Journal of Mechanical Design

Guest Editorial

Special Issue: Simulation-Based Design Under Uncertainty

Uncertainty quantification and propagation using probabilistic and nonprobabilistic methods are essential in many engineering and nonengineering disciplines. In mechanical design, there is an ever-increasing need to design systems considering uncertainty and variability using simulation models. The past decade has seen a significant growth in uncertainty quantification, propagation, and design. The "Simulation-Based Design Under Uncertainty" special session of the ASME Design Automation Conference (DAC) has been attracting many papers every year for more than twelve years. Design under uncertainty has implications in decision-making as well as reliability, quality, safety, and risk tolerance of many products. This special issue covers various related topics under the general umbrella of simulation-based design under uncertainty, including methods, models, and case studies.

The idea for the special issue came from the Editor, Dr. Shapour Azarm, who expressed the need to highlight recent advances in the area of design under uncertainty covering all the aspects of uncertainty quantification, propagation, and significance in design. Considering the year-after-year interest from both academia and industry in the "Simulation-Based Design Under Uncertainty" special session in DAC, the interest from other ASME Design Engineering Conferences in design under uncertainty, and the ever-increasing need to design mechanical and structural systems for reliability, quality, safety, and risk tolerance, we were immediately and enthusiastically supportive and responsive to Dr. Azarm's initiative. We would like to thank him for that.

The papers in this special issue were submitted to the ASME *Journal of Mechanical Design* in response to a Call for Papers (CFP) issued in November 2015 with a submission deadline of late April 2016. We received 58 papers among which 19 went through at least two rounds of review following the guidelines and standard review procedures of the journal. The 12 full papers and 2 technical briefs that are presented in this special issue highlight developments in uncertainty propagation and design using probabilistic and nonprobabilistic methods, uncertainty reduction and risk management in design, algorithms for robust design, model validation, design for resilience, multidisciplinary analysis and optimization under uncertainty, time-dependent reliability, system reliability and redundancy allocation, and additive manufacturing.

Below are the highlights of all the papers in this special issue. Y. Zhang, M. Li, J. Zhang, and G. Li proposed a new robust optimization (RO) framework using Gaussian processes, considering not only parameter uncertainty but also model uncertainty to represent the uncertainty in simulation models. Model uncertainty in RO can reduce the risk of the obtained robust optimal designs becoming infeasible even if the parameter uncertainty is considered.

Another paper, co-authored by S. M. Göhler, T. Eifler, and T. J. Howard, presented a review of robustness metrics and classified all the metrics based on the information necessary to calculate them. The authors identified four different classes of robustness metrics using sensitivity, size of feasible design space, functional expectancy and dispersion, and probability of compliance information. The paper aimed at providing a comprehensive overview of robustness metrics as well as guidance to understand the different types of robustness metrics and remove potential ambiguities associated with the term robustness.

A methodology to decide the degree of conservativeness in an initial design considering the risk of future redesign was presented by N. B. Price, N.-H. Kim, R. T. Haftka, M. Balesdent, S. Defoort, and R. Le Riche. While early in the design process, there is often mixed epistemic model uncertainty and aleatory parameter uncertainty, and later in the design process, the results of high-fidelity simulations or experiments reduce epistemic model uncertainty and may trigger a redesign process. The authors proposed a margin-based design/redesign method where the design is optimized deterministically, but the margins are selected probabilistically. Their method allows for tradeoff between expected final design performance and probability of redesign while ensuring reliability with respect to mixed uncertainties.

T. Xia, M. Li, and J. Zhou continued on the subject of robustness proposing a sequential robust optimization approach for multidisciplinary design optimization for problems with both aleatory and epistemic uncertainties represented by intervals. The proposed approach obtains first a solution by giving full autonomy to the subsystems using a tolerance range for the coupling variables in order to propagate uncertainty in the coupled system. Then, an auxiliary sequential optimization process is implemented to get the optimal robust solution.

Another paper by P. Pandita, I. Bilionis, and J. Panchal contributed to the important area of stochastic optimization of high-dimensional problems with expensive black-box functions. Design optimization under uncertainty is notoriously difficult for problems with an expensive objective function. The paper used concepts of Bayesian global optimization (BGO) to alleviate the high cost of information acquisition and select sequential simulations optimally. It reformulated the expected improvement (EI) information acquisition function (IAF) in BGO to filter out parametric and measurement uncertainties. The proposed approach alleviates the effect of the curse of dimensionality using a fully Bayesian interpretation of Gaussian processes and adaptive Markov chain Monte Carlo to improve robustness.

Two papers addressed the timely area of engineering resilience quantification and assessment and their implications in system design. Engineering resilience has recently gained popularity. However, there are different opinions among designers, engineers, practitioners, and policy makers on what is engineering resilience, and how it can be quantified, designed, and implemented in engineering and nonengineering systems.

In the first paper on engineering resilience, N. Yodo and P. Wang presented a literature survey on existing engineering resilience studies from a system design perspective. Focusing on engineering resilience metrics and their design implications, the authors provided a definition of engineering resilience and proposed resilience quantification metrics, analysis methodologies, and design tools which can be applicable for a broad range of engineering systems.

The second paper, co-authored by Z. Hu and S. Mahadevan, proposed a new resilience metric using time-dependent system reliability concepts and described a methodology to design a system which meets a specific system resilience target. The time-dependent reliability analysis is used to identify the dominant system failure paths involved in the estimation of system resilience. A sensitivity analysis is also presented to identify the important design parameters which affect the system resilience.

J. Wang and M. Li proposed a redundancy allocation approach to increase the reliability of multistate systems with component dependencies and load sharing. These two features, present in most real-world applications, have hindered the development of successful redundancy allocation algorithms. A novel redundancy allocation scheme based on a semi-Markov model and optimization is proposed and successfully demonstrated on several two-component problems. The authors concluded that their approach constitutes an important first step but further developments are needed for systems with an arbitrary number of subsystems.

M. M. J. Opgenoord, D. L. Allaire, and K. E. Willcox presented a variance-based sensitivity approach for simulation-based design under uncertainty to reduce the effect of input uncertainties on the output. Global sensitivity analysis (GSA) methods are typically used to rank input variables and eventually select the important ones. The authors proposed a distributional sensitivity analysis (DSA), which, similarly to GSA, enables the ranking of the input variables, and in addition, links the output variance as a function of the uncertainty reduction of the input variables. With this information, the designer can target the reduction of uncertainty associated with a specific input. The approach is applied to the design of a commercial airliner.

An approach to propagate model uncertainties in multidisciplinary analysis was presented by S. Dubreuil, N. Bartoli, C. Gogu, and T. Lefebvre. The uncertainties are modeled as random fields using a polynomial chaos expansion constructed over the design and coupling variables space. The proposed approach results in a semi-intrusive formulation with emphasis on approximating each discipline using a Kriging metamodel. The latter represents intrinsically the model uncertainties. Among other examples, the developments are demonstrated on two conceptual aircraft design problems.

A model validation method for dynamic engineering models under uncertainty was presented by Z. Wang, Y. Fu, R.-J. Yang, S. Barbat, and W. Chen. Validating dynamic engineering models is an important topic in simulation-based design under uncertainty. Although significant progress has been made, the existing metrics lack the capability of managing uncertainty in both simulations and experiments. This paper presented an area-based metric to systemically handle uncertainty and validated computational models for dynamic systems over an input space by simultaneously integrating the information from multiple validation sites. A truncated Karhunen–Loève (KL) expansion represents the responses of the dynamic system in order to manage the complexity associated with a high-dimensional data space.

L. Brevault, S. Lacaze, M. Balesdent, and S. Missoum presented a reliability analysis in the presence of both aleatory and epistemic uncertainties. Their methodology is then applied to predict the fallout zone of a launch vehicle. An interval framework is used to quantify the epistemic uncertainties. The proposed method allows designers to determine the bounds of the failure probability and involves a sequential approach using subset simulation, Kriging, and an optimization process. To reduce the simulation cost, a refinement strategy of the surrogate model is proposed taking into account the presence of both aleatory and epistemic uncertainties.

Finally, this special issue includes two technical briefs. In the first one, J. Zhou, M. Xu, and M. Li proposed a reliability-based design optimization (RBDO) method under mixed probabilistic (aleatory) and interval (epistemic) uncertainties considering the variation of the objective because of the uncertainties. The authors proposed a single-loop robust optimization approach to efficiently calculate the worst-case solution due to the interval uncertainty using the Utopian solution. The remaining problem is then solved using existing reliability-based design optimization (RBDO) methods. An example demonstrates the applicability of their approach and illustrates the necessity to consider the variation of the objective for robustness reasons.

The second technical brief, co-authored by F. Lopez, P. Witherell, and B. Lane, discussed the origin and propagation of uncertainties in additive manufacturing focusing on models for laser powder bed fusion (L-PBF). Modeling assumptions, unknown simulation parameters, numerical approximations, and measurement error are considered. The quantification and algorithms for the reduction of each source of uncertainty are discussed. A case study of a thermal model for predicting the melt pool width was presented.

We hope these papers stimulate further research ideas and advances in the area of simulation-based design under uncertainty. We sincerely thank all the authors who responded to our CFP, whether or not their paper appeared in the special issue. We also thank all the reviewers for their prompt response to our multiple requests and short deadlines. Last but not least, we would like to thank Ms. Amy Suski who patiently and effectively helped us with many logistical details.

Enjoy reading the papers!

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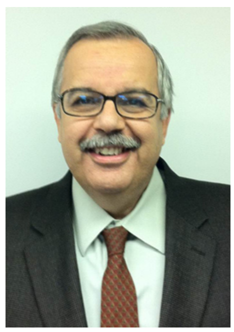

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