniques are used, as highlighted by Vanderplaats, due to the fact that “most real commercial problems are proprietary and cannot be published”[1]. Although necessity has meant that use must increase as “New designs are expected to improve performance, meet new stringent weight targets and at the same time they need to be more economical to manufacture”[4]. Examples have been documented elsewhere, such as, a steering knuckle mass which was reduced by “five percent or more with no loss in strength”[2]. Optimisation has been used to “increase the first frequency of a car body by ten percent for the cost of under one percent added mass”[2], and Delphi Automotive describe an automotive dash cross beam in which they “reduce the mass by 33% and material cost by 39%"[3], however, this paper will highlight the tools, processes used, and the benefits of these for an automotive supplier.

Meridian Lightweight Technologies Inc. are the world leaders in the design, engineering and manufacturing of high quality magnesium die cast components. CAE is used extensively throughout the development of their products and this will now be highlighted as an example of good practice and specific examples will be demonstrated using the optimisation tools that have already been described. The manner in which Meridian Technologies successfully use CAE led designs both in conceptual designs, and in development of these concepts, through to production once the business has been secured is discussed.

Meridian's components range from the structural part of a car dash board, through to car seats and grille reinforcements used at the front of the vehicle. These components are large, high pressure die castings (typically around 3mm wall thickness, the width of a car and 5kg in weight), which lend themselves to topology, topometry and shape optimisation. A customer may have defined the a-surface of a component and then require the development of that structure in magnesium so that it meets the customer's structural targets. In this case topology is used to define the ribbing required before topometry is used to define the required wallstock of the structure. Alternatively, a customer may come to Meridian with a package space and loading requirements for a structure, in which case, topology is used initially to determine the a-surface shape of component. Once this has been established, topology can be used to determine the ribbing needed, shape optimisation is used to determine the final dimensions of the part and finally topometry determines the required wall thickness of the castings.

These components are optimised to ensure no plastic deformation occurs in linear loadcases and there is no failure in non-linear loadcases. In addition, Meridian's components are required to contribute to the vehicles in ways such as global stiffness and crashworthiness as well as achieving certain local stiffness requirements such as providing stable platforms for the steering wheel assembly and the airbags, whilst ensuring the designs are as light and cheap to produce as possible.

Meridian's products are structurally quite complex and thus utilise many different types of optimisation tools where appropriate. Leiva supports this idea when discussing topology and topometry "a complex structure can benefit from both [types of optimisation], as some parts of it could only be designed by one type of optimization, whereas other parts could only be designed with the other type"[4].

### 5.1. Conceptual Design Example 1 – A Rear Cross Car Beam

A structure was required for a coupe convertible which had the following functions; Provide hinge points for the folding roof, provide attachment points for the roll over hoops and to fit into the design volume provided by the customer. The customer provided "designable" regions, i.e. the package space that was available and "non-designable" regions, i.e. the attachment points for the b-pillars, the floor, the hinge points, and the roll over hoops. These regions can be seen in Figure 1.


Figure 1: Non-designable and designable regions

These two regions were then combined to form the complete package. This was then used as the base for the initial topology run. A topology run was set up with two loadcases that represented the rollover of the vehicle and the roof opening. There were two requirements for these loadcases, one, that the structure did not fail in the rollover loadcase, and two, that there was no fatigue failure in the roof opening loadcase. To ensure that no failure occurred in the rollover loadcase the amount of plastic strain seen by the magnesium was limited below a certain percentage, and to ensure no fatigue failure in the roof opening loadcase the stress seen in the magnesium was also limited.

Optimisation techniques are currently available only in linear software (although coupling of optimisation with non-linear software is now available in software such as GENESIS). Hence to define the loadpaths in this design the non-linear rollover loadcase was approximated to a linear loadcase in the topology run.

A topology run was set up with the linear interpretation of the rollover loadcase, and a linear roof opening loadcase with the designable region as per Figure 1 with the objective to minimise strain energy in the structure and the constraint of only using 30% of the material by mass. The results of this initial topology and the interpretation can be seen in Figure 2.

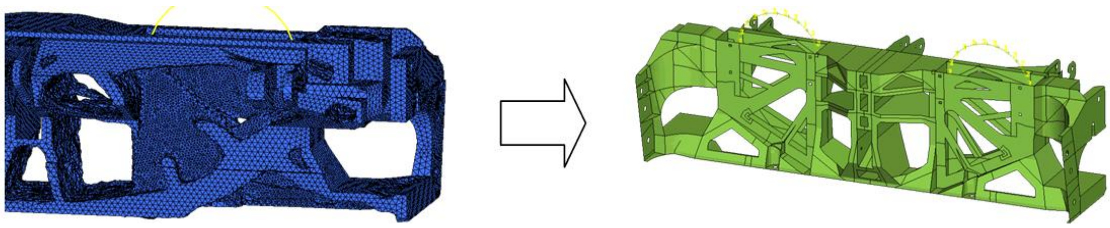


Figure 2 – Topology results for the rear cross car beam

Once the loadpaths from the topology run were interpreted into a castable design a shape optimisation study was then carried out to define the size of the sections in this structure, the result of which is seen in Figure 3.

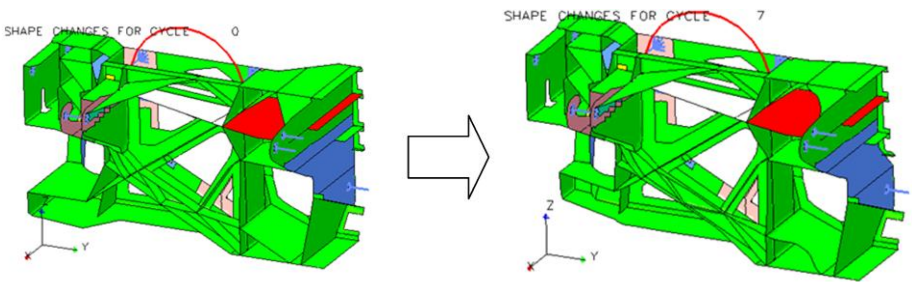



Figure 3 – Shape optimization results

Finally, once the position and the size of the sections were established a topometry optimisation was then carried out to determine the required thickness of the wallstock whilst meeting the stress constraints. The minimum wallstock that could be cast was 2.3mm. Thus this was set as the minimum and the structure was then optimised to minimum mass. The results and interpretation of this can be seen in Figure 4.

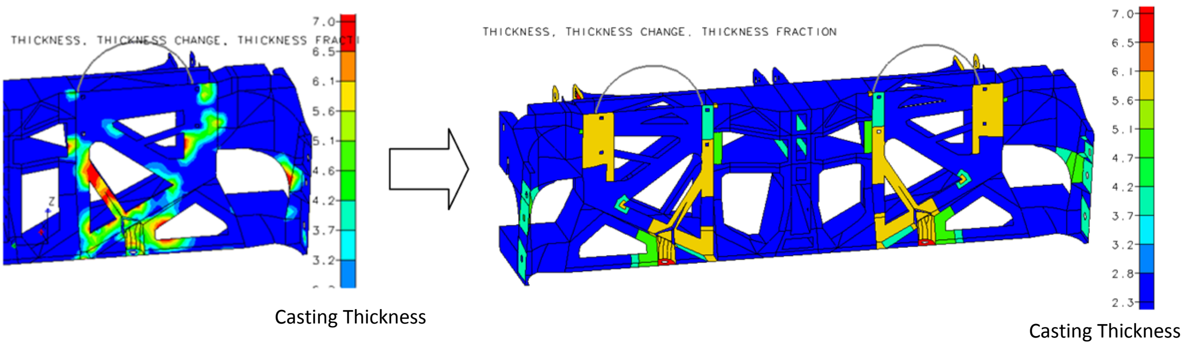
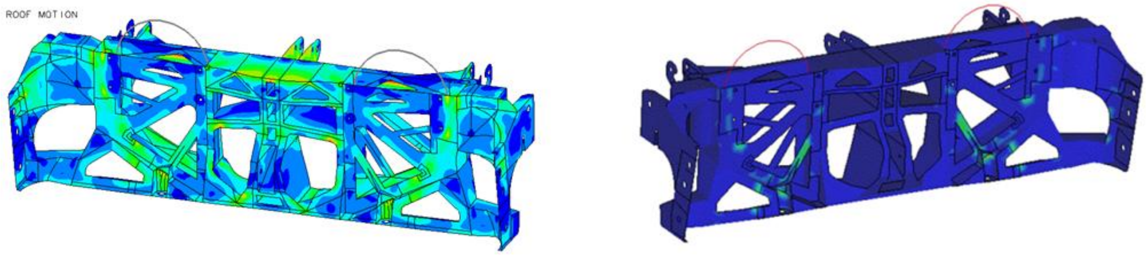



Figure 4 – Topometry results

To ensure that that the design met the two loadcases a linear verification model was then set up to ensure that the stress limit was not exceeded in the roof opening loadcase and a non-linear model was set up to ensure that the plastic strain was not exceeded in the rollover. The results of these two runs can be seen in Figure 5.




Roof opening loadcase - Stress Rollover loadcase – Plastic Strain

Figure 5 – Verification runs

As can be seen in the roof opening loadcase the majority of the structure is stressed suggesting a very efficient structure, whist in the roll over loadcase the diagonal members that were upgauged by the topometry run are clearly strained.

The final CAE model is seen in Figure 6. This can be delivered to the customer to prove the structural performance of the component and additionally a surface CAD model of the part can be produced within approximately 10 minutes from the CAE model which can also be delivered to the customer for an initial package check.

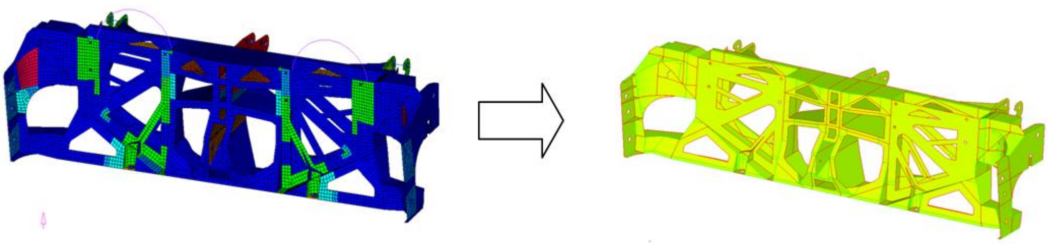


Figure 6 – The final CAE model and surface CAD model

5.2. Conceptual Design Example 2 – A Front End Carrier

In this example the customer had defined the a-surface of the component but required Meridian to develop the structural performance of the component. The a-surface model of this component as supplied is shown in Figure 7. This structure bolts onto the vehicle longitudinals.

This structure has the following functions;

- Support the headlamps, horn and radiator
- Provide support to the bonnet
- Provide vehicle torsional stiffness
- Withstand low speed impacts

Figure 7 – Model supplied to Meridian

In addition an NVH target was set for the structure. A topology run was set up with multiple loadcases and the back of the structure was filled with designable material to define where the major loadpaths were and thus where the ribbing should be. The requirement was once again set up to minimise strain energy whilst only using 30% of the available material, and a manufacturing constraint was set up so that the ribs could be cast in the longitudinal direction. The results of this topology run and the interpretation of these results into a rib pattern can be seen in Figure 8.

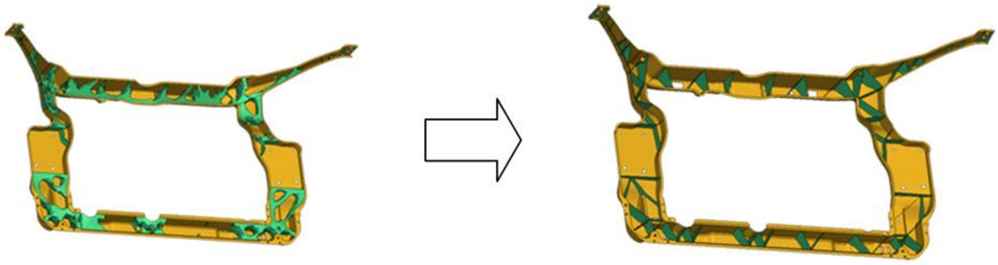


Figure 8 – Results of the topology run and their interpretation into a rib pattern

Once the ribbing had been defined, a topometry run was then set up to determine the thickness of the wallstock throughout the structure, as demonstrated in the previous example.

5.3. From Concept to Production

The previous two examples shown were both examples of conceptual designs used by Meridian to try to secure future business. Once the business has been secured the same optimisation techniques are then used to ensure that the final design is as efficient as possible. A good example of this was the R56 beam as produced by Meridian for the second generation BMW mini. This is shown in Figure 9.

Figure 9 – The R56 cross car beam

This design was an example where the a-surface was provided by the customer to Meridian who then developed the structural performance of the beam for several loadcases including; providing a stiff platform for the steering wheel, providing support to the passenger airbag, providing a structural loadpath in side impact and not breaking in frontal impact. The original topology runs carried out by Meridian that led to the initial CAE concept can be seen in Figure 10, this can then be compared to the final CAD model. The major loadpaths in the original Topology run can clearly be seen. The early use of topology ensures that ribbing is added in the most efficient way and only where necessary. This can be compared to a previous generation Meridian beam (which did not utilise optimisation techniques) as seen in Figure 11 where ribbing was simply added in an 'X' structure throughout the beam to make the beam as stiff as possible in all directions, regardless of where the ribbing was actually needed, resulting in a beam not being as efficient as it could be.

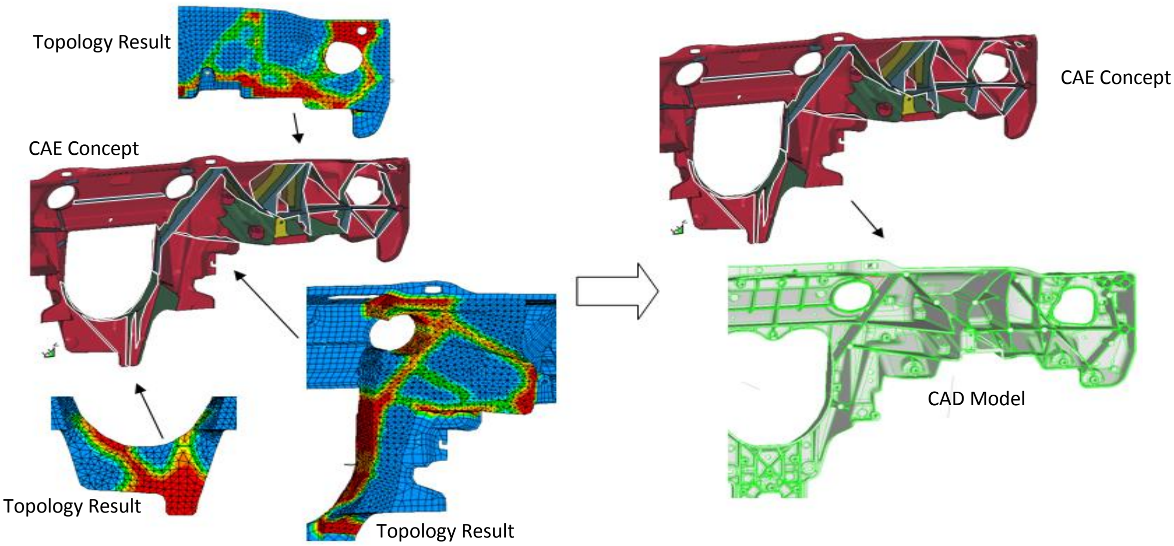



Figure **10** – Initial topology runs done at concept through to final production

Figure 11 – Previous generation Meridian beam

Throughout development, it is inevitable that as the loadcases and package matures that the design will need to change. When this happens the same optimisation tools can and should be used. One such iteration is now discussed as an example of this.

The R56 beam in an interim stage of development was 4.81kg and met all the required loadcases. An optimisation sweep was then carried out on this beam using the following steps; local topology runs were performed to redefine specific areas of ribbing as shown in Figure 12, a topometry run was performed to highlight which areas needed to be reinforced or could be reduced in section, and finally, a topometry run was performed to highlight any areas where mass-saving holes could be introduced, as seen in Figure 13.

Figure 12 – An example of a local topology run

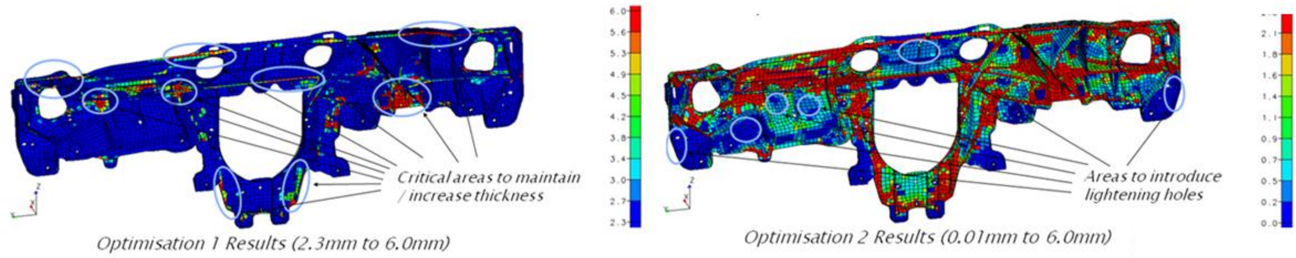



Figure 13 – Topometry runs

The resulting beam still met all of the required loadcases but the mass was reduced to 4.49kg. Thus mass was reduced by nearly 7% whilst crash performance and NVH performance remained unchanged.

**6. CAE Led Design in the Product Lifecycle**

The use of CAE early on in the development of Meridian's products has significant effects on the product lifecycle in terms of reducing development time and costs, of both concepts and final designs, especially when compared to a more traditional CAD led approach. This is particularly important when developing concepts, since it is becoming more and more common for OEMs to expect suppliers to offer conceptual designs when quoting for business, carried out at the suppliers' risk. Also, once the business has been secured, by using these techniques, development times are reduced, helping OEMs to get products to market quicker and the final designs will be as light and cheap as possible. All of this, results in cost savings for both the supplier, the OEM and ultimately the final consumer.

These benefits are a direct result of the early use of CAE optimisation. As stated by Vanderplaats "Optimization will improve the quality or reduce design for any system, subsystem or component to which it is applied"[2]. All of this is achieved at very little expense as the "benefit will exceed the cost" [2] and give companies who use optimisation tools, a competitive edge over companies that do not employ such techniques as "the companies that strongly embrace this technology will have a clear competitive edge for the betterment of all"[2].

To fully understand this we will now compare a traditional CAD led design to the CAE led designs that are carried out by Meridian in Figure 14.

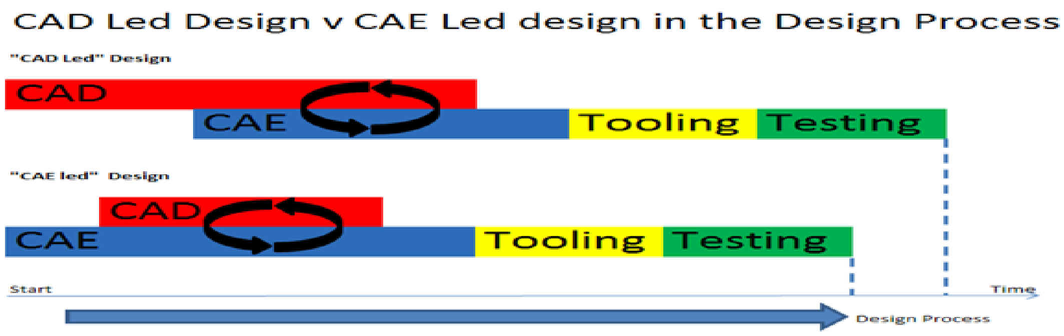



Figure 14 – Comparison of a CAD led design to a CAE led design

In a traditional CAD led design, a concept is first produced in a 3D CAD package. Once an initial design has been developed, CAE is used as a verification tool, as Vanderplaats states, "we normally use computer analysis to judge the quality of our designs"[3], not to actually design the parts. Results of this analysis are fed back to the designer, the CAD is updated and a new CAE model is built and this process is repeated until a final design is reached and verified. Once the structural performance of the design has been proved, prototype tooling is produced, and finally prototypes are then cast and tested. Although the use of CAE in judging designs has significantly reduced the product lifecycle time by minimising the amount of prototypes needed, as supported by Schramm when he wrote that "Physical experiment has been widely reduced or eliminated to be replaced by computational methods"[6] there are however, significant opportunities to further reduce the time taken to develop a design by utilising optimisation techniques.

Leiva summarises CAD led designs when he says "The design of many of these objects has been done over the years based on judgement, experience of history. Structural analysis to study the behaviour of parts has only been used in the last few decades, optimization has been used even less"[8], and it is by introducing optimisation techniques that the change from CAD led designs to CAE led designs can be made. When describing current design processes Schramm stated that "Simulation can now keep up with design changes and therefore drive design decisions"[6], but by introducing optimisation techniques, the CAE model should not only keep up with design changes, but should actually lead the design.

In a CAE led design, such as the type used by Meridian, the design process can be summarised as follows. The initial design is developed in CAE using optimisation techniques thus ensuring the major loadpaths are used. From this a CAE model can be built and hence the design can be verified - all of this can be achieved before any CAD needs to be created. Once an initial concept has been created and proved, CAD can then be produced. Inevitably there will still be iterations once the initial concept has been developed as the design matures. There is still, therefore, a feedback loop. This results in a final design that is verified before prototype tools are cut and prototype parts are produced and tested. As can be seen in Figure 14 this results in a shortening of the design process time.

The benefits of CAE led concepts also give significant benefits to Meridian. To demonstrate this we will consider the concept design process, in order to show the impact on timing and cost. To do this, we will make the following assumptions;

- Timing Assumptions
  - The time taken to produce the initial CAD in a 3D CAD package takes 6 man weeks which is typical given the complex nature of Meridian's parts which have draft, fillets and ejector bosses etc.
  - To produce an initial concept in the CAE environment including a topology study, topometry study and structural assessment, takes 2 man weeks
  - To carry out a structural assessment of a design takes 1 man week
  - A CAD led approach requires 2 iterations to achieve acceptable structural performance
- Cost Assumptions
  - We will assume that for these concepts all CAD and CAE is outsourced
  - The hourly rate of a CAE analyst is £45/hour (based on 2007 Prices)
  - The hourly rate of a CAD analyst is £35/hour (based on 2007 prices)
  - A working week is 40 hours

Using these assumptions we can now compare the cost and timings of a CAD led design and a CAE led design as seen in Figure 15.

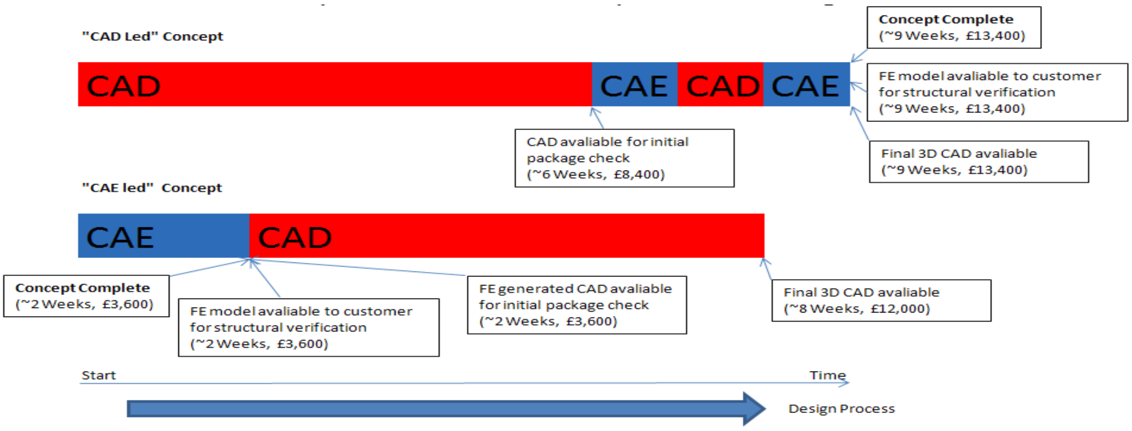



Figure 15 – CAD led concept v CAE led concept in design process

In the CAD led concept, initially a 3D CAD model is produced which takes 6 man weeks and costs £8,400. Once this has been done, initial CAD can be provided to the customer for an early package check. This design is then assessed in CAE and then goes through an additional design iteration before the concept is complete resulting in the following (Note that most of the deliverables are at the end of the design process);

- CAD is available for an initial package check after 6 man weeks and £8,400
- The Final FE model is available to prove the structural performance after 9 man weeks and £13,400
- The Final 3D CAD is available and the concept is complete after 9 man weeks and £13,400
- The geometry and weight of the component is known, and can thus be costed, after 9 man weeks at a cost of £13,400

In comparison, the CAE led design creates a concept purely in the CAE environment within two man weeks at a cost of £3,600. From this a simple surface CAD model can be produced and delivered to the customer for an initial package check. In addition, the FE model can be delivered to the customer to prove the structural performance of the structure. Once the customer has seen this concept and if, and only if, they are still seriously interested in the concept, then the expense and time of producing a 3D CAD part is incurred, resulting in the following deliverables (Note the deliverables are now much earlier in the design process);

- The initial concept is complete after 2 man weeks at a cost of £3,600
- The FE model is available to the customer to prove the structural performance of the concept after 2 man weeks at a cost of £3,600
- A simple surface model is available to the customer for an initial package check after 2 man weeks at a cost of £3,600
- The geometry and weight of the component is known, and can thus be costed, after 2 man weeks at a cost of £3,600
- The Final 3D CAD can be delivered to the customer after 8 man weeks at a cost of £12,000.

As can be seen in Figure 15, by using CAE led design, as opposed to CAD led design, Meridian has achieved the following; Conceptual designs are delivered with reduced cost and timing by approx 75% when 3D CAD is not required, and 10% when 3D CAD is required. The CAE led approach is likely to result in lighter and cheaper conceptual designs, and is therefore more likely to secure new business. Finally, production designs are likely to be lighter, cheaper and more efficient.

In addition to the quantifiable benefits highlighted above, there are also the unquantifiable benefits of improved customer perception of Meridian Technologies advanced engineering capabilities, improved customer confidence in Business Development quotes when quoting for business, and improved customer perception of magnesium and its capabilities.

In a year when Meridian are aggressively pursuing new business they may undertake up to 30 conceptual studies and of these, approximately 10% would be of enough interest to potential customers to warrant full 3D CAD to be generated. Thus these CAE led concepts would cost as follows;

| | | |
|---|---|---|
| CAE studies | 30 x £3,600 | = £108,000 |
| 3D CAD | 0.1 x 30 x £8,400 | = £25,200 |
| **TOTAL** | | **£133,200** |

If these studies were all traditional CAD led designs then the cost would be as follows;

CAD led studies 30 x £13,400 = **£402,000**

Thus a direct saving of over 66% or £268,800 can directly be attributed to using optimisation techniques. This is a significant saving, particularly as these concepts are nearly entirely unfunded by the customer.

## 7. Conclusion

This paper has used Meridian as an example to show how optimisation can be routinely used in the design process. Furthermore, based on Meridian's successful implementation of the tools of topology, shape optimisation and topometry into their design process, the paper argues that optimisation is not simply an option to consider as part of the design process; rather, the evidence presented suggests that it is a necessity, given the benefits it produces in terms of cost, productivity and, ultimately, environmental benefits such as reduced materials usage and fuel consumption. These tools are used right from the start of the design process for conceptual designs and then throughout the development of any products right through to production. It has been shown that these tools reduce the time taken to produce fully matured designs.

When considering conceptual designs, costs are reduced by up to 75%, which is particularly relevant since OEMS are increasingly expecting suppliers to provide conceptual designs at their own cost. These conceptual designs result in faster generation of more efficient and lighter products, which are more likely to result in securing new business.

The optimisation tools used by Meridian are routinely available, yet remain remarkably underutilised. As Vanderplaats argues, "the key to their use is that we must change the way we do design. The changes are not big, only necessary"[3]. This paper has attempted to demonstrate the validity of Vanderplaats' argument and has illustrated both the manner in which optimisation may be used to drive the design process, and the benefits that accrue as a result.

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