12-13th March 2026, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Köln, Germany.

WEIMUS project proposal: “Weiterentwicklung der Methoden zur Unsicherheits- und Sensitivitätsanalyse bei Simulationen schwerer Unfälle”

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Objectives

- Overcome the limitations of the Wilks' approach
- Find the method to explore better the input parameters space, considering high computational costs of the simulations in the SA field
- Find the way to achieve the reproducibility of the U&S analysis results

Project proposal suggests to:

- Apply multilevel/multifidelity Monte Carlo method to the SA simulations
- Apply on the regular basis more sophisticated approaches in the U&Sa (not only Pearson and Spearman correlation coefficients)

State of the art

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List of finished big projects related to the topic:

- BEMUSE (Best-Estimate Methods Uncertainty and Sensitivity Evaluation) – 2004-2010
- PREMIUM (Post BEMUSE Reflood Models Input Uncertainty Methods) – 2012-2015
- SAPIUM (Systematic APproach for Input Uncertainty quantification Methodology) – 2017-2019
- MUSA (Management and Uncertainties of Severe Accidents) – 2019-2023
- ATRIUM (Application Tests for Realization of Inverse Uncertainty quantification and validation Methodologies in thermal-hydraulics) – 2021-2025
- Uncertainty analysis in the frame of State-of-the-Art Reactor Consequence Analyses (SOARCA) Project

State of the art

GRS method is widely used

[1] Glaeser, H., 2008. GRS method for uncertainty and sensitivity evaluation of code results and applications. Science and Technology of Nuclear Installations, 2008(1), p.798901.

- Wilks formula to define the number of samples
- Monte Carlo (Simple random sampling)

Limitations of the approach:

- There should be no code crashes;
- All relevant input parameters are taken into account and their distributions are accurately known;
- FoMs should be independent (better use Wald‘s approach).

[2] Porter, N.W., 2019. Wilks' formula applied to computational tools: A practical discussion and verification. *Annals of Nuclear Energy*, *133*, pp.129-137.

→ Those limitations are often not taken into account

Previous Work

- WAME project – (2019-2022)

„Methodische Weiterentwicklung optimierter Echtzeitmodelle zur Verbesserung der Entscheidungsfindung im Falle auslegungsüberschreitender Störfälle in Kernkraftwerken"

- [3] Stakhanova, A., Gabrielli, F., Sanchez-Espinoza, V.H., Hoefer, A. and Pauli, E., 2022. "Uncertainty and sensitivity analysis of the QUENCH-08 experiment using the FSTC tool", Annals of Nuclear Energy, 169, p.108968.
- [4] Stakhanova, A., "Development of Decision Supporting Methods for Emergency Teams in Case of Severe Accidents in Nuclear Power Plants", PhD thesis, 2023
- [5] Stakhanova, A., Gabrielli, F., Sanchez-Espinoza, V.H., Hoefer, A. and Pauli, E.M., 2023. "Uncertainty and sensitivity analysis of the ASTEC simulations results of a MBLOCA scenario in a generic KONVOI plant using the FSTC tool", Annals of Nuclear Energy, 192, p.109964.

- In the frame of the project U&S analysis of the QUENCH-08 and KONVOI-1300 models has been performed

Results of the WAME project are the motivation for this project proposal

Previous Work

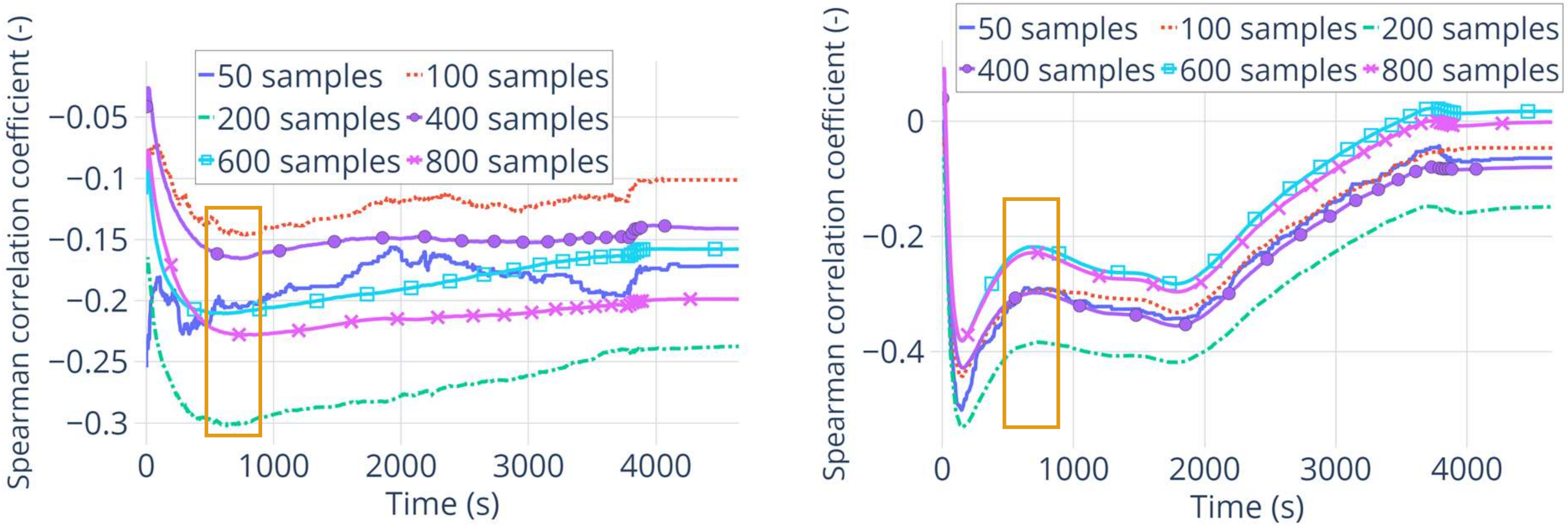

Figure 1 - Evolution of the Spearman correlation coefficient value in time calculated for four uncertain input parameters for sets of simulations with different number of samples. Left - argon mass flow rate; Right - internal diameter of the test bundle ASTEC model structures. From [4]

- Changing samples number could result in the difference in correlation coefficient values and therefore affect the judjement about the input parameter importance

Previous Work

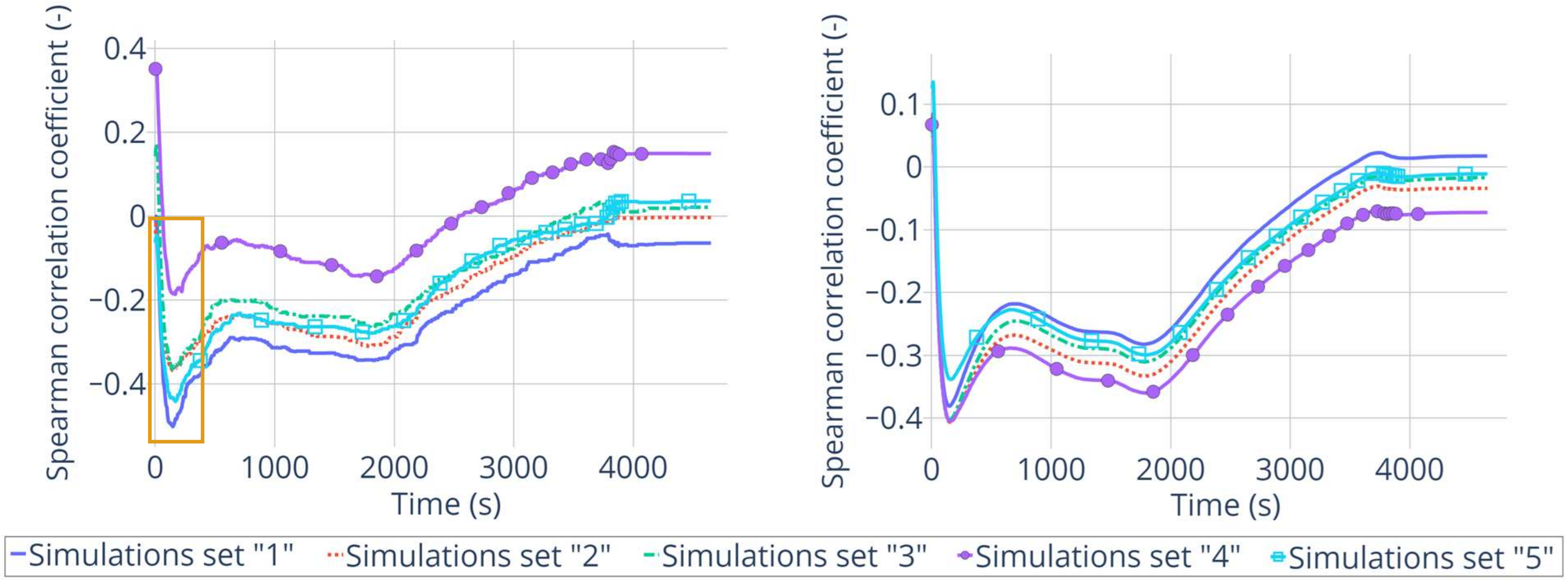

Figure 2 - Spearman correlation value evolution in time for internal diameter of the test bundle ASTEC model structures calculated for five sets of simulations 50 or 600 samples each. Left – 5 sets 50 samples each. Right – 5 sets 600 samples each. From [4]

- Repeating the simulations using the same number of samples could result in the difference in correlation coefficient values and therefore affect the judjement about the input parameter importance

Proposal for improvement

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Multilevel / Multifideliy Monte Carlo approach

- Run simulations with different level of approximation
- Reduce number of computationally expensive simulations
- Run many simplified simualtions

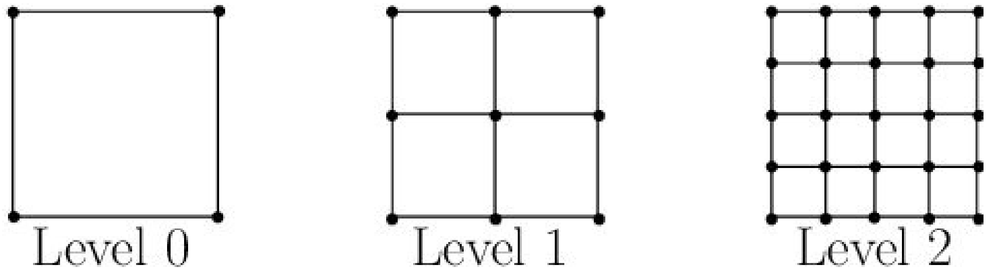

Figure 3: Illustrative example of a hierarchy used in the MLMC method [https://doi.org/10.22725/ICASP13.085]

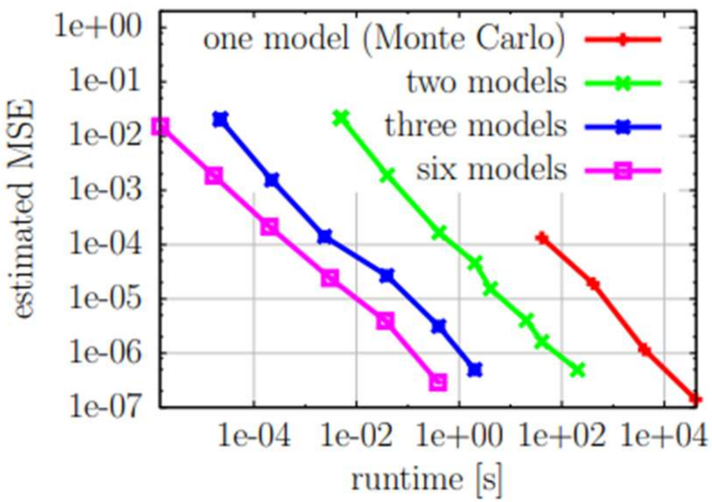

Figure 4: From https://doi.org/10.1137/15M1046472

[6] Ayoul-Guilmard, Q., Ganesh, S., Krumscheid, S. and Nobile, F., 2023. QUANTIFYING UNCERTAIN SYSTEM OUTPUTS VIA THE MULTI-LEVEL MONTE CARLO METHOD− DISTRIBUTION AND ROBUSTNESS MEASURES. *International Journal for Uncertainty Quantification*, *13*(5).

[7] Baumgarten, N., Krumscheid, S. and Wieners, C., 2024. A fully parallelized and budgeted multilevel monte carlo method and the application to acoustic waves. *SIAM/ASA Journal on Uncertainty Quantification*, *12*(3), pp.901-931.

Work plan

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Year	2027				2028				2029			
Part	M03	M06	M09	M12	M15	M18	M21	M24	M27	M30	M33	M36
1	■	■										
2			■	■	■	■						
3							■	■	■	■		
4											■	■

Part I: Introduction to the project scope (M01-M06)

Part II: Design, Implementation, and Validation of MLMC Framework for SA Simulations (M07-M18)

Part III: Advanced Sensitivity Analysis Leveraging MLMC-Enriched Ensembles (M19-M30)

Part IV: Finalizing the outcomes of the project (M31-M36)

Work plan

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Part II: Design, Implementation, and Validation of MLMC Framework for SA Simulations (M07-M18)

- Develop a multi-level hierarchy of the MLMC method suited to ASTEC into the KIT KATUSA tool
- Compare results against classical MC and Wilks approaches on the prepared ASTEC dataset
- Check the reproducibility through resampling experiments (analogous to presented on Figures 1 and 2)

Part III: Advanced Sensitivity Analysis Leveraging MLMC-Enriched Ensembles (M19-M30)

- Use less widely used (in SA field) metrics to check the importance of the input parameters: for example, Shapley additive explanations, distance correlation coefficient, Hilbert-Schmidt independence criterion
- Hierarchical sensitivity analysis with MLMC – e.g., screening influential parameters at a coarse level, then refining interaction detection at a fine level.

Exploitation

- ✓ Result of the project should be the improved more robust methodology for U&S analysis of the SA simulations

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- ✓ This methodology will be implemented in the KATUSA tool developed at KIT

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- ✓ Methodology could be used by interested parties

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Thank you for your attention!

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