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Comparison of different global sensitivity analysis methods for aerospace vehicle optimal design

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Abstract

Space vehicle design is a complex process that involves operations such as multidisciplinary analyses, reliability analyses and multi-objective non-linear optimizations. Because these analyses cannot be applied directly to such complex systems, specific strategies relying on Multidisciplinary Design Optimization (MDO) and Reliability Based Design Optimization (RBDO) methods have been developed in an effort to solve these simulation and design problems. However, a prescreening of the most important variables of the problem is still needed before MDO and RBDO can be applied.

Sensitivity analysis is the study of how the variation in the model output can be apportioned, qualitatively or quantitatively to variations in the model or model inputs[1]. It aims to identify and rank the most influential model inputs and to provide an indication on the behavior of the model output based on variations in the model inputs. Moreover, it can be used for uncertainty characterization of the inputs. In the early phases of the design process, the design is relying mostly on simplified models and the uncertainties on the final design and performances are large. The alternative design space is wide due to the number of design variables and their variation boundaries. The use of global sensitivity analysis methods allow to characterize the design variables on the entire design space and to filter out the uncertainty factors with negligible effects on the output, decreasing the computational burden and the complexity of the model while allowing to allocate resources on the modeling of the most influential uncertainties on the outputs. The screening of the most important effects will allow for the decision maker to settle on which factors will be considered as uncertain or deterministic for the optimization problem.

In the first part of this communication, a review of various global sensitivity methods will be detailed including variance decomposition methods (Sobol, ANalysis Of VAriance), differential analysis (Morris), sampling based methods (Standard Regression Coefficients), while comparing the features and highlighting the hypotheses of applicability. This paper will present the methods in a unified notation to facilitate understanding and comparison.

In the second part, a benchmark of the sensitivity analysis methods presented will be performed on different typical disciplines involved in launch vehicle design: propulsion, mass budget and geometry design, aerodynamics, and trajectory. This benchmark will outline the accuracy of the methods depending on the complexity and characteristics of the disciplinary models, in parallel to a comparison of the advantages and drawbacks of each method.

Finally, we will synthesize important insights that emerge from the comparative study, we will examine in which conditions applying each of the presented methods and also we will stress the challenge imposed by a trade-off between the accuracy of the results and the constraints of time and cost associated with the chosen method. Moreover, we will foreground the importance of some particular results which are not captured by global sensitivity analysis such as the relative influence of different main contributors to the discipline output variations depending on the part of the vehicle modeled (*e.g.* different influences of the propellant mass for the upper or lower stages of the launch vehicle).

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Reference:

[1] A.Saltelli, M.Ratto, T.Andres, F.Campolongo, J.Cariboni, D.Gatelli, M.Saisana, and S.Tarantola, (2008). Global sensitivity analysis: the primer. Wiley-Interscience.