

# Multidisciplinary Design Optimization of Vehicle Weight Reduction

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## ABSTRACT

Multidisciplinary Design Optimization (MDO) is often required in aircraft design to address the multidisciplinary feasibility issues due to the disciplines, for example, aerodynamics, propulsion, and structures, are heavily coupled. However, in automobile designs, can we apply different type of MDO decomposition originated from aircraft design, to some MDO problem, for example, a vehicle weight reduction example? Also, to effectively and efficiently accommodate design changes, multi-party collaboration between discipline specialists, and fast decision making, a web-based MDO platform with knowledge-based repository for resource sharing, capability of version control, and enhancing data security, is very much needed. Two types of MDO decomposition: All-at-Once (AAO) and Collaborative Optimization (CO) are formulated for the weight reduction example. A typical six-step MDO process, from building single discipline work flow to comparing optimization results, is illustrated step-by-step.

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## INTRODUCTION

In automotive industry, vehicle weight reduction is critically related to the cost and quality of vehicle. The weight reduction in general simultaneously affects engineering disciplines such as NVH and safety compliance, MDO therefore comes into the picture, and also brings along great challenges: firstly, MDO problems in automotive industry usually involve large number of design variables, large number of design constraints, and computationally expensive CAE simulations. Secondly, MDO often requires single domain/discipline specialists to build their single discipline work flows, followed by MDO experts decompose coupled disciplines with different formulations, therefore any changes made in single disciplines should be tracked and recorded in some version control system, so the MDO work flows can accommodate the changes easily. Thirdly, when MDO problems become large scale and heavily constrained in terms of number of design variables and constraints, optimization may not be able to find feasible designs at all. Therefore, post-processing approaches of how to identify best infeasible designs, or some methodical way of constraint relaxation is needed to share meaningful results forward to upper management. Finally, upper management may prefer to access the resultant charts conveniently such as through an internet browser, anytime, anywhere in the world.

In this paper, a web service oriented, collaborative MDO platform (called SOMO), used together with a Process Integration and Design Optimization (PIDO) desktop tool is used to conduct a

comprehensive MDO study, on a 2001 Ford Taurus model from the National Crash Analysis Center (NCAC). SOMO addresses the aforementioned challenges by offering project sharing, version controlling, and online data analysis/charting of MDO results. Two MDO formulations, AAO and Collaborative Optimization (CO) are implemented and compared on the weight reduction problem of the 2001 Ford Taurus model. The objective of this MDO study is to minimize the vehicle weight with 49 components' thickness being considered as design variables. Within those 49 design variables, 21 of them are selected as common design variables across both safety and NVH disciplines. There are in total 11 design constraints corresponding to NVH and safety (IIHS and NCAP) regulations. Both AAO and CO formulations are run through the web-based platform, results are then compared and discussed.

## MULTIDISCIPLINARY DESIGN OPTIMIZATION IN VEHICLE WEIGHT REDUCTION

The original MDO related study can be traced back to Sobieski's work in early 1980's, in which he used a linear decomposition approach to subdivide the design of a large engineering system into a grouping of related and more manageable subsystems [1]. Since then MDO related researches have blossomed, especially in the aerospace industry, with the emergence of different decomposition approaches of multidisciplinary problems, such as AAO [2, 3], Multiple-

Discipline-Feasible (MDF) [4], Individual-Discipline-Feasible (IDF) [1, 4], Concurrent subspace Optimization (CSSO) [5,6], CO [7, 8], etc. While these decomposition approaches are quite applicable for those heavily coupled disciplines, for most vehicle design problems, especially the weight reduction problems, the formulations of AAO, MDF, and IDF become identical, and decomposition using CSSO is not necessary, except for the CO formulation, which becomes simpler but still holds in place. This is because unlike the aircraft design problems, where for example the subsystems of aerodynamics, propulsion, and structures are heavily coupled since output variables of some subsystems become input variables to one or more subsystems in a non-hierarchical fashion, the MDO of vehicle weight reduction problems share input variables only. Similar to the CO formulation regarding the mathematical formulation, Analytic Target Cascading (ATC) [9] is another viable approach for the vehicle design problems. However it is typically used to solve object-based system optimization problems reside in product development, while CO focuses on discipline-based decomposition and optimization problems [9]. Therefore, in this paper, only two formulations, AAO and CO are compared and discussed. Figures 1 and 2 summarize the typical AAO and CO formulations.

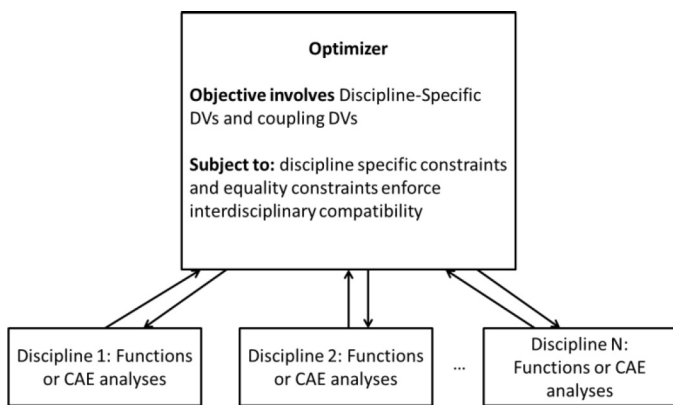


Figure 1. AAO formulation

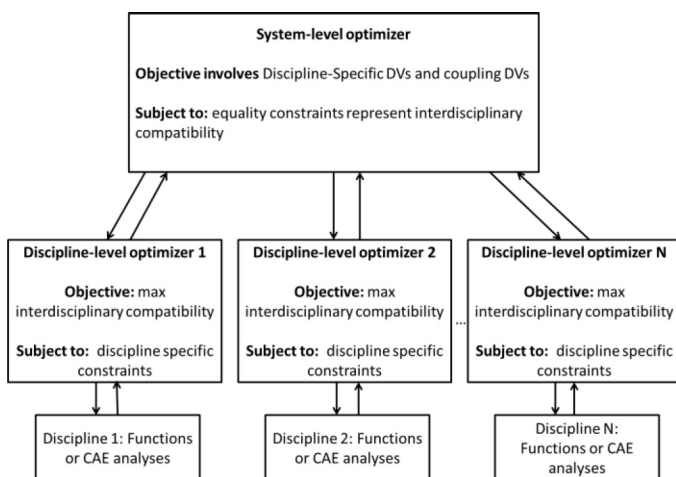


Figure 2. CO formulation

## A COLLABORATION AND DISTRIBUTED EXECUTION FRAMEWORK - SERVICE ORIENTED MULTIDISCIPLINARY ORCHESTRATION (SOMO)

With the fast development of computer hardware and software technology, Computer Aided Engineering (CAE) for product design is used more and more every day, especially for complex product development process involving multiple engineering disciplines. Design optimization is moving from single component level to subsystem and system level across multiple disciplines. Many challenges surface along with this kind of transition mainly to the fact that no one experts in all of the engineering disciplines. CAE analysis, as the foundation of design optimization, still takes significant amount of computational resources and time which often leads to the need of concurrent execution of the design tasks. Although interactions between engineers, managers, and stakeholders are mandatory to ensure the overall consensus of the final product, this could significantly slow down the entire process if too many iterations occur between these parties, or more importantly, the way of communication could be inefficient because of lack of a proper common software platform which facilitates fast design changes and decision making processes. For example, engineers typically would like to organize their CAE models, simulations, and optimization studies in a traceable fashion, such as by version controlling. Managers may want to access the CAE results easily and conveniently so they can make timely decisions. Stakeholders, in a much larger scope, would like to streamline the product design processes, by improving collaboration between teams and organizations, establishing some knowledge-based repository for resource sharing, and enhancing data security.

SOMO [10] is a web-based collaboration and distributed execution framework, which manages and runs multidisciplinary simulations, enforces collaboration with a shared platform for models, work flows, simulations, optimizations, and results. It is developed to address the aforementioned challenges if SOMO is used together with the PIDO tool - modeFRONTIER [11], because work flows which describe the MDO process and data flow are constructed in modeFRONTIER before they are published to SOMO's repository. Figure 3 illustrates an example scenario of collaboration. Figure 4 describes the architecture of SOMO.

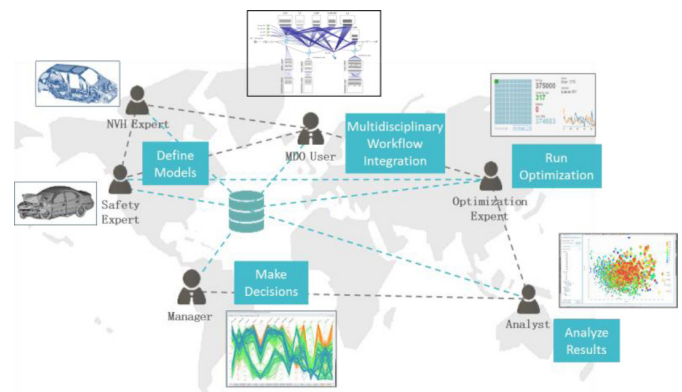


Figure 3. Example scenario of collaboration among analyst, analyst, and manager

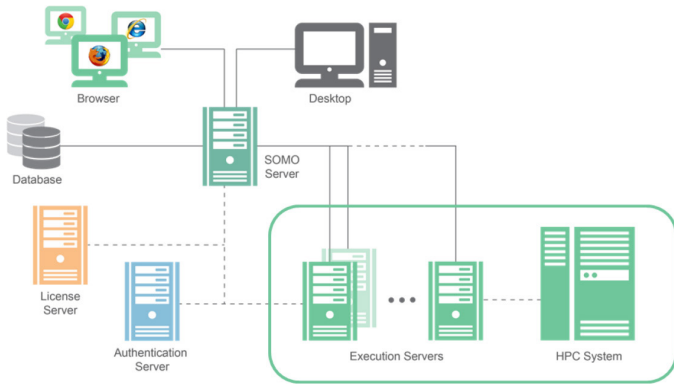


Figure 4. Illustration of SOMO architecture

## MDO EXAMPLE: WEIGHT REDUCTION OF A 2001 FORD TAURUS MODEL

A 2001 Ford Taurus model [12] from the National Crash Analysis Center (NCAC) is used to illustrate the MDO process. NCAP (New Car Assessment Program) full frontal and IIHS (Insurance Institute for Highway Safety) offset impact are considered for the safety domain (frontal impact protection) with responses of chest G and crash distance, whereas seven locations for intrusion and two body-in-white of torsion and vertical bending modes are included for the NVH discipline. The objective of this MDO problem is to minimize the vehicle weight with the thickness of 49 components considered as design variables. Out of those 49 design variables, 21 are shared across all disciplines: both safety (IIHS and NCAP) and NVH. Figure 5 shows the description of this MDO problem, whereas Table 1 provides a summary of attributes in terms of each involved discipline, i.e. finite element size, CAE solvers, required CPU and associated run time in the High Performance Computing (HPC) environment.

In this example, the main computational challenge is that for a vehicle model with over a million elements, a single 40% offset crash analysis using LS-DYNA takes three hours on 32-CPU multithreading HPC clusters without considering the additional job queueing time, whereas a Full Frontal analysis takes two hours, which means that a single design evaluation requires approximately five hours if the analyses are performed sequentially. With this in mind a full optimization study with only a few hundred design evaluations would take several weeks to months.

Table 1. summary of attributes in three disciplines

| Attributes           | Full Frontal              | 40% Offset                                     | NVH                                   |
|----------------------|---------------------------|------------------------------------------------|---------------------------------------|
| Elements             | 1,064,616                 | 1,128,735                                      | 466,108                               |
| Nodes                | 936,234                   | 1,007,337                                      | 374,032                               |
| Run-time             | 2 h (32 CPUs)             | 3 h (32 CPUs)                                  | 7 mins (4 CPUs)                       |
| CAE Solver           | LS-dyna                   | LS-dyna                                        | MSC.Nastran                           |
| Response             | Chest G<br>Crush distance | Intrusion<br>(Footrest, LeftIP, RightIP, etc.) | Torsion Mode<br>Vertical Bending Mode |
| Finite Element Model |                           |                                                |                                       |

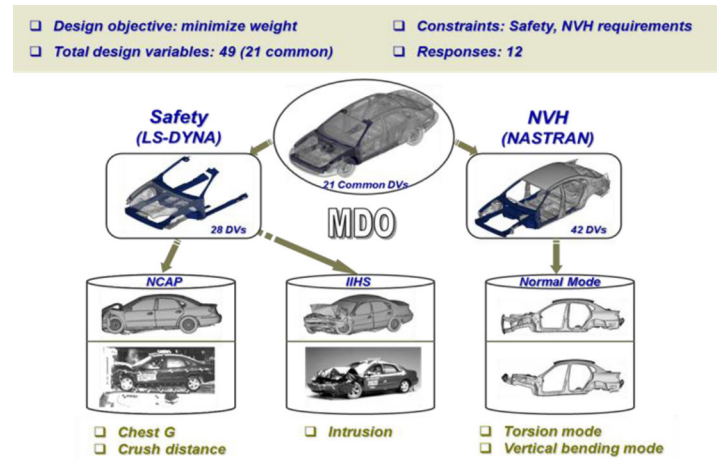


Figure 5. Optimization statement of the weight reduction example

It is important to underline again that there is no strong coupling between the disciplines: NCAP Full Frontal, IIHS 40% Offset, and NVH, so they can be performed in parallel for each design evaluation, which translates into approximately three instead of five hours per design evaluation. In spite of this, the total turnaround time of a direct optimization study would remain unacceptably high unless more designs could be computed concurrently.

Regardless the disciplines are strongly coupled or not, with the aforementioned MDO decompositions, disciplines could be evaluated in parallel, which is one of the main advantages of MDO decomposition. However, in this paper we are presenting a more popular way of conducting MDO study in industry, which usually begin from Design of Experiment (DOE) study, and then Response Surface Modelling (RSM) is used to obtain approximation relationships between all responses and their related design variables, after some quality check of the trained RSMs, the MDO is conducted by using the trained RSMs (which is often called virtual optimization), optimal solutions suggested by MDO are often needed to be verified with CAE solvers.

In the following sections, detailed description of the entire MDO process with the AAO and CO formulations is presented.

### Step 1: Build Single Discipline Work Flows and Run DOE for Each Discipline

This step can be completed by specialist who has enough knowledge to build the work flow for the discipline s/he has expertise with. Design variables, outputs, CAE simulations, and the sequence of conducting the CAE simulations are explicitly defined and tested in this step to ensure the DOE runs will be successful. Figures 6 (a-c) shows the completed work flows for disciplines of IIHS, NCAP, and NVH. In this example, all DOE runs are submitted to HPC and running 20 CAE jobs concurrently, to ensure the DOE study finishes within a reasonable time frame. In total, 490 Uniform Latin Hypercube (ULH) DOE runs are finished with 454 valid designs. The best feasible design gives a total weight of the vehicle of 297.09kg, which serves as a baseline to be compared with solutions from optimization.

