Sensitivity Analysis for a Steam Generator Clogging Simulation Code

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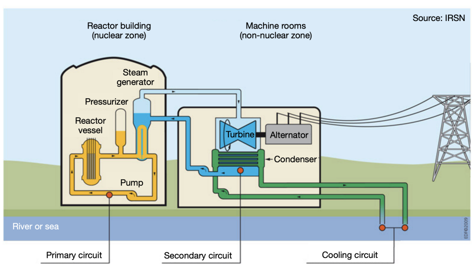
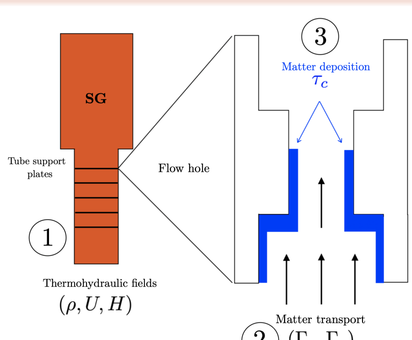
1. Industrial context

- **Steam generator** (SG) $\rightarrow$ heat exchanger between the primary and secondary circuits of a pressurized water reactor.



- Corrosion in the secondary circuit produces iron oxide impurities $\rightarrow$ **clogging** of the SG over time.
- Clogging is measured during reactor outages using image processing techniques.
- **Chemical cleanings** can be performed to reduce it $\rightarrow$ economic impacts.
- Challenges for maintenance planning and optimization.
- Special focus is given to the hot leg (HL) at the top of the SG in $z_{\max}$.

2. Clogging physical modelling



1. Thermohydraulic stationary two-state vector quantities are computed.
2. Solid and soluble iron-oxide particles are transported to the flow hole.
3. Clogging kinetics is characterised by the clogging rate τ_c.

Steps $2-3$ boil down to mixed PDE-ODE coupled system with 2 transport equations and 1 nonlinear ODE.

3. The "THYC-Puffer-DEPO" code

- Numerical implementation of the clogging physical modelling by [1].
- Multi-physics simulation chain of three codes: **THYC** code $\rightarrow$ stationary thermohydraulic fields, **Puffer** $\rightarrow$ solubility maps and **DEPO** $\rightarrow$ solving the mixed transport-ODE system.
- For 50 years of simulation of 1 SG, unitary call ~ 5 h (on HPC facilities).

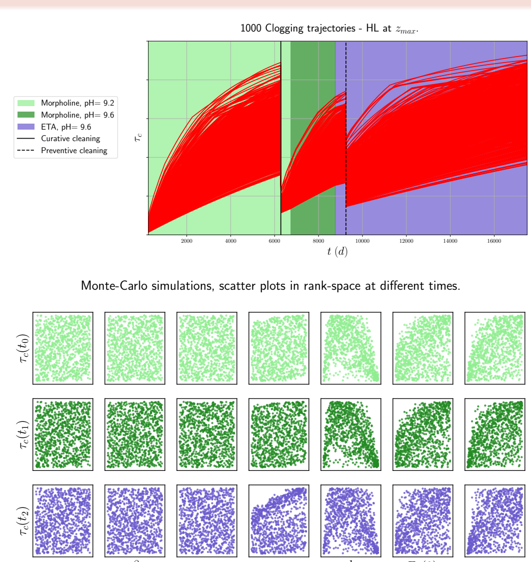
4. Uncertain input variables

$$\boldsymbol{X}_{\text{DEPO}} = (\alpha, \beta, \epsilon_e, \epsilon_c, d_p, \Gamma_p(0), a_v)$$

- α, β: empirical correlation parameters;
- ϵ_e, ϵ_c: clogging deposit porosities;
- d_p: diameter of particles;
- $\Gamma_p(0)$: initial solid particles fraction;
- a_v: calibration parameter.

Input variables are supposed to be **independent** and probability distributions are determined by expert knowledge.

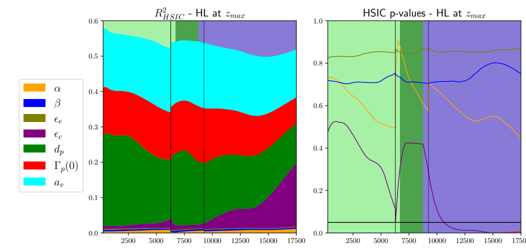
5. Monte Carlo simulations



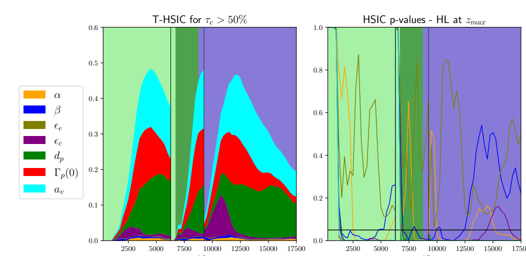
6. Given-data SA

- HSIC indices [2] allow to uncover deep input-output dependency structures.
- Both **global**, **target** and **conditional** analyses can be performed with HSIC [2].

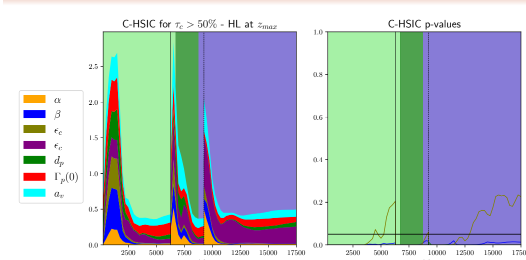
7. Global HSIC



8. Target HSIC ($\tau_c > 50\%$)



9. Conditional HSIC ($\tau_c > 50\%$)



10. Conclusion and perspectives

- Part of the SA results obtained in a previous study [3] with Sobol' indices are confirmed.
- HSIC indices allow to refine the analysis and to observe changes in the input sensitivity hierarchy at different operating times.
- **Perspectives**: doing Bayesian calibration of a_v wrt. various chemical conditioning regimes.

References

[1] T. Prusek, *Modélisation et simulation numérique du colmatage à l'échelle du sous-canal dans les générateurs de vapeur*, PhD thesis, Univ. Aix-Marseille and EDF R&D, 2012

[2] A. Marrel and V. Chabridon, *Statistical developments for target and conditional sensitivity analysis: application on safety studies for nuclear reactor*, Reliability Engineering and System Safety, 214, pp.107711, 2021

[3] L. Lefebvre et al., *Improving the Predictivity of a Steam Generator Clogging Numerical Model by Global Sensitivity Analysis and Bayesian Calibration Techniques*, Nuclear Science and Engineering, 197:8, pp. 2136–2149, 2023