SAPIUM a systematic approach for input uncertainty quantification

J. Baccou, D. Bestion, M. Couplet, G. Damblin, P. Fillion, F. Fouet, B. Iooss, J. Freixa, Y. Oh D, F. Reventos, et al.

SAPIUM: A SYSTEMATIC APPROACH FOR INPUT UNCERTAINTY QUANTIFICATION

J. Baccou[1], D. Bestion, M. Couplet, G. Damblin, P. Fillion, F. Fouet, J. Freixa, B. Iooss, R. Mendizábal, D.Y. Oh, A. Petruzzi, P. Probst, F. Reventos, T. Skorek, T. Takeda, J. Zhang

[1] Institut de Radioprotection et de Sûreté nucléaire (IRSN), PSN-RES/SEMIA, Centre de Cadarache, 13115 St Paul-Lez- Durance, FRANCE

jean.baccou@irsn.fr

ABSTRACT

Uncertainty assessment is a key step in nuclear applications to ensure that a system cannot move towards unsafe conditions. This topic has already been addressed by several OECD/NEA projects such as UMS or BEMUSE. However, if uncertainty propagation methods have now become mature for industrial applications, the input uncertainties quantification on the physical models still requires further investigations. It is precisely in this context that the SAPIUM project has been proposed in order to reduce as much as possible (or at least better understand) the user-effect observed in the previous PREMIUM activity that was a first attempt to analyze available methods to handle this issue. The underlying idea of the proposed work is not to focus on method benchmarking but on the construction of a clear and shared systematic approach for input uncertainty quantification as it is already addressed in industries and R&D for related topics. The main outcome of the project is a first "good practices" document that can be exploited for safety study in order to increase the agreement among experts on recommended practices as well as on remaining open issues for further developments. End users are therefore the developers and the users of BEPU methodologies, as well as the organizations in charge of evaluating them. Since it is an on-going activity, this paper describes the general content of the SAPIUM activity. All the details of the contributions will be available in the final document that will be issued in 2019.

1. INTRODUCTION

Assessment of uncertainties associated with Best-Estimate (BE) calculations has become of prime importance in nuclear safety analyses. From a methodological point of view, the treatment of uncertainties can be split in two main topics that require different approaches to handle them. The first one assumes that all input uncertainties have been previously estimated (by expert judgement for example), and the objective is to estimate the impact of input uncertainties on output uncertainties. It is referred as uncertainty analysis and is often based on input uncertainty forward propagation [**Erreur ! Source du renvoi introuvable.**]. The second one is focussed on the quantification of input uncertainties (IUQ). It is based on the discrepancy code/experiment and its inverse propagation to derive input uncertainties [2].

The question of input uncertainty propagation has been already addressed by several CSNI projects such as UMS [3] or BEMUSE [4]. While it appeared that uncertainty analysis methods have now become mature for industrial applications, a special attention should be devoted to the input uncertainties evaluation on the physical models. Therefore, following this recommendation, the PREMIUM [5] benchmark (2012-2015) was organized as a first step towards the development and the application of model IUQ methods.

However, even if this project has been a useful activity to test the different available IUQ approaches, the analysis of PREMIUM Phases III and IV has shown a large dispersion between participants. Moreover, the results were not satisfactory when moving from the experiment used for quantification (FEBA) to the experiment used for validation (PERICLES). One main reason could be attributed to the lack of common consensus and practices in the followed process and method.

A main lesson learned from the PREMIUM benchmark was that a systematic approach devoted to model input uncertainty evaluation (i.e. quantification and validation) should be developed to improve the reliability of the analysis and to ensure the extrapolation of its results to the Nuclear Power Plant (NPP) case. Therefore, following a first investigation [6] that led to the identification of five key generic elements that could be considered in the construction of a systematic approach, the SAPIUM project was proposed to progress on the issue of the quantification (and validation) of the uncertainty of the physical models in system thermal-hydraulic codes.

In this paper, we first recall the objectives and the organization of this project. Then, since this project is an on-going activity, Section 3 only introduces the main key elements of the SAPIUM methodology and their connections to previous OECD projects as well as to some current practices in research and industries. All the details of the SAPIUM contributions will be available in the final document that will be issued in 2019.

2. SCOPE, LIMITATION AND ORGANIZATION OF THE SAPIUM PROJECT

SAPIUM (Systematic APproach for Input Uncertainty quantification Methodology) is devoted to input uncertainty quantification based on inverse propagation of the information associated to the discrepancy between simulation results and experimental data, using verified and validated codes (frozen version, no recalibration of the models). More precisely, the objective is to develop a systematic approach that clearly compiles the different practices and offers a shared understanding about "appropriate" practices for input uncertainty quantification in order to improve the reliability of the analysis and to progress on the validity of extrapolation of its results to the NPP case. Therefore, the main outcome of the project is a first “good practices” document that can be exploited for safety study in order to reduce user effect and to increase the agreement among experts on recommended practices as well as on remaining open issues for further developments. End users are research institutes and universities, manufacturers, utilities and safety authorities. In other words, they are the developers and the users of BEPU approaches, as well as the organizations in charge of evaluating these approaches.

This project can be considered as a follow-up of PREMIUM. However, it is not a benchmarking of available methods for input uncertainty quantification but provides a methodological document (only simple additional studies will be considered to get reliable insights into methodological key issues). It is also important to mention that it is not intended to develop in this project a unique (statistical) method for uncertainty quantification but to provide the description of the different generic steps and requirements that a method must have to successfully address the key issues identified in previous benchmark studies. Therefore, it is not expected to derive at the end of the project certified input uncertainties to be used in NPP studies.

In scientific computing, there exist different sources of uncertainties that can be categorized in three classes [7]. The first one is related to model inputs that include model parameters of closure laws, geometry, initial and boundary conditions. The second one is associated to the numerical approximation error such as discretization or iterative convergence errors. The last one concerns all assumptions, conceptualizations, abstractions, approximations, and mathematical formulations on which the model relies. In SAPIUM, we focus on the first class and more precisely on parameters involved in the physical models implemented in the code. The associated uncertainty is referred as (model) input uncertainty.

The SAPIUM project is organized as a writing group that includes 10 organizations coming from industry, TSO, regularity body and university. Each of them provides his own experience on input uncertainty quantification and validation through contributions to the writing of document sections and to the review of the final report. Moreover, for some of them, they can perform short applications to facilitate the discussions and reach a consensus on the SAPIUM process.

The SAPIUM project lasts two years (January 2017 – March 2019). The starting point of the project is the available state of knowledge coming from previous OECD/NEA projects (such as BEMUSE and PREMIUM) as well as current practices in regulation, industries and research. A special attention is devoted to EMDAP [8] and USNRC CSAU [9] processes that focus on the development of systematic approaches for evaluation model development and BEPU analysis. It is also planned to exploit the large literature on VVUQ formal procedure and especially the comprehensive framework for verification, validation, and uncertainty quantification in scientific computing proposed by Oberkampf and Roy [10].

3. KEY ELEMENTS OF THE SAPIUM METHODOLOGY

The SAPIUM methodology is structured following 5 key elements that provide a general framework for the construction of IUQ methods [6]. They are shown in Figure 1.

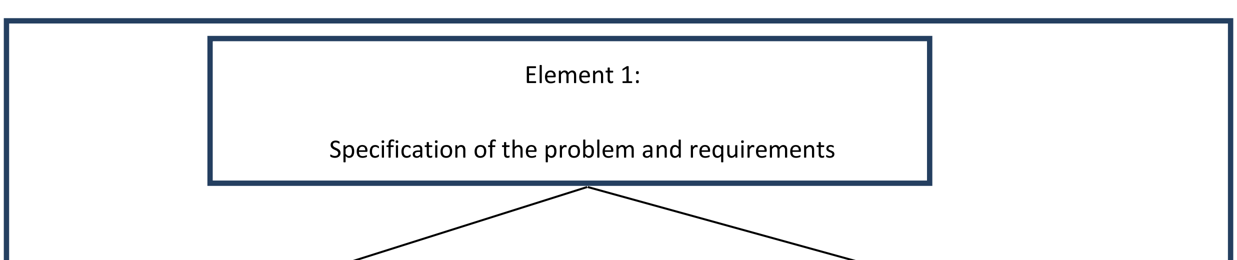

Figure 1. The 5 key elements of the IUQ framework.

Besides the first element that is common to any kinds of studies, Elements 2 (experimental database) and 3 (simulation model) provide the information for the quantification and validation. Connections between them are required for their construction. Since IUQ methods are based on the comparison between simulation results and experimental values, these two steps are therefore crucial for their development. They will control the reliability of the final input uncertainties and the capability of the method to extrapolate the results to real situations.

The objective of Element 2 is the construction of a representative experimental database for the problem specified in Element 1. It should be based on available SETs and IETs but can also require extra experiments if necessary. This work requires proposing criteria to evaluate the adequacy of an experiment that depends on the analyst's objectives and the completeness of the database. It is also interesting to investigate how formal methods such as Multi-Decision Criteria Analysis (MCDA, [11]) or Analytical Hierarchical Process (AHP, [12]) can be exploited to objectively and automatically rank experiments according to their adequacy. One important issue of this element also concerns the question of dependency of the experimental database with respect to the reactor transient. An analysis of different strategies (specific vs generic database) will be provided in the final SAPIUM document. Finally, the problem of separation of the experimental database in two separated parts, one for input quantification and the other for input validation is a key question that will be addressed.

Element 3 is related to the simulation model. It consists in assessing its applicability for simulating the considered SETs/IETs. It requires nodalization strategy and model option selection that should be consistent between the experimental facility and similar components in the nuclear power plant. In some situations, a special attention should be also devoted to the construction of error metrics (to evaluate the accuracy code/experiment) and the definition of a scale of accuracy. Finally, a review on sensitivity analysis methods will be provided to identify model input parameters whose uncertainties will be quantified.

Element 4 consists in inferring from the discrepancy between the experimental and the simulation results, the information related to input uncertainties. The experimental knowledge is here associated to a subset of the database constructed in Element 2 (the remaining subset will be used for input uncertainty validation). A structured review of the different approaches followed in various fields belonging to science and engineering will be provided. Key questions of this element are also related to the weighting of the information provided by each experiment according to their adequacy to the specified problem and to the strategy to adopt in presence of several experiments (quantification per experiment or a unique quantification for all experiments considered together?) as well as in case of several quantifications (how to combine input uncertainties, keeping in mind that several options exist?). The classical verification process of V&V approaches [7] should be also extended to the SAPIUM framework to confirm the quantified input uncertainties.

Element 5 is focused on input uncertainty validation. This step usually cannot be done in the input space since the comparison of the results with the reality is not possible. It is therefore performed in the output space after input uncertainty propagation through the simulation model. Following VVUQ formal procedure, the technical treatment of the validation process then encompasses three main tasks. The first one is based on a comparison between the simulation model output uncertainty and experimental data not used in the quantification. The second one is a prediction that exploits the previous comparison and includes additional uncertainty estimation resulting from interpolation and extrapolation beyond the existing experimental database to satisfy the intended use. Finally, the last task consists in checking whether the input uncertainties are acceptable for the intended use. The validation process first requires the availability of a set of experiments that will be used in the comparison. It is taken from the experimental database constructed in Element 2 of the SAPIUM methodology and not used for the quantification. A review of available approaches to propagate input uncertainties through the simulation model will be performed. A special attention will be also devoted to the definition and the computation of validation indicators for comparison with experimental data.

The treatment of some elements is already (partially) addressed in previous works. Their conclusions and results can be adapted to the framework of IUQ methods. Elements 1-3 are common to any BEPU methodology focusing on the application of a quantified (fully verified and validated, with model input uncertainties quantified and validated) code for accident analysis and can therefore benefit from the CSAU and EMDAP practices. The PREMIUM benchmark has been devoted to Elements 4 and 5 and the sources of discrepancy between participants that prevented from reaching a consensus on the final input uncertainties are included in Elements 1, 2, 3 and 4 respectively. The lesson learned will orientate the recommendations associated to these elements.

Moreover, the development of Elements 3 and 5 can exploit the BEMUSE contributions that focused on several issues such as nodalization strategy and model options or selection of input parameters and input uncertainty propagation. Finally, the large literature on VVUQ approaches will be used for Element 5 and the construction of validation metrics.

The methodological contributions described in the SAPIUM document will be illustrated on different simple demonstration cases to help the reader for practical issues. In order to avoid any misleading interpretation of the results, it is planned to consider different cases with increasing complexity related to the amount of experimental data and of influential physical phenomena.

4. CONCLUSIONS

This paper has presented the outline of the new OECD/NEA SAPIUM project. It is devoted to the construction of a systematic approach for input uncertainty quantification.

Contrarily to the PREMIUM activity that was related to the same topic, the contributions are mainly methodological and will lead to a new formal insight on input quantification to avoid or reduce as much as possible user-effect. Several illustrations of the elements composing the SAPIUM methodology will be also provided to help the practitioner to handle the different introduced tools.

The final objective is to write a first "good practices" document to drive input uncertainty studies by exploiting the available state of knowledge coming from previous OECD projects as well as current practices in research and industries.

5. REFERENCES

[1] R. Smith, "Uncertainty Quantification: Theory, Implementation, and Applications", Computational Science and Engineering, SIAM, 2014.

[2] A. Tarantola, "Inverse Problem Theory and Methods for Model Parameter Estimation". SIAM, 2005.

[3] OECD, "Report on the Uncertainty Methods Study". NEA/CSNI/R(97)35, 1998.

[4] OECD, "BEMUSE Phase VI Report, Status report on the area, classification of the methods, conclusions and recommendations," OECD/NEA/CSNI/R(2011)4, 2011.

[5] OECD, "PREMIUM Phase V report: Final Report", OECD/NEA/CSNI/R(2016)18, 2017.

[6] J. Baccou, J. Zhang and E. Nouy, "Towards a systematic approach to input uncertainty quantification methodology," Proceedings of the NURETH-17 Conference, Xi'an, China, 2017.

[7] W.L. Oberkampf and C.J. Roy, "Verification and Validation in Scientific Computing", Cambridge University Press, 2010.

[8] USNRC, "Transient and accident analysis methods," RG-1.203, USNRC, 2005.

[9] Expert group, "Quantifying Reactor Safety Margins: Application of Code Scaling, Applicability and Uncertainty Evaluation Methodology to a Large-Break Loss of Coolant Accident," NUREG/CR-5249, USNRC, 1989.

[10] C.J. Roy and W.L. Oberkampf, "A comprehensive framework for verification, validation, and uncertainty quantification in scientific computing," Computer Methods in Applied Mechanics and Engineering, 200(25-28), 2131-2144, 2011.

[11] D. Bouyssou, T. Marchant, M. Pirlot, P. Perny, A. Tsoukiàs, and P. Vincke, “Evaluation and decision models – A critical perspective”, Kluwer’s International Series, 2000.
[12] T.L. Saaty, “Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World”, Analytic hierarcy process series, RWS Publications, 1982.