MSC/CONSTRUCT - Topology and Shape Optimization of Large Real World Structures using the distributed parallel MSC/NASTRAN

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1. Introduction

In the tough international competition, companies can only survive if, besides highly innovative power, they can provide strongly cost optimized products. Therefore in new procedures like the Simultaneous Engineering the calculation engineer is already integrated in the concept phase of the product development process. Efficient methods of working require powerful optimization algorithms to be provided in addition to the discrete methods (FEM/BEM) that proved worth while to support the calculation engineer in the draft and design phase (see Figure 1). Almost all FEM codes have integrated sizing optimization capabilities to support the calculation engineer.

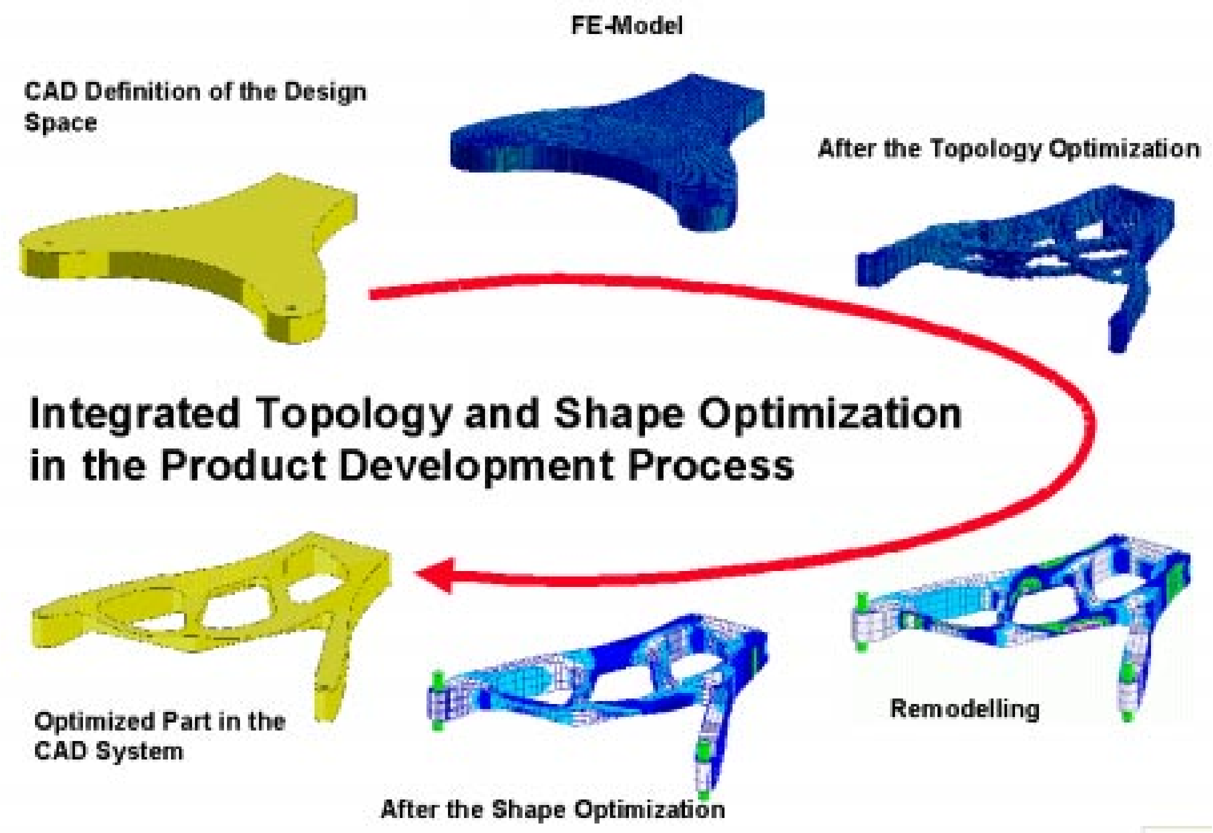

Figure 1: Topology and Shape Optimization in the Product Development Process

In this context new optimization criteria and control strategies for sizing, shape and topology optimization were found at the Institute of Machine Design of the University of Karlsruhe, Germany, in 1991. Based on these new strategies the computer program CAOSS (Computer Aided Optimization System Sauter) was developed at the institute in cooperation with FE-DESIGN, Karlsruhe, Germany. In 1994 the program was awarded the European Academic Software Award by the European Commission, DG XIII, to be the best program in the field of mechanics. This formed the basis for the product which is now known as MSC/CONSTRUCT with it's options TOPOLOGY and SHAPE and is licensed to MSC on a worldwide basis since 1997. An important step forward was the integration of MSC/CONSTRUCT within the MSC/PATRAN environment.

For both sizing and shape optimization a first design proposal, which is used as the start design, must exist. The objective of general structural optimization methods, such as topology optimization, is to provide even this first design proposal. The designer creates only the design space which includes the future component. Subsequently the functionally required boundary conditions are applied. The efforts for the modeling and preparation are extremely low. The optimum structural shape with the appropriate topology is calculated utilizing a FEM program and issued as a design proposal which might be refined by the designer.

Compared with the sizing and shape optimization the numerical efforts of this iterative process strongly increase. Therefore currently only components with 15.000 to a maximum of 30.000 elements could be calculated, even when using powerful workstations. Due to the high number of iterations (typically between 20 to 30 iterations) and the fact that approx. 90 to 95% of the CPU time is used by the FEM program for the analysis, the performance and the resource requirements of the FEM program are of particular importance.

For the last two years certain FEM solvers (like MSC/NASTRAN) were ported to hardware platforms with distributed memory. Using those, a considerable reduction of the price/performance ratio combined with impressive speedups was shown for the parallel code. This facts make the utilization of these codes interesting to industrial users. Within the HIPOP (**HI**gh **P**erformance **OP**timization) project the coupling of the distributed parallel MSC/NASTRAN (PMN) and MSC/CONSTRUCT was realized.

The benchmarking of real world applications from companies like BMW, PININFARINA, AUSTRIAN AEROSPACE and FE-DESIGN showed the reliability and efficiency of the approach. Even for models far beyond 200.000 degrees of freedom and with a number of load cases speedups of 3 to 4 were achieved on 8 processors.

2. Applied Software

2.1 MSC/CONSTRUCT SHAPE Optimization

Using shape optimization methods with a parametric approach as implemented in the most FEM programs the number of design variables must not be too large. This causes the numerical efforts to increase drastically due to the nonlinear increase of the calculation of the sensitivities. Therefore with these approaches, models with more than 200 design variables begin to incurr significant numerical overhead. The control algorithms with mechanical knowledge, which are implemented in the shape optimization program MSC/CONSTRUCT SHAPE for linear statics, are independent of the number of design variables ([3],[4],[5]). Therefore they allow a high number of design variables.

Thus real world models can be handled in industrial applications. Also the high number of design variables is advantageous for the higher flexibility of the solution, e.g. the creation of optimal structures which would not be possible with a restricted parametric approach.

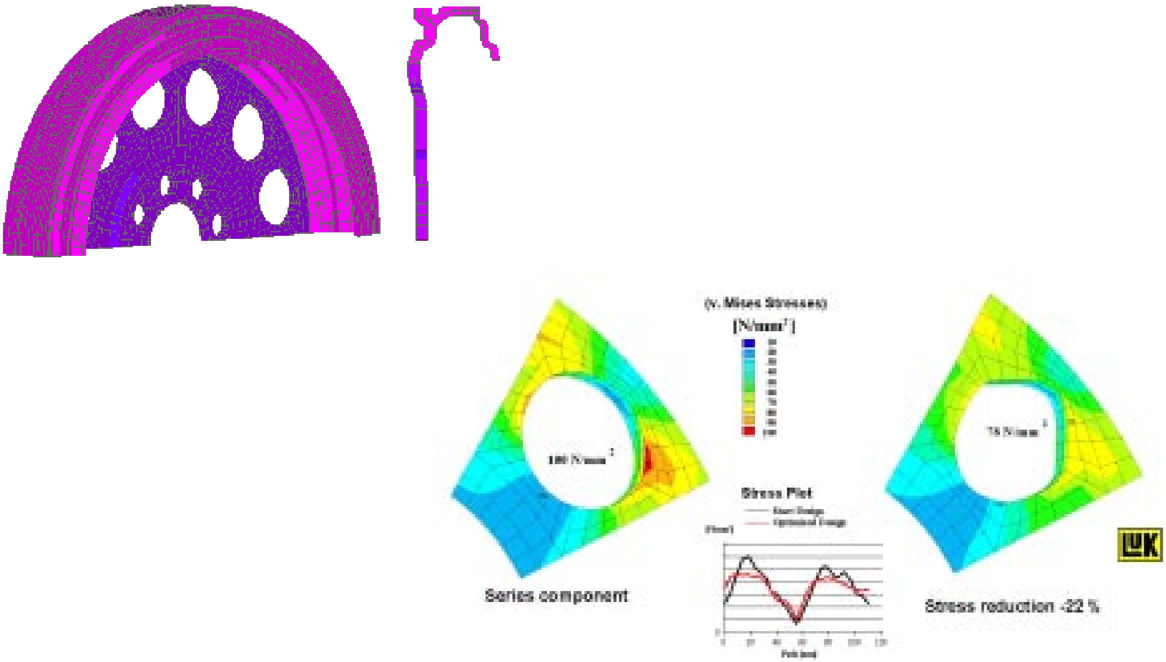

Figure 2: Shape Optimization of a Flywheel

The pictures show a 10.000 element 3D model of a primary flywheel clutch (see Figure 2). The evolution from a cylindrical geometry of the bores to a more complex geometry which fits optimal to the loads and boundary constraints is obvious. This solution would be gained using a parametric approach only with extreme efforts.

To meet productional and functional requirements appropriate functionalities were implemented in MSC/CONSTRUCT SHAPE.

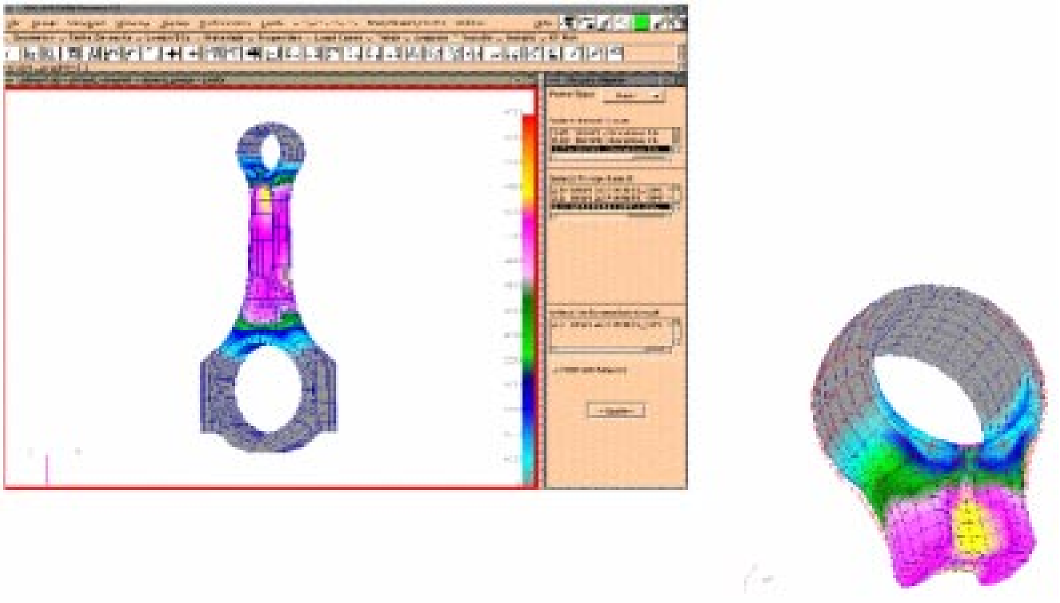

Figure 3: Postprocessing of a Shape Optimized Connecting Rod

A further benefit of MSC/CONSTRUCT is, that its preprocessing and postprocessing is fully included in MSC/PATRAN. Therefore the model setup capabilities provided from MSC/PATRAN can directly be utilized for the definition of the optimization model. The look-and-feel of the user interface is in MSC/PATRAN design which on the one side maintains the user in its known environment and on the other side guarantees a straightforward introduction to the optimization with MSC/CONSTRUCT.

2.2 MSC/CONSTRUCT TOPOLOGY Optimization

Topology optimization is the latest type of optimization for the area of mechanically loaded components. With topology optimization structural parts are identified which do not contribute to the components behaviour. In other words: In a given design space material is distributed in such a way that under certain constraints specific objectives are met.

Currently there are three main fields where topology optimization is applied:

- The very early design phase, where the design can easily be changed. Here the topology optimization starts from a rough design proposal.
- When potential for reducing the components stresses and weight needs to be identified. Here the topology optimization starts from an already existing design model.
- When parts of an already existing structure are completely redesigned .

As for the shape optimization MSC/CONSTRUCT TOPOLOGY also uses for the topology optimization a mechanical approach ([8],[9],[10]).

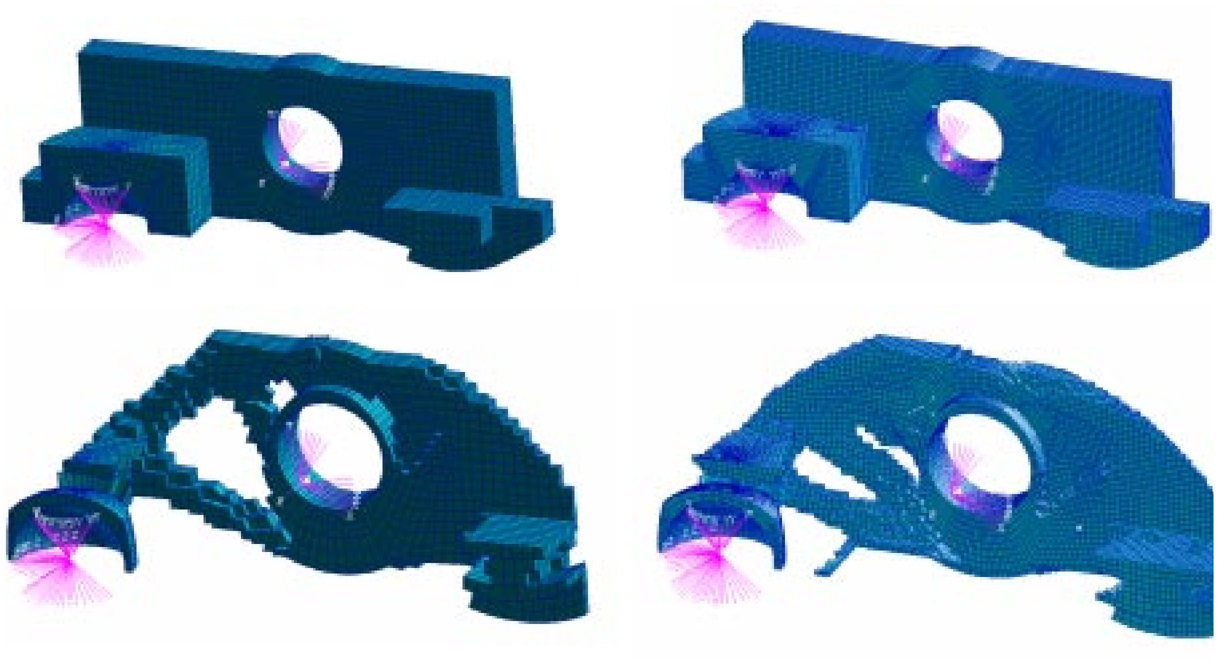

Figure 4: Topology Optimization of a Solid Rocker Arm

Compared with the shape optimization the main difficulty in topology optimization is the extremely high number of design variables in connection with the high number of required FEM calculations (approx. 20 to 30). As seen in Figure 4 the solution depends on the resolution of the initial structure. Therefore even on high performance workstations the model size was restricted to 20.000 to maximum 30.000 elements before HIPOP. Through the implementation of an approach with mechanical knowledge in MSC/CONSTRUCT TOPOLOGY the CPU time requirement of the topology optimization module is only 5 to 10%.

2.3 Parallel MSC/NASTRAN (PMN) Solver Technology

In the ESPRIT III project Europort-1, Porting Work Area Parallel MSC/NASTRAN (PMN), MSC started to port MSC/NASTRAN to distributed parallel hardware architectures. The distributed parallel modules developed in this project are available since September 1997 in the commercial MSC/NASTRAN release V69.2.

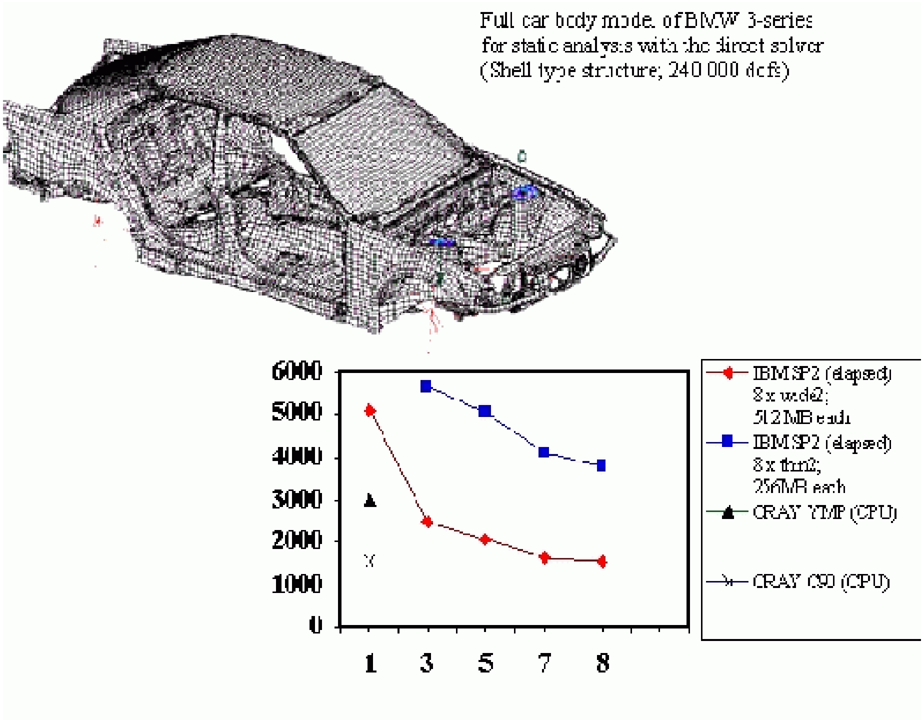

Figure 5: Benchmark from EUROPORT1 (Courtesy of BMW AG and MSC)

On serial computers and for large problems, the numerical solution modules typically require 85% to 95% of the total elapsed time. Therefore, parallelizing just these modules on their own gives a significant increase of performance. This strategy is well suited to giving a good return from moderately parallel systems. By taking this approach, it is possible to gain benefits from parallelization without the need for extensive modification to the code structure.

In the frame of this project a considerable reduction of the price/performance ratio was shown for the parallel code, which makes the utilization of PMN interesting to industrial users.

The speedups shown in Figure 5 are measured only for the solution module itself and do not contain the computing times required for the element stiffness matrix generation as well as for the data recovery.

2.4 HIPOP Sofware

Besides aspects of streamlining the optimization process through adaption techniques, the major task within the HIPOP project was to replace the serial MSC/NASTRAN with the parallel MSC/NASTRAN (PMN).

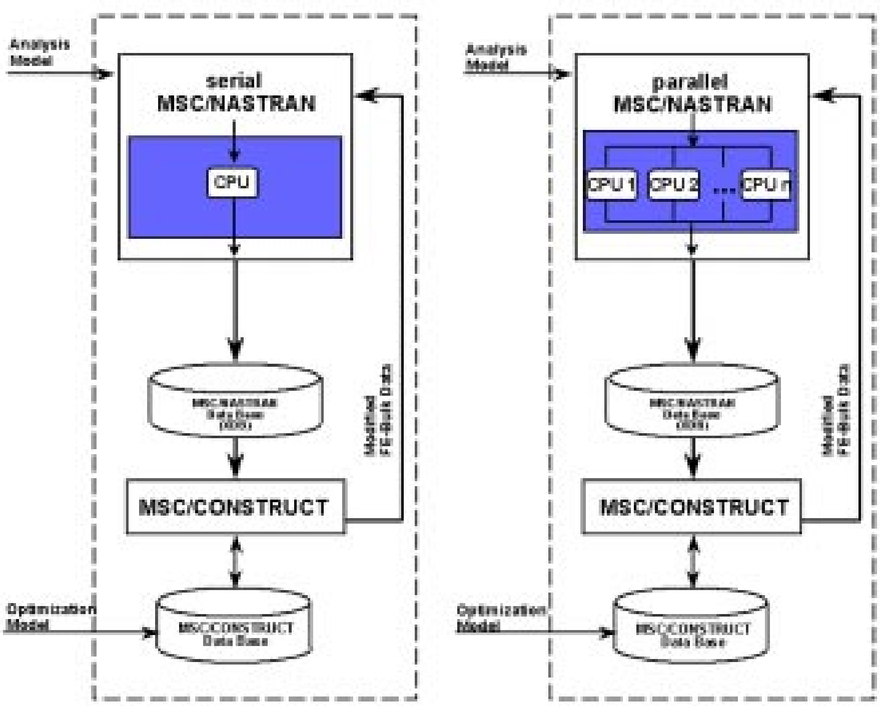

Figure 6: Flow chart of MSC/CONSTRUCT and Parallel MSC/NASTRAN (PMN)

3. The Benchmarking Machine

The benchmarks were executed on an IBM-SP2, located at the Scientific Supercomputing Center (SSC) of the University of Karlsruhe, Germany. This is the currently most powerful IBM parallel computer in Europe. The machine comprises 256 nodes with a total peak performance of 107 Giga Flops, 130 Giga Byte Main Memory and 2.1 Tera Byte disk space.

Figure 7: Scientific Supercomputing Center (SSC) Karlsruhe

3.1 Node Types

The machine runs three types of processors:

- 16 thin2 nodes with 67 MHz Power2 processors:
  These nodes with each 128 MB main memory are used for serving the parallel file system (PIOFS). Each server is connected to 8 disks with 2GB each meaning that a total of 256 GB PIOFS workspace is provided. For safety reasons the data in the PIOFS is currently mirrored, which results in a net capacity of only 128 GB.
- 160 thin P2SC nodes with 120 MHz P2SC processors:
  These nodes are used for the parallel production jobs. Each node has 512 MB main memory.
- 80 wide2 nodes with 77 MHz Power2 processors:
  These nodes have 256 MB, 512 MB or 2 GB main memory. They are used for different applications like server and compute node for serial and parallel batch jobs and for interactive use.

The machine is partitioned into several pools for different requirements. For our benchmarks two homogeneous node pools were available, the so-called ”production pool” and the ”general pool” (FE pool). The production pool consists of 160 P2SC nodes, each of which is equipped with 512 MB local main memory and 2 GB local wide SCSI-2 disks. The FE pool contains 8 wide2 nodes with 2 GB local main memory and 8 GB local SSA disks each. Parallel jobs using a heterogeneous node pool are currently not supported on the machine in Karlsruhe. The theoretical peak bandwidth of the communication network in this machine is approximately 150 MB per second.

3.2 3.2File Systems

The machine runs totally under the control of DCE/DFS (Distributed Computing Environment/Distributed File Systems). This makes the file handling very user friendly as the user has not to take care on which specific disk his data are stored.

Data Management during the Optimization Process

Besides aspects of fast CPUs and large main memory, the I/O and therefore the data flow management is very important for FEM applications. Figure 8 shows the data flow realized with the newly developed control programs for the use of the general and the production class nodes.

The application programs and the model data are located on the DFS-Servers in the User home File System ($HOME). When the user starts the optimization the control program copies the model data to the working directory ($WORK). During the optimization the model data is stored in this file system ($WORK is a Parallel Input Output File System) whereas the temporary data (scratch files) is written to the local disks using the $TEMP_LOCAL environment variable.

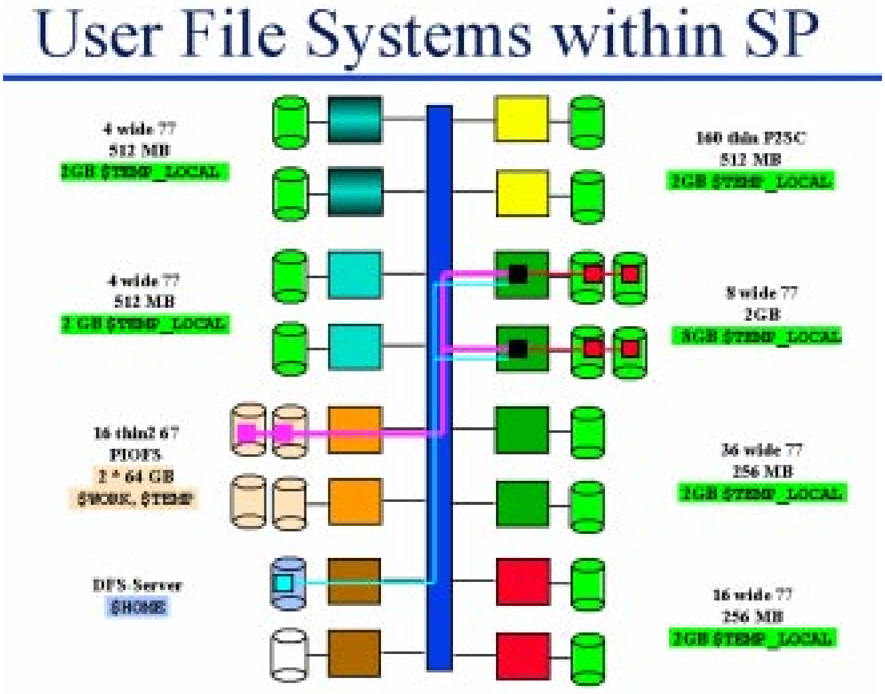

Figure 8: User File Systems within SP

This ensures maximum I/O rates while having a large file system for the data accumulated during the optimization at the same time. During the optimization process of this extremely large structures 20 to 40 GB temporary disk space is easily needed.

4. Topology Optimization with MSC/CONSTRUCT and PMN

The target of the BMW benchmark was to evaluate the use of current topology optimization in the design of extremely large and complex structures. To show this the shell structure of a BMW 3-series car was selected.

In this approach the sheet metal from the wheel housing was completely removed and replaced by solid elements. The topology optimization software should then find the maximum stiffness for a given amount of material which satisfies all 6 load cases. The four different boundary conditions simulate various driving situations, for instance cornering.

To get an adequate resolution for the resulting structure an extremely fine mesh is required. For testing and evaluation purposes firstly the wheel housing was filled with a relatively coarse tetrahedral mesh. This resulted in a model containing 20,718 nodes and 14,821 elements, the shell elements of the remaining structure already counted.

To achieve the required resolution and to simplify the setup of the topology optimization model a second structure was created using the voxel technology. The voxel technology has its origin in the CAD/CAE-world where it is used e.g. to simulate engine maintenance processes. For our purposes it allows a very simple representation of the wheel housing and furthermore voxels are extremely easy to generate.

Like 2-dimensional pictures are printed with simple pixels, any CAD model can be described with the 3-d pendant of the pixels: the voxels. A voxel is simply a small cube with a certain edge length. The smaller the edge length the higher the resolution of the model. The data volume is reduced dramatically (often the reduction to 1 per cent of the original data volume is possible) by transforming the description of volumes, planes and points of the original CAD model to a common voxel model.

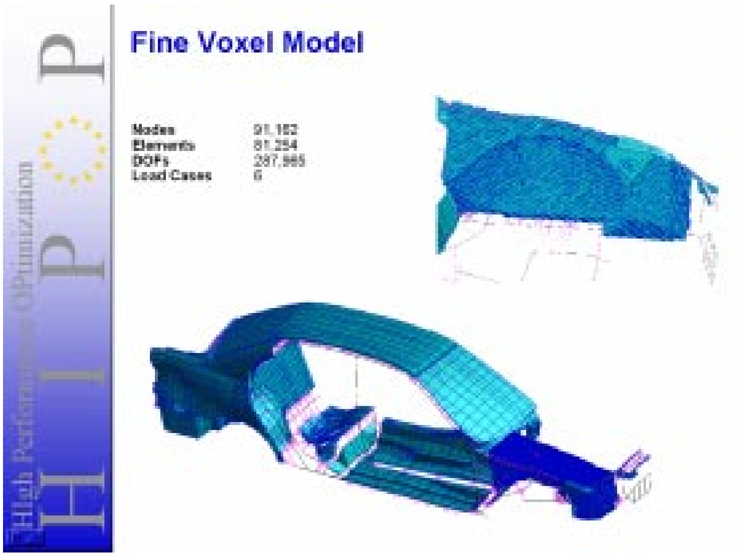

Figure 9: BMW Series-3 Benchmarking Model

The difficulty with voxel-based FE models is that one comes easily to extremely large structures and therefore require high resources. The voxel model generated for the HI-POP project contains 91,162 nodes and 81,254 elements resulting in 287,965 degrees of freedom. This model needs to be solved for the above mentioned 6 load cases with 4 different boundary sets.

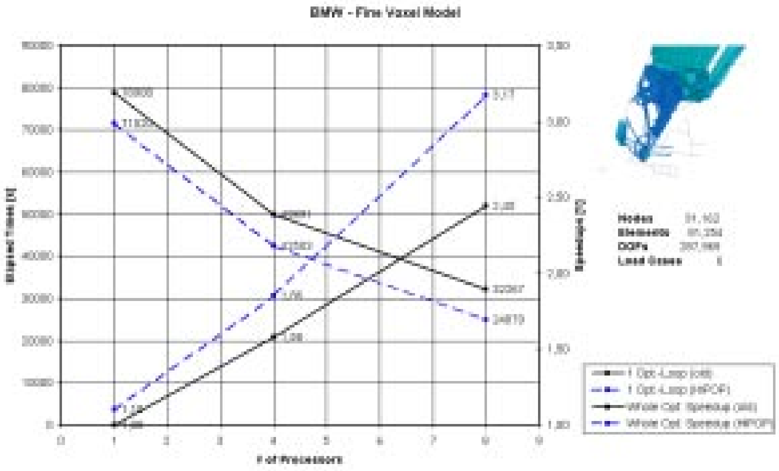

Figure 10: Benchmark BMW Fine Voxel Model

In Figure 10 the resulting elapsed computing times (left axis) and the corresponding speedups (right axis) versus the number of processors are shown.

The data recovery operations were not part of the parallelization and do not scale with the number of processors. This can clearly be seen from the diagram when looking at the elapsed times of the optimization loop. The curve of the times for one optimization loop with the HIPOP improvements is parallel to the one with the initial software (1 Opt.-Loop (old)).

From the diagram one can learn that the elapsed time required for one optimization loop was reduced from 79,000 sec. to 25,000 on 8 processors. That means that the improvements lead to a speedup factor of 3.17.

5. Coupled Shape Optimization with MSC/CONSTRUCT and SOL200

An optimization model is required for an optimization in the same way as an analysis model is required for a finite element analysis. For shape optimization it also covers the statement of allowable shape changes. In the MSC/NASTRAN SOL200 these shape changes are expressed by socalled shape basis vectors ([7] Moore, G.J.: MSC/NASTRAN Design Sensitivity and Optimization, User's Guide, Version 68, 1994). The numerical optimization algorithm than determines the best linear combination of these shape basis vectors.

To set up a SOL200 optimization model one major task is to derive shape basis vectors, which have sufficient influence on the optimization objective and constraints ([1] Raasch, I.; Irrgang, A.: Shape Optimization with MSC/NASTRAN; MSC/NASTRAN European Users' Conference, Rome, 1988,[2] Chargin, M.; Raasch, I.: Structural Optimization with MSC/NASTRAN revisited [3]in Version 66, MSC/NASTRAN European User's Conference, Paris, 1990,[6] Raasch, I.: Structural Optimization with Solution 2001 in the Design Process; MSC/NASTRAN World Users' Conference, Lake Buena Vista, 1994). Because the creation and definition of the shape basis vectors must be made manually, it is time consuming and costly especially for 3D structures.

Other optimization approaches are the optimality criteria procedures like the ones implemented in MSC/CONSTRUCT SHAPE. They often have the advantage to generate the new shape without the necessity of shape vectors. Their disadvantage is their lack of handling arbitrary object functions and constraints. Therefore the idea within HIPOP was to use an optimality criteria for the generation of shape basis vectors and to use the mathematical optimization approach of the SOL200 to fulfill arbitrary objectives and constraint functions.

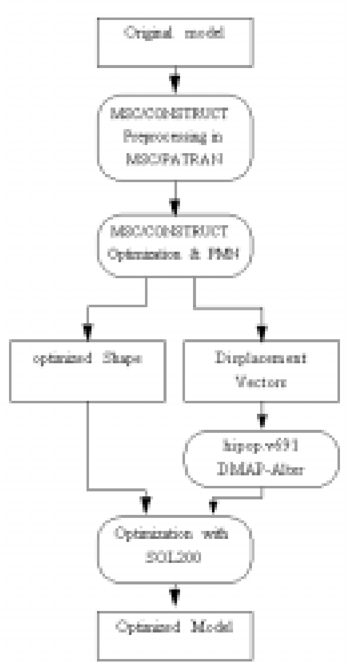

Figure 11: Flow chart of the coupled MSC/CONSTRUCT SHAPE and SOL200 shape optimization.

This idea was realized as shown in Figure 11. The optimization preprocessing was made within MSC/PATRAN. Using the MSC/CONSTRUCT GUI within MSC/PATRAN the modifiable design nodes were defined and the optimization control file was generated. The optimization control file includes e.g. the definition of the objective function, the constraints as well as optional restrictions. Then the nonparametric shape optimization with MSC/CONSTRUCT SHAPE was started. This resulted in an optimum shape and a corresponding displacement vector, which describes the change from the original shape to the optimum shape of MSC/CONSTRUCT. With the hipop.v691 DMAP alter a modal analysis was run providing eigenforms which were then considered to be further shape basis vectors. The above mentioned displacement vector from the MSC/CONSTRUCT SHAPE run and these eigenform shape vectors were the parameters for the SOL200 optimization which was finally started.

This approach of coupling the easy and efficient modeling and optimization using MSC/CONSTRUCT SHAPE with the robust and general shape optimization capabilities of the SOL200 was verified with the crank shaft model shown in Figure 12.

The left plot in Figure 13 shows the displacements through the shape optimization with MSC/CONSTRUCT SHAPE based on the start model. The objective of this optimization was the reduction of the stress levels of the design nodes and therefore the homogenization of these stresses. It led to a new shape of the crank shaft which formed the input model for a MSC/NASTRAN modal analysis for a couple of eigenfrequencies. The corresponding eigenmodes were than considered as further shape basis vectors for the following SOL200 shape optimization which included constraints on the eigenfrequencies.

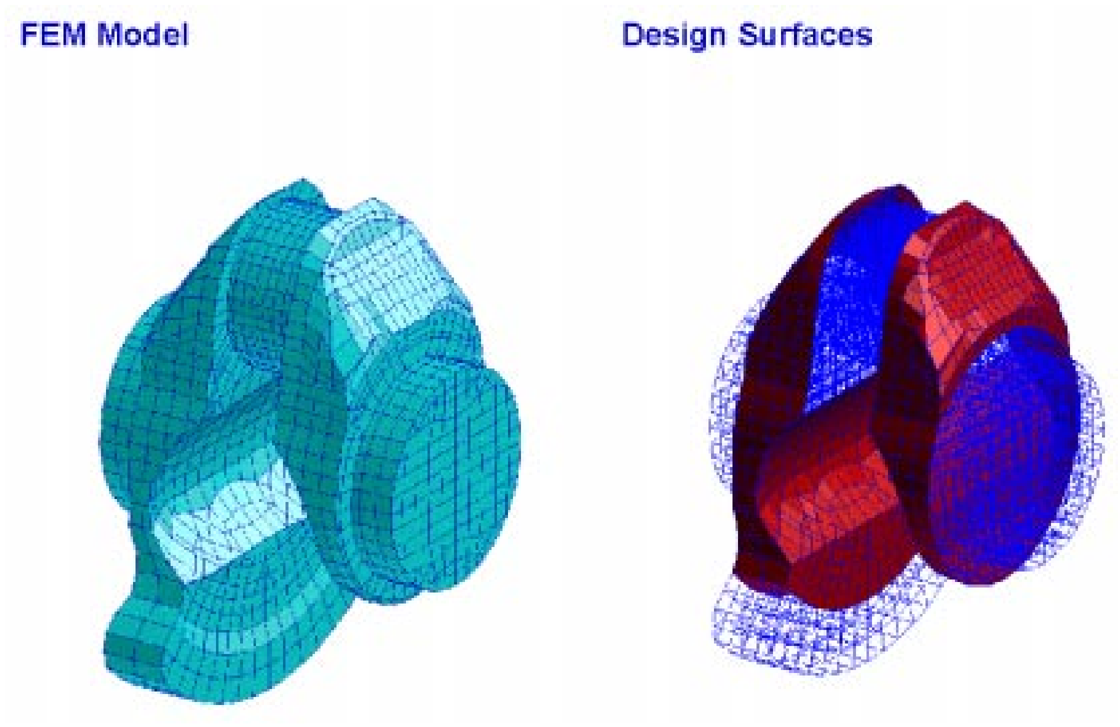

Figure 12: Initial FE Model for the Crank Shaft Shape Optimization (left) and Design Surfaces (right). Courtesy of BMW AG.

Comparing the plots of Figure 13 one may learn that the shape optimization using MSC/CONSTRUCT SHAPE led to a design which was already very close to the optimum design found by the following SOL200 shape optimization. SOL200 then found only minor shape changes.

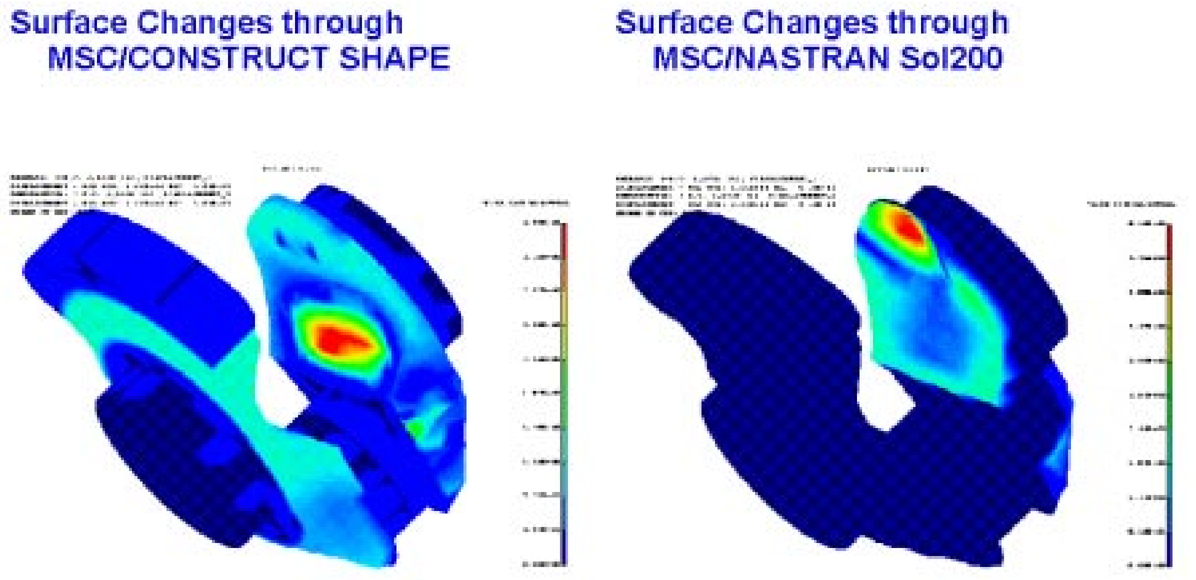

Figure 13: Surface Changes through the Preoptimization with MSC/CONSTRUCT SHAPE (left) and through the following SOL200 Optimization (right). Courtesy of BMW AG.

Besides cutting the preprocessing time from 2 weeks to 5 hours the use of MSC/CONSTRUCT SHAPE led also to a reduction of the computing time for the SOL200 run by a factor of 10. This is due to the fact that running the SOL200 shape optimization based on a good start design reduces the number of required iterations.

The shape optimization using MSC/CONSTRUCT SHAPE and the SOL200 therefore shows the following benefits:

- The generation of shape basis vectors could be performed automatically.
- This process is fully embedded in MSC/PATRAN and easy-to-use.
- The combination of this software resulted in tremendous time savings without losing generality.

6. Conclusion

The work done in the HIPOP (High Performance OPtimization) project resulted in sound improvements of the throughputs. With this software the topology and shape optimization of large real world models is possible and much more important: efficient. With the performance improvements within MSC/CONSTRUCT the speedups of MSC/NASTRAN can directly be applied to the optimization and therefore result in the same speedups for the whole optimization. This was shown utilizing Parallel MSC/NASTRAN (PMN) on a distributed memory machine like the IBM-SP2 applying it to a large test structure from the automotive industry.

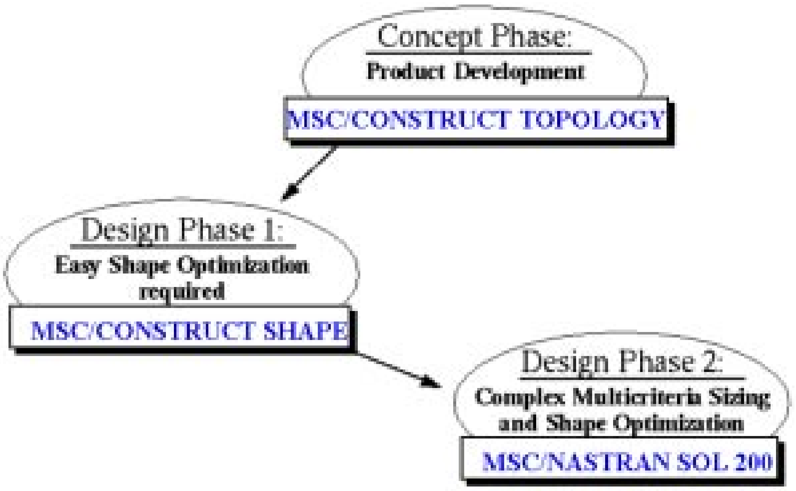

Figure 14: How MSC/CONSTRUCT TOPOLOGY and SHAPE and the SOL200 fit into the product development process.

Combining MSC/CONSTRUCT SHAPE with the SOL200 allows not only the automation of the shape optimization process but also result in tremendous time savings for the preprocessing and for the computing.

With the software modules presented in this article the design engineer as well as the analyst have tools to get clear design decisions throughout the product development process. The use of MSC/NASTRAN guarantee for the robust and reliable results.

The performance improvements and the functional extensions made in MSC/CONSTRUCT will be available with the next release.

7. Acknowledgements

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8. References

8.1 Shape Optimization

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