Automated Multi-Disciplinary Optimization (MDO) Process Development and Application on Vehicle Program

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Summary

This paper – which is based on a recent presentation by Giri Nammalwar et al. to the 2011 SIMULIA Customer Conference in Barcelona, Spain – presents a highly automated process for Multi-Disciplinary Optimization (MDO) of a vehicle program to achieve weight reduction while balancing the performance for Crash, Body NVH, Full vehicle NVH and Durability attributes. The full vehicle automated MDO process development resulted in tools and techniques that provided a significant time reduction compared to the conventional process resulting in a 8 week execution time.

The activity of an automated process development was based on the foundation of scalability and modularity. The focus was to create an automated process that could cut down the amount of resources that need to be engaged on full-time basis for executing an MDO project. The emphasis was to capitalize on the existing technologies for both software and hardware, to enhance the technology as needed and to integrate different tools to fully automate the Ford MDO process. This process was developed to be highly scalable by maintaining the modularity of the software tools and enable seamless integration into Ford's Product Development Process.

In order to test the efficacy of this automated process and to fine tune its requirements, the MDO process was implemented on a production vehicle program. This process relied on CAE models to cut down significant time as it is always easier to incorporate changes at CAE level as compared to CAD. The disciplines identified were Vehicle NVH, Body NVH, Safety and Durability. Critical shapes and sections at A, B, C, & D pillars, roof header and rocker, weld pitch at key locations and 60 BIW (Body in White, i. e. body sheet metal structure) component gages were included as parameters and applied directly on the crash model. These

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parameters were then automatically transposed on to the NVH and Durability models. A DOE matrix spanning the design space defined by the ranges of the design variables was created using the 'Optimal Latin Hypercube' technique. The DOE matrix was used to automatically generate designs which were evaluated using the High Performance Computing (HPC) facility at FORD. The load cases evaluated included several Crash Modi, Bending/Torsion Stiffness, Modal Evaluation, Dynamic Stiffness, NTF and VTF, Idle and Rough road load cases using LS-DYNA, NASTRAN as primary solvers along with some FORD's proprietary codes. Output responses were extracted automatically to generate an Input/Output table. iSight was used to create a Response Surface Model (RSM) fitting all the responses and several optimization scenarios were carried out using the RSM to arrive at a few optimal solutions. The automated MDO process enabled faster turn around to identify optimal designs which resulted in weight reduction while maintaining Crash, Body NVH, and Vehicle NVH performance targets.

Keywords: Multi-Disciplinary, Optimization, Vehicle

1 Introduction

CAE based Optimization techniques and processes have improved dramatically over the past two decades. It is important to understand how optimization technology has evolved during this period in order to appreciate the state-of-art automated MDO process discussed in this paper

1.1 Chronology of Optimization Tools & Techniques Development

In the early 1990s Design Sensitivity Analysis (DSA) techniques were developed to provide insight into which variables were the most sensitive for a chosen output response. However, the variables were limited to structural parameters such as gauge and beam cross-sections, and the output responses were also limited to single load cases. In the mid 1990s optimization techniques were introduced as part of FEA solver procedures and were an improvement over the DSA techniques developed earlier. This was the time when, using Computer Aided Engineering (CAE), the auto industry published the first feasibility study on vehicle crashworthiness, e. g. Yang et al. (1994). During this time there was a focus on shape change by means of topology change of structure.

In early 2000's the first attempts were made to combine multiple load cases as a part of the optimization techniques. Though Box and Wilson introduced the basic framework of developing response surface designs already in 1951, see Rustaji (1994), the DOE and Response Surface Model (RSM) techniques were beginning to be introduced as a means to compute sensitivities of large scale models in a practical manner, see Craig et al. (2002). During this phase several studies were done on the application of Multi-disciplinary optimization (MDO) to automotive vehicle structure design with the focus on High Performance Computing in MDO applications; see Sobieski (2001), Kodiyalam (2002), Hoope et al. (2005).

During that time, shape optimization, using CAD models as the driver of the shape change, was attempted. The challenge was that each time the analyst had to recreate the full vehicle FE model with all its complexities from the CAD data in which shape changes were applied. By this time morphing technology had been introduced. Morphing technology was quickly adapted to generate parametric CAE models by the mid 2000's. Just as its CAD counterpart, parametric CAE models quickly formed the basis for generating multiple design combinations and their associated 'runnable' analysis models in an automated and robust manner.

In the mid and late 2000's integration of Parametric CAE models with DOE and RSM based optimization schemes became more and more commonplace. There were studies that had applied this concept for MDO on vehicle programs. However, it was still time intensive and had limits on the class of variables that could be defined. Due to its time intensive nature it had severely restricted the exploration of design space and thus had a limited contribution to the vehicle development program. The enhanced, automated MDO process developed through this work addressed these challenges and brought the MDO process to the forefront of vehicle development activity.

1.2 MDO in Vehicle Development

Vehicle body structures and sub-systems need to be designed to withstand multi-disciplinary load cases such as Crash (non-linear transient), NVH (frequency domain), Stiffness (linear static), Durability (linear static), Aerodynamics (CFD), etc. The structural requirements to meet loads in one discipline are very often detrimental to requirements for loads in other disciplines. Unless loads from all disciplines are considered simultaneously during the optimization process, the resulting design will not be well balanced for structural performance. With the focus on vehicle fuel economy, carrying out optimization to reduce weight while meeting the performance targets for all the above varied load cases is of paramount importance. Multi-Disciplinary Optimization (MDO) is essential to achieve this objective.

1.3 Challenges in current MDO Process

The inability to adopt MDO as a step in the mainstream vehicle development process stems from the process limitations that have traditionally made the MDO process time intensive. Following are typical challenges encountered during full vehicle MDO exercises:

Parameterization Time: The faster turnaround of an MDO project hinges on the ability to introduce different class of design variables in the full vehicle FE models with all their complexities. Usually these complexities of a full vehicle model counterweigh the faster execution of parameterization activity.

Multi-attribute Model Synching: Once the parameters are defined on any one FE model e.g. NVH FE model, there should not be any need to re-define them for other attribute FE models like Safety FE models. Traditionally the need to recreate these parameters for other attribute models has created a bottle-neck in the MDO process timing. Parameters applied on one attribute model such as a crash model should be efficiently and automatically applied to other attribute models such as NVH and Durability models. If attribute models are ‘synchronized’ then this is achievable.

Design Generation Time: The currently available job submission schemes may do a good job for one design at a time. However automated schemes are required to carry out the same analysis on multiple designs (for example the designs derived through a DOE). Using the parametrized CAE models, runnable analysis models for hundreds of designs need to be generated in an automated fashion.

Computation Time: One of the longest activities in the MDO process is the run-time taken by the solvers. Faster computing facilities with multiple CPUs and associated solver licenses are crucial for completing the analysis within the available time.

Automated Post-processing: There needs to be an automated process for extraction of results from different runs. Post-processing the results from hundreds of jobs without any scripts is a major hurdle to achieve a faster turnaround time for MDO.

1.4 Automated MDO Process Details

The automated MDO process consisted of a set of tools and processes that were used to facilitate faster project turnaround. The major steps of the process include

Model synchronization: Full vehicle safety, trimmed body NVH and durability models are first unified & then synchronized using a proprietary ‘model-sync’ tool from DEP.

Parametrization: One of the unified/synchronized FE models is selected and nominated as the ‘donor’ model. A comprehensive set of shape, section, gage, welding parameters are created on this donor model. These parameters are automatically transposed on all the other attribute ‘driven’ models.

Design generation: A Design of Experiments (DOE) matrix with the Optimal Latin Hypercube sampling technique is generated discretizing the entire design space. Using DEP’s Meshworks, Crash, NVH and durability models are automatically generated for every design point of the DOE matrix.

Job Submission: The generated designs are submitted for analysis in the HPC computing facility using DEP’s Designer Environment. This environment automates the process of job submission after receiving certain basic inputs from the user.

Automated results extraction: FORD’s in-house process of results extraction is integrated with DEP’s Designer Environment to achieve complete automation with minimum one time inputs from the user.

Optimization: The post-processed results are tabulated in the form of an Input/Output matrix where the input is the parameter values and the outputs are the responses. Using the Input/Output matrix, a Response Surface Model (RSM) is generated by fitting all the responses. Using the RSM several optimization scenarios are carried out to pick a suite of optimal solutions.

This entire process can be executed to complete the MDO in 8 weeks. The process flow is shown in Figure 1.

2 Vehicle Program Application

To validate the process and to fine tune the requirements, the MDO process steps were implemented on a current vehicle program. As a first step, a cross functional team consisting of Design and Release Engineers, Attribute Development Engineers, Attribute CAE Engineers and DEP engineers was established. The cross-functional team selected the critical load cases to be included in the study along with important design variables and the output responses to be monitored. Also, team decided on which design level model to use for the study.

The team decided to select all the design variables from Body Structure, however, the process is flexible enough to include Chassis and PT components as design variables. For this study, Body NVH and Durability models and Safety CAE models of a particular design level was used. These FE models were run through a synchronization tool which got all the attribute models to the same design level.

During this time there were active interactions with different attributes to identify the donor model for any part that had a design content mismatch. Once the synchronization was completed, the design variables were created on the safety FE model. The design variables included different class of variables like shape, welds and gage. Figure 2 describes some of these design variables. These variables were only created once on one of the Safety FE models. This safety model then became the donor model for providing the design variables to the other FE models like trimmed body models, body-in-prime models, durability models and models for other Safety load cases. One donor model was able to provide 6 other models in this project. This limit on the types of models generated through the donor was imposed by the scope of the project but the process was completely scalable, without any restrictions on the total number of attributes that could be handled simultaneously.

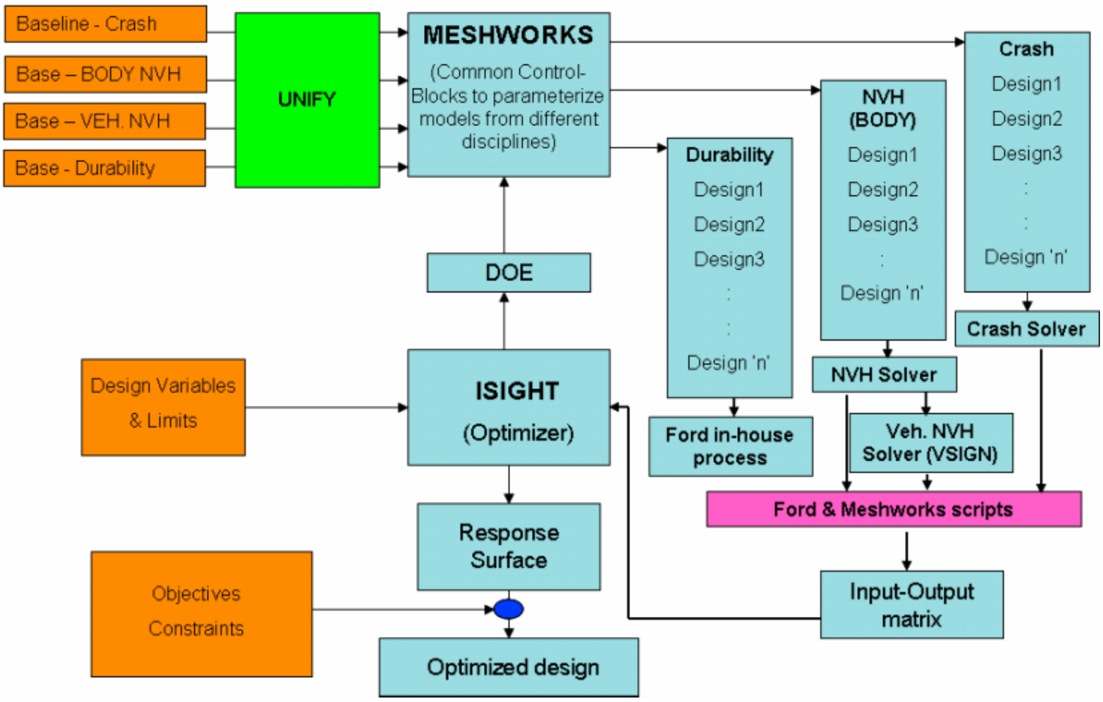

Figure 1. Process flow for Automated MDO Process

Simulia's iSight was engaged to discretize the design space using the Optimal Latin Hypercube algorithm. The discretization resulted in a DOE matrix which was directly readable into Meshwork as it is a neutral code that can be plugged into different optimizers. DEP's Meshworks was used for design generation. The design generation was done in batch mode using the down time of the machines i.e. nights and weekends in Ford North America. Different machines were engaged to get maximum parallelization of hardware resources during the design generation activity. In total there were about 3000 runnable models generated in batch mode through this process.
These generated designs were submitted to Ford's High Performance Computing (HPC) cluster in batch mode using DEP's Designer Environment which was

seamlessly integrated with Ford's internal job submission process. This environment was developed to submit the jobs in batch mode such that machine's down time could be utilized for job submission activities. There was a tremendous effort put forth by Ford HPC center in load balancing and in providing a turnaround of 3 weeks for app. 3000 jobs. Results of these 3000 jobs have been processed in an automated batch processing mode to eliminate/minimize user interface. There were close to 100 responses that were post-processed in the form of ASCII tables. Some of the FE models used are as shown in Figure 3. A sample response curve is shown in Figure 4. Data is masked for confidentiality.

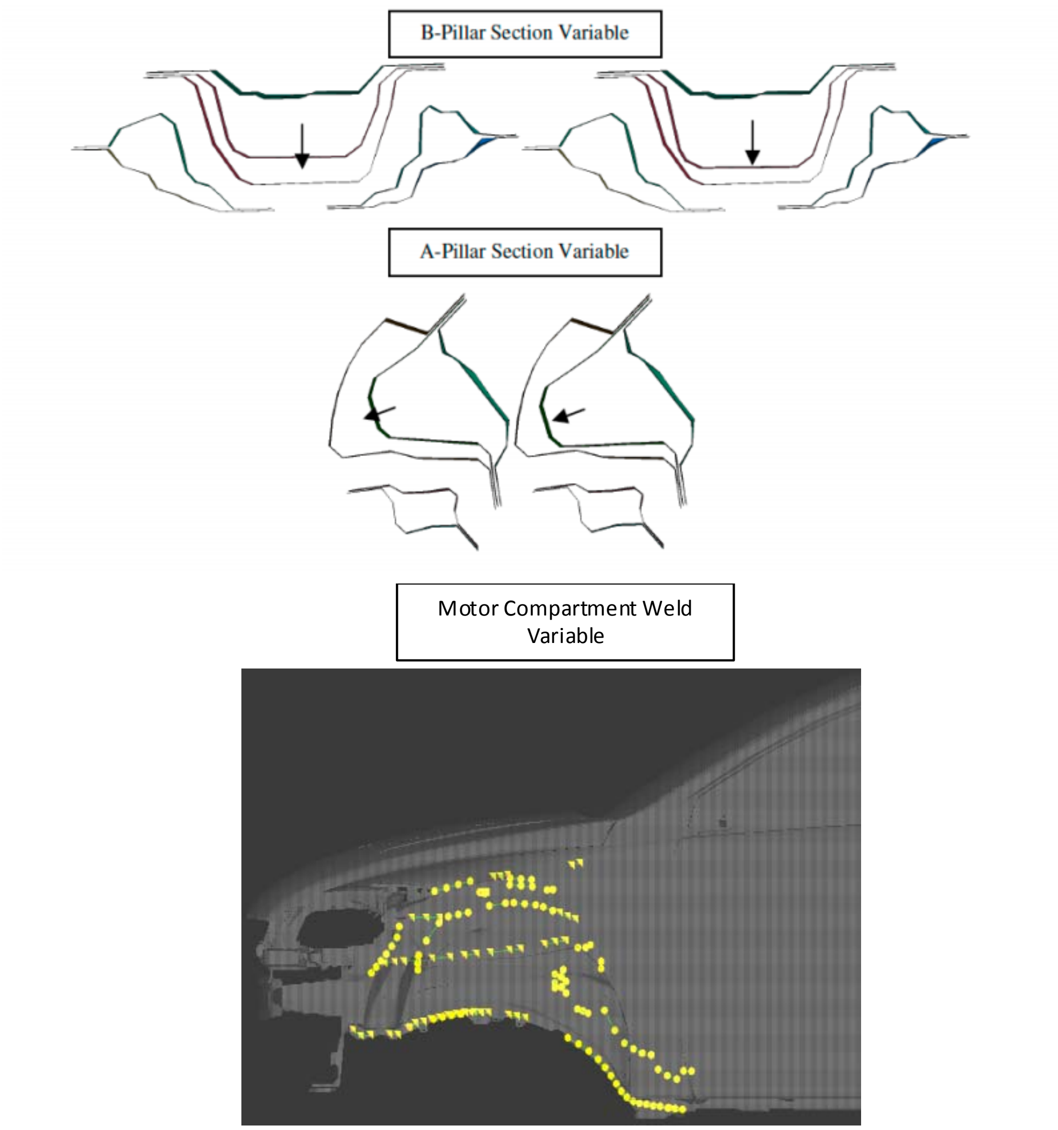

Figure 2: Design Variables

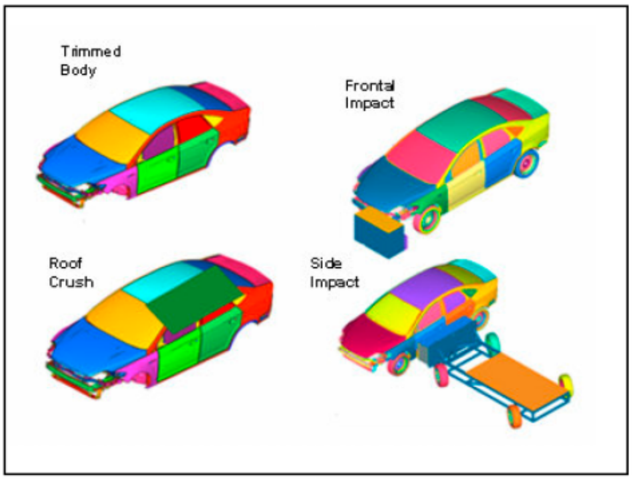

Figure 3: Types of FE Models

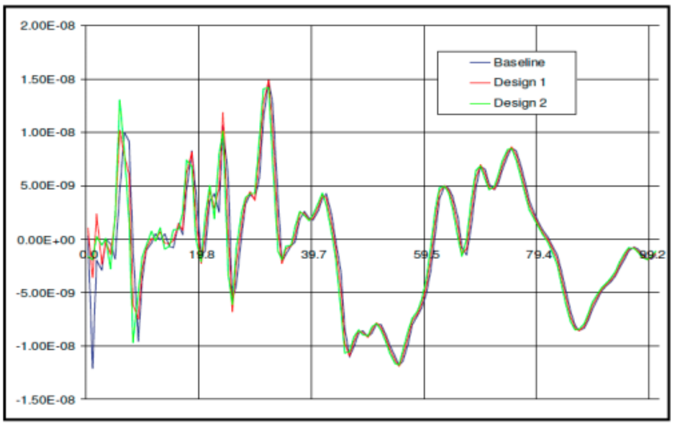

Figure 4: Sample CAE result curve

It is a well known difficulty to define (single number) metrics for response curves as shown in Figure 4. Quality of any subsequent analysis as well as of optimization itself is heavily depending of proper selection of these metrics

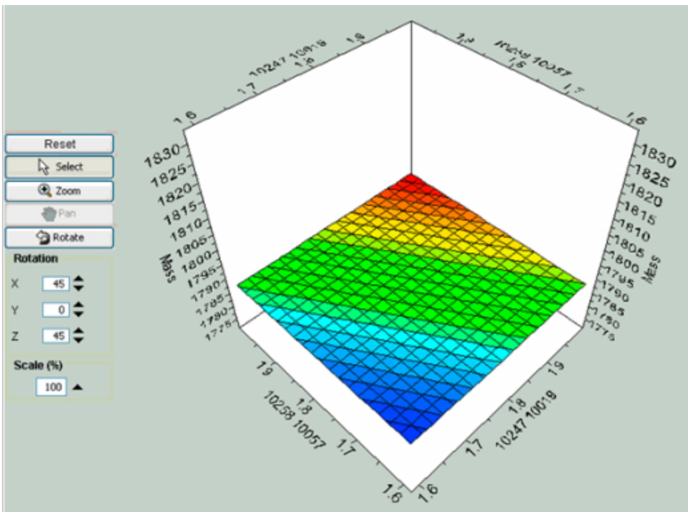

Figure 5: Sample Response Surface

I/O tables generated using DEP's Meshworks were used as an input to Simulia's iSight to generate different response surfaces. A sample response surface plot is shown in Figure 5, a sensitivity plot obtained from response surfaces is shown in Figure 6.

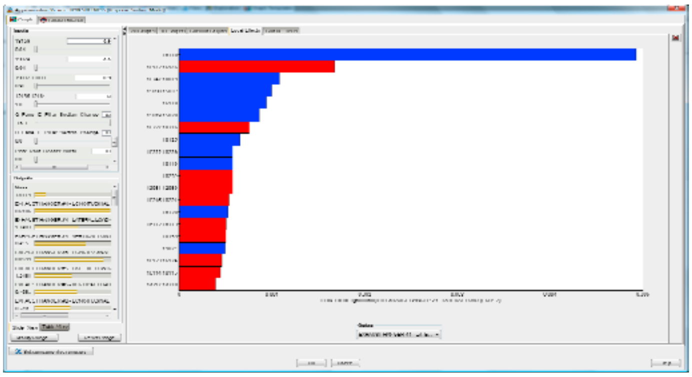

Figure 6: Sample Design Sensitivity Chart

Response surfaces were used for Optimization. Different optimization schemes were used and tradeoff studies were done to evolve optimal designs. The total work flow is shown in Figure 1. These tradeoff studies had to be done due to large number of responses that were leading to an over constrained optimization problem. A cross-functional team was actively involved during this phase of the optimization study to identify all the critical constraints in order to reduce the total number of constraints.

Once the optimal design solutions were available, confirmatory runs were done to verify the results. The optimization resulted in approximately 2.5 kg of weight saving along with an optimum weld pattern recommendation for Engine compartment

3 Conclusions

The core team developed an automated MDO process and applied it on a vehicle program to realize approximately 2.5 kg of weight savings. During program execution, the team addressed many of the challenges that exist today in a traditional MDO process by leveraging the current technology and by developing tools to seamlessly integrate all processes to achieve execution time and resource reductions. The tools and techniques developed during the execution of this project and the process improvements achieved enable MDO to be executed several times during the product development phase i.e. during the early stages of the product development with a focus to optimize and develop the overall architecture, during the platform development phase to optimize the underbody components and finally during the tophat development phase to optimize the upperbody components. The tools developed as part of this study are currently used by FORD engineers to automate MDO tasks. This process is highly scalable to include additional attributes, load cases or design variables.

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