IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

Sensitivity and optimization methods applied to the dynamic fuel cycle

Example of SUR and RSUR application

Technical workshop on nuclear scenarios

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Overview

- Issues
- Principle of SUR and RSUR Algorithms
  - SUR algorithm
  - RSUR algorithm
- Calculation packages and Algorithms
  - CLASS code
  - Promethee
- Application case
  - Scenario study
  - Using the SUR algorithm
  - Using the RSUR algorithm
- Conclusions

Hypothesis and parameterization

Large number of different hypothesis types in fuel cycle scenario calculations

- General description of the nuclear park or strategy: Reactors (type, number…), fuel cycle options (open, recycling…)…
- Technological parameters: Reactors (power, fuel mass…), fuel (enrichment, Pu content or burnup to be achieved…), facilities characteristics (constrains, performances)…
  - Controled or defined by the operators
- External parameters: electricity mix could impact to the reactor loading factor…
  - Uncontroled by the operators and should impact reactor and fuel cycle

Parameters values are not exactly known → Parameterization and definition of variation ranges

Parameterization approach

- Standard parameterization:
  - manual
  - Random
  - Batch by batch
  - …

→ N values by parameter
$N_1 * N_2 *$…
Very large number of calculations to investigate the space of possible

- Advanced parameterization - Resort to an algorithm:
  - dichotomy
  - genetic algorithm
  - neural networks
  - …

→ The algorithm choice depend of your goals and your problem

Which parameters combinations that respect the scenario constraints?

Type of problem presented in this talk

- Parameters:
  - Controled or not
  - Numbers < 5
  - …
- 1 target
- Goal: Find the subspace of parameters that respects the target value of an observable

→ SUR and RSUR algorithm

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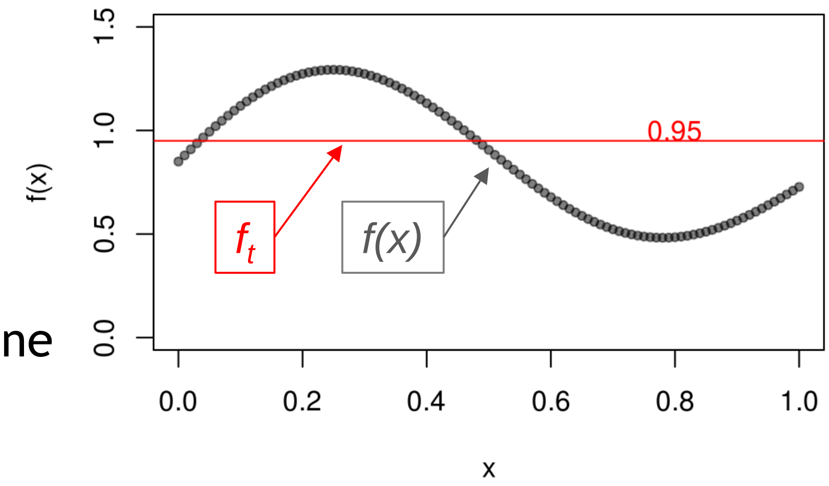
SUR (Stepwise Uncertainty Reduction) algorithm

Goal

- x_1, x_2 ,x_3 *and* x_4 *parameters*
- $f(x_1, x_2, x_3, x_4)$ *observable*
- target value f_t

Find the subspace of parameters where an observable $f(x_1, x_2, x_3, x_4)$ is > or < at f_t

Or investigate all the (x_1, x_2, x_3, x_4) to determine the boundary where $f(x_1, x_2, x_3, x_4) = f_t$



Example

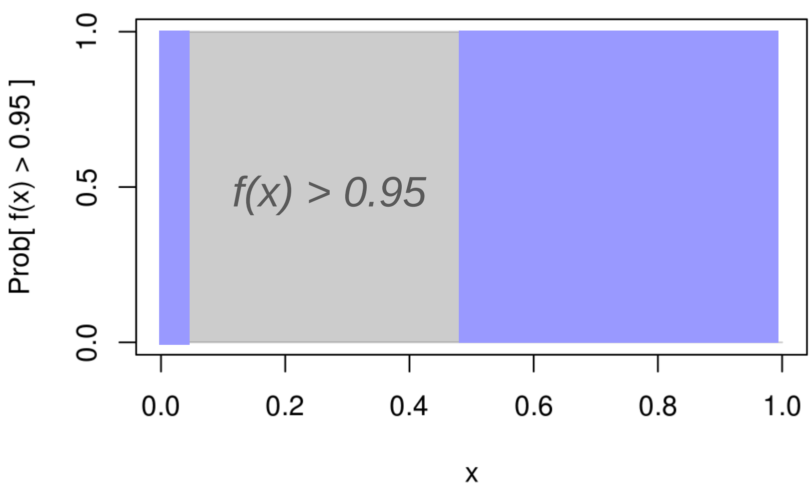
f(x) known fonction and $f_t = 0.95$

We aim to reach full certainty about:

f(x) > or < 0.95

↕

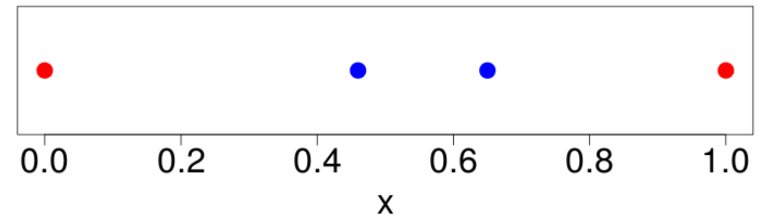
Prob[f(x) > 0.95] = 0 or 1

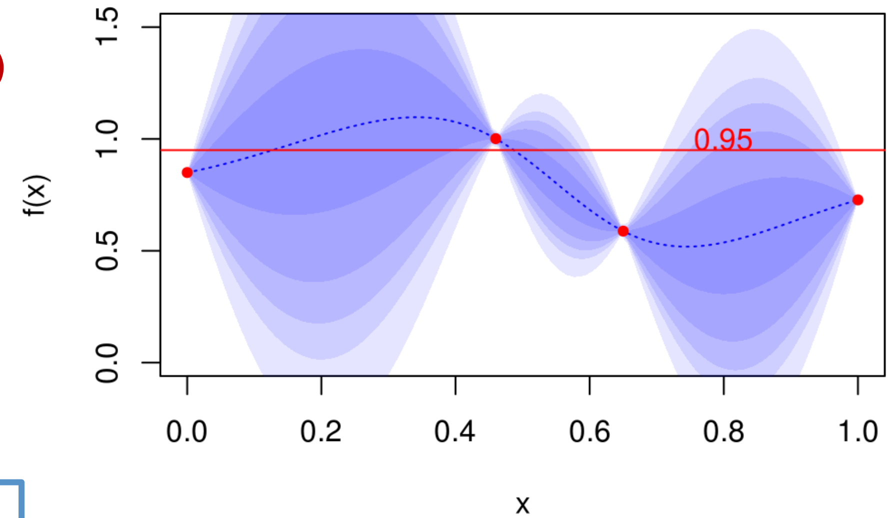


Principle of SUR and RSUR Algorithms

Calculation steps

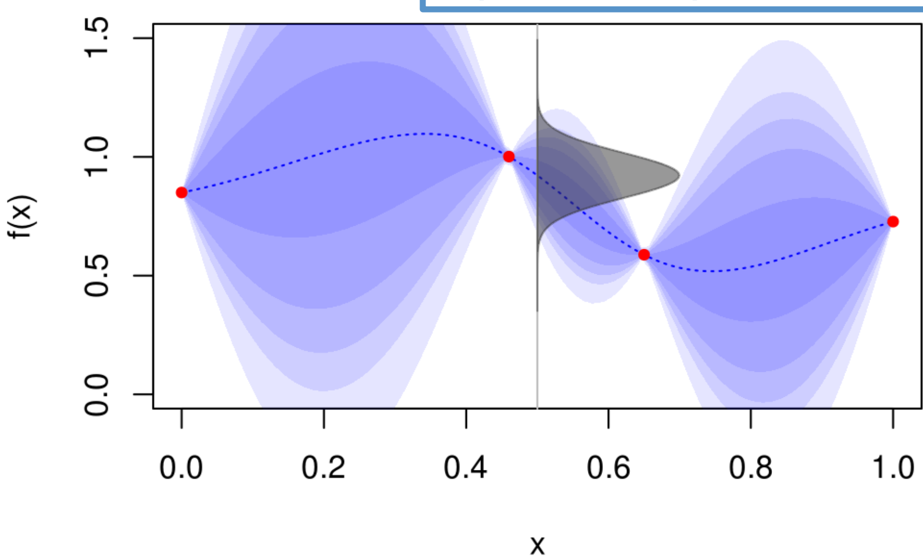
1. Calculation of the $f(x_i)$ for 1st set of points
   - $f(x_i)$ ~ results of the calculation for $x = x_i$
   - x_i ~ value chosen by random draw or LHS
     (+ the bounds of the parameters space)

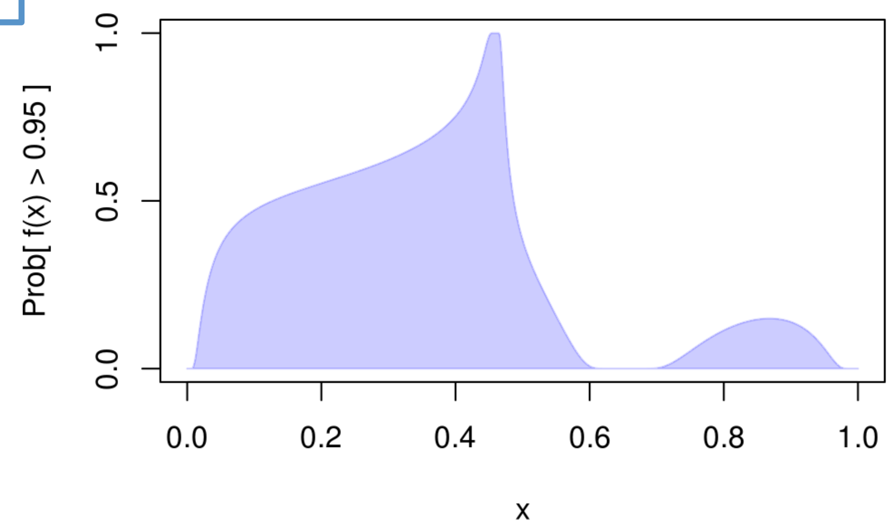




2. Interpolation by kriging
   - Surrogate function $f_1(x)$
   - Uncertainty between the x_i
   - Gaussian predictor:
     - $mean(f_1(x))$
     - $var[f_1(x)] = standard\ deviation(f_1(x))^2$

→ $P_1 = Prob(f_1(x) > 0.95)$

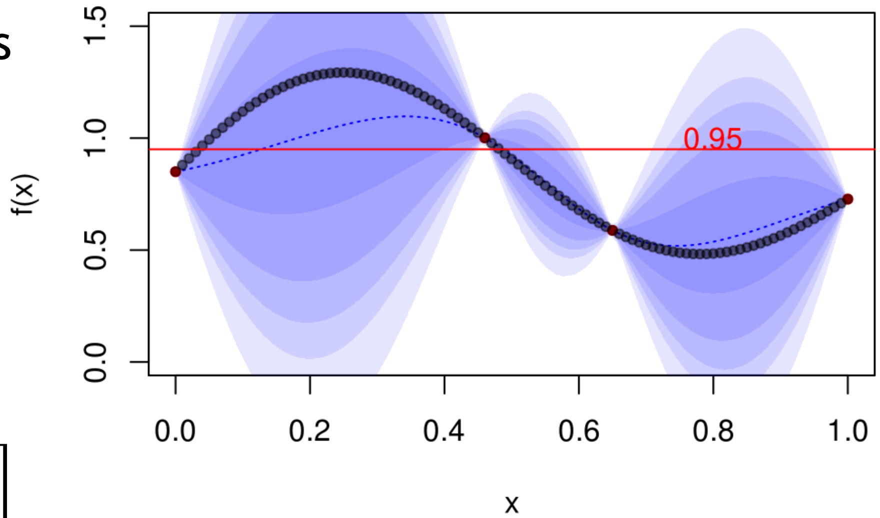




Principle of SUR and RSUR Algorithms

Calculation steps

1. Calculation of the $f(x_i)$ for 1st set of points



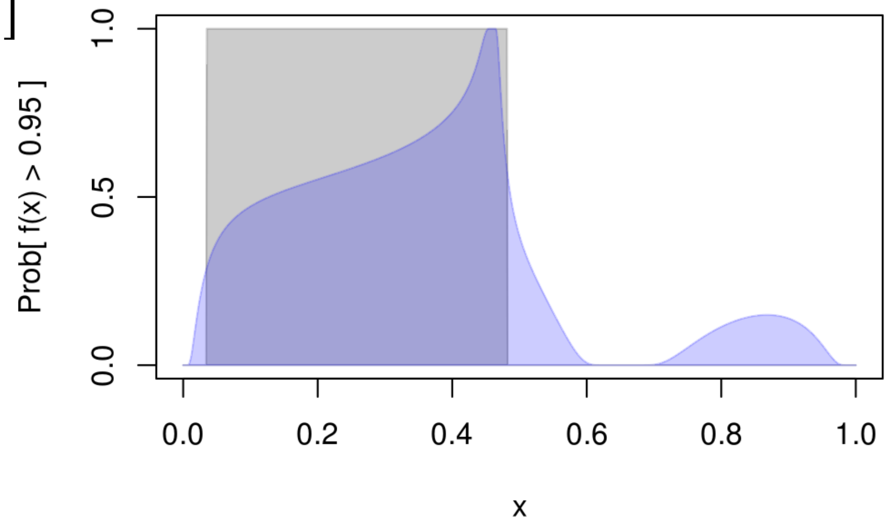
2. Interpolation by kriging

3. Search the next most **"valuable"** points x

Valuable is x such that

$$Min\left[\int P_{n+1}(x)(1-P_{n+1}(x))\,dx - \int P_n(x)(1-P_n(x))\,dx\right]$$

n ~ number of batch
P_n ~ probability that $f_n > 0.95$ with the previous points
P_{n+1} ~ probability that estimate $f_{n+1} > 0.95$
with previous points + the new point



4. Perform calculations for this new points

5. Repeat steps 2, 3 an 4

Principle of SUR and RSUR Algorithms

Calculation steps

1. Calculation of the $y(\vec{x})$ for 1st set of points

2. Interpolation by kriging

3. Search the next most **"valuable"** points x

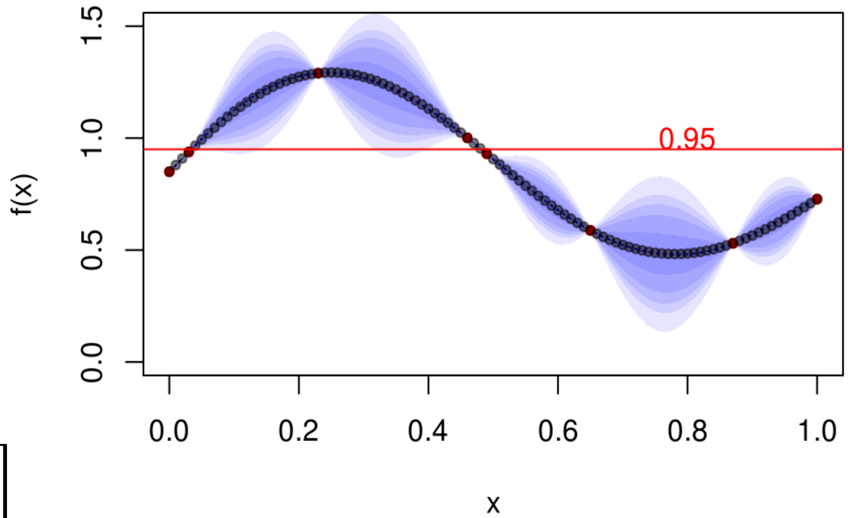
   Valuable is x such that

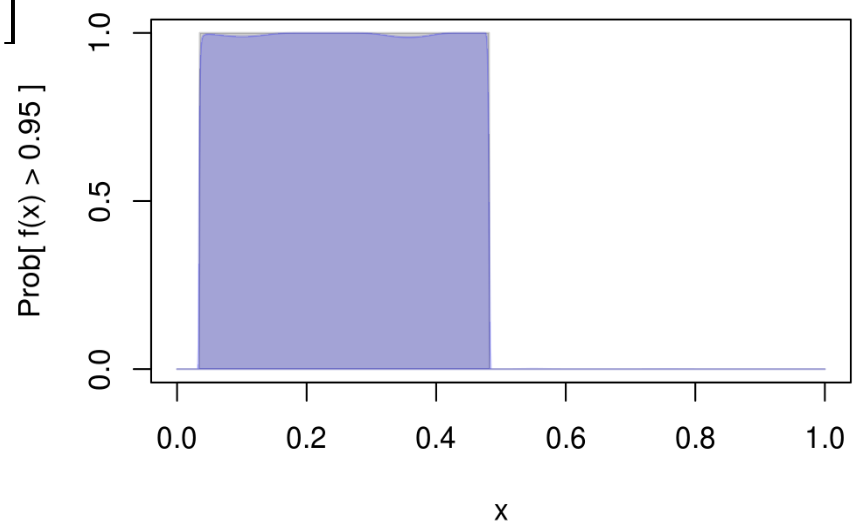
$$Min\left[\int P_{n+1}(x)(1-P_{n+1}(x))\,dx - \int P_n(x)(1-P_n(x))\,dx\right]$$

n ~ number of batch
P_n ~ probability that f_n > *0.95* with the previous points
P_{n+1} ~ probability that estimate f_{n+1} > *0.95* with previous points + the new point

4. Perform calculations for this new points

5. Repeat steps 2, 3 an 4





Principle of SUR and RSUR Algorithms

RSUR (Robust Stepwise Uncertainty Reduction) algorithm

Goal

- x_1 and x_2 control parameters
- x_3, and x_4 uncontrol parameters
- $f(x_1, x_2, x_3, x_4)$
- target value f_t

Find the subspace of parameters where an observable $f(x_1, x_2, x_3, x_4)$ is > or < at f_t for ***x_3 and x_4* the uncontrolled (or penalization) parameters.**
Or investigate all the (x_1, x_2) to determine the contour line where $f(x_1, x_2, x_3, x_4) = f_t$ *and the values of* (x_3, x_4) are penalizing.

SUR versus RSUR - Search "valuable" points $\vec{x}$:

SUR approach

P_n ~ probability that $f_n > 0.95$ with the previous points

$$Min\left[\int P_{n+1}(\vec{x})(1-P_{n+1}(\vec{x}))\,dx - \int P_n(\vec{x})(1-P_n(\vec{x}))\,dx\right]$$

RSUR approach

$$P_n \rightarrow P_n^*(x_1, x_2) = Max_{(x_3,x_4)}[P_n(x_1,x_2,x_3,x_4)]$$

$$Min\left[\int P_{n+1}^*(\vec{x})(1-P_{n+1}^*(\vec{x}))\,dx - \int P_n^*(\vec{x})(1-P_n^*(\vec{x}))\,dx\right]$$

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Calculation packages at IRSN/SNC

CLASS (Core Library for Advanced Scenario Simulation)

- **Dynamic fuel cycle simulation tool**
- **Open source package of C++ libraries using ROOT libraries**

https://root.cern.ch/

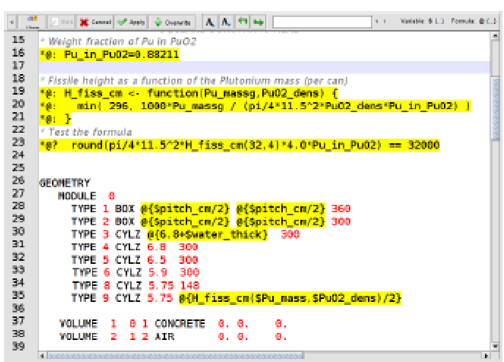
- **Collaborative development (CNRS and IRSN)**
- **Presented in details in the previous talks:**
  - “Reactor model in CLASS”. B. LENIAU
  - “Pu multi-recycling in PWR”. F. COURTIN
  - “Am mono-recycling using PWR - a waiting strategy”. A-A. ZAKARI-ISSOUFOU

Calculation packages at IRSN/SNC

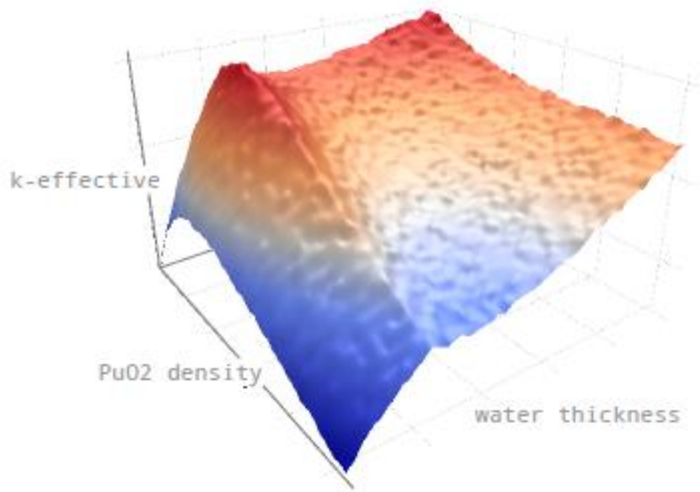
PROMETHEE

http://promethee.irsn.org

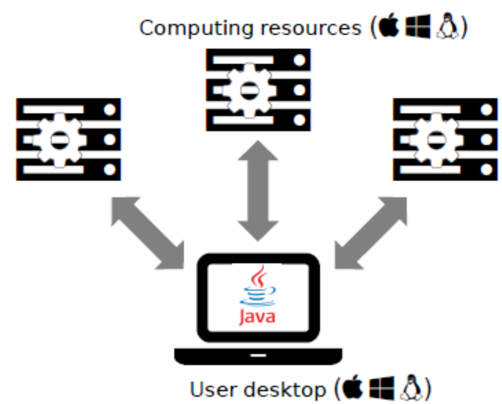
- **Generic front-end dedicated to parametric studies** (Editor integrated)
- **Parallel distribution of calculations relies on its cross-platform back-end** (any kind of computing resources are compatible: clusters, workstations…)
- **Plugins available with IRSN codes, MCNP, CLASS…** (new code plugin ~ working day)
- **Extensible architecture to plug algorithms for advanced engineering based on R language** (response surface, uncertainties propagation, optimization, calibration, inversion)



Input text file editor with parameters



Response surface model from MORET neutron simulation software



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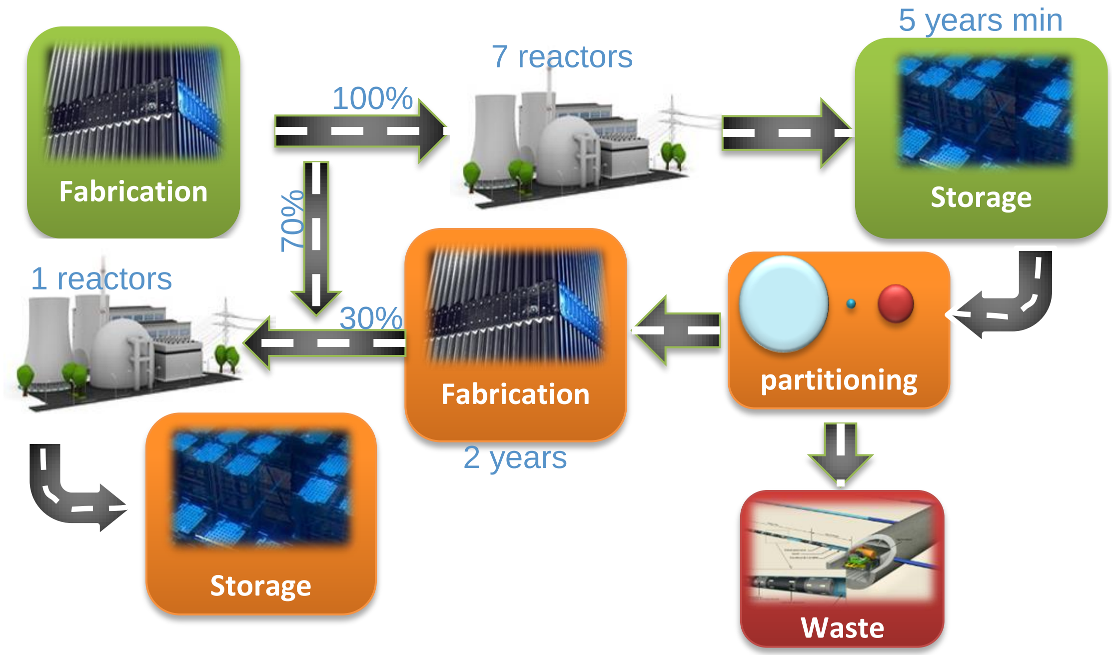
Scenario study

Nuclear reactors fleet

- PWR 2.785 GW_{th}
  - 7 reactors using UOX fuel
  - 1 reactor using fuel composed by 70% UOX and 30% MOX
  - The fuel achieves the defined burnup (BU_{UOX} & BU_{MOX} [35 , 55])
- Fuel cycle strategy
  - Only used UOX is recycled
  - Minimum waiting before recycling $5 \leq T_{cool} \leq 15$ years
  - Instantaneous partitioning
  - Recycling in chronological order
  - Fuel fabrication : 2 years



Application case

Scenario study

Context and Issue

Example of context

The electricity production with renewable sources increases and is consumed in priority.
The consumption stays constant or increases slower than the electricity production capacity.
The installed nuclear power stays constant and the facilities are unmodified.

> The load factors (LF) of the reactors decrease and the constrains of the fuel cycle facilities stay constant.

Issue

What are the fuel Burnup (BU_{UOX} & BU_{MOX}), the time before partitioning (T_{cool}) and the load factors (LF) of the PWR UOX that respect a constraint on the Pu content (C_{Pu}) in the fresh MOX fuel?

(The C_{Pu} is a constraint in the fabrication plant.)

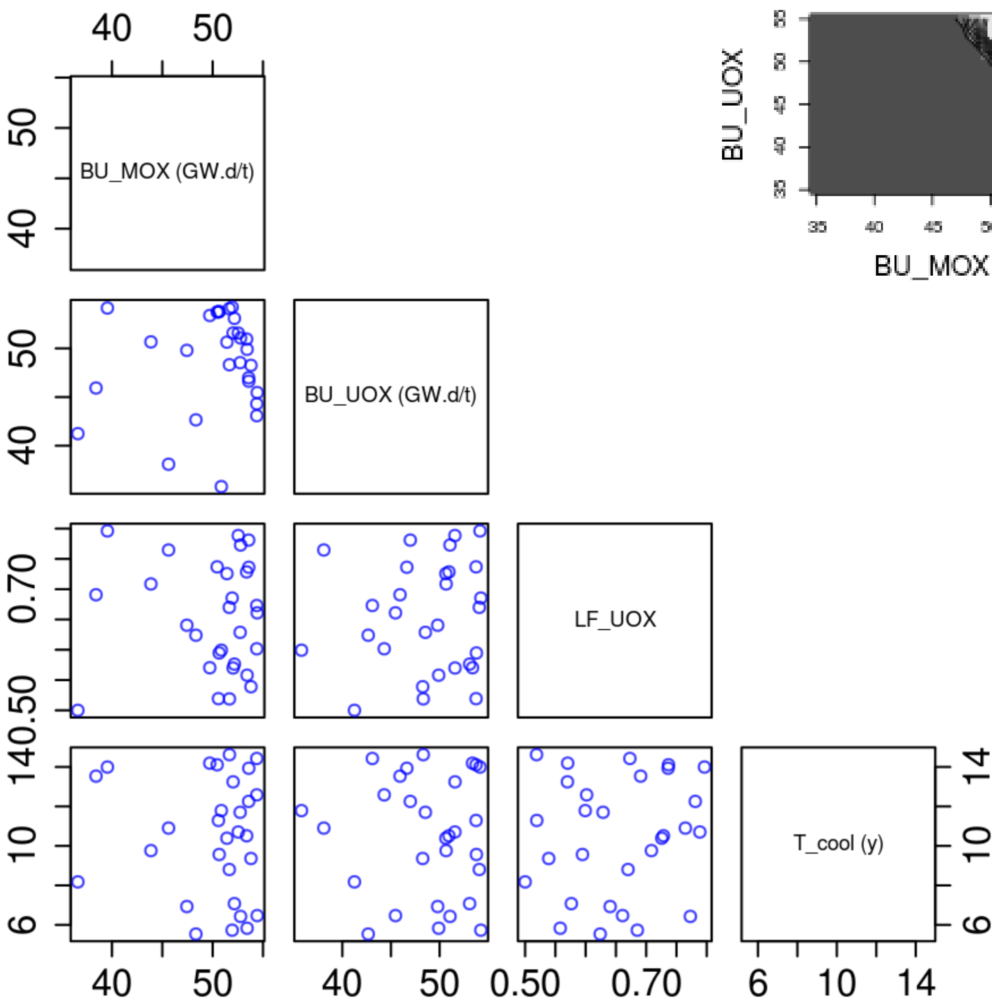
Parameter range and target value

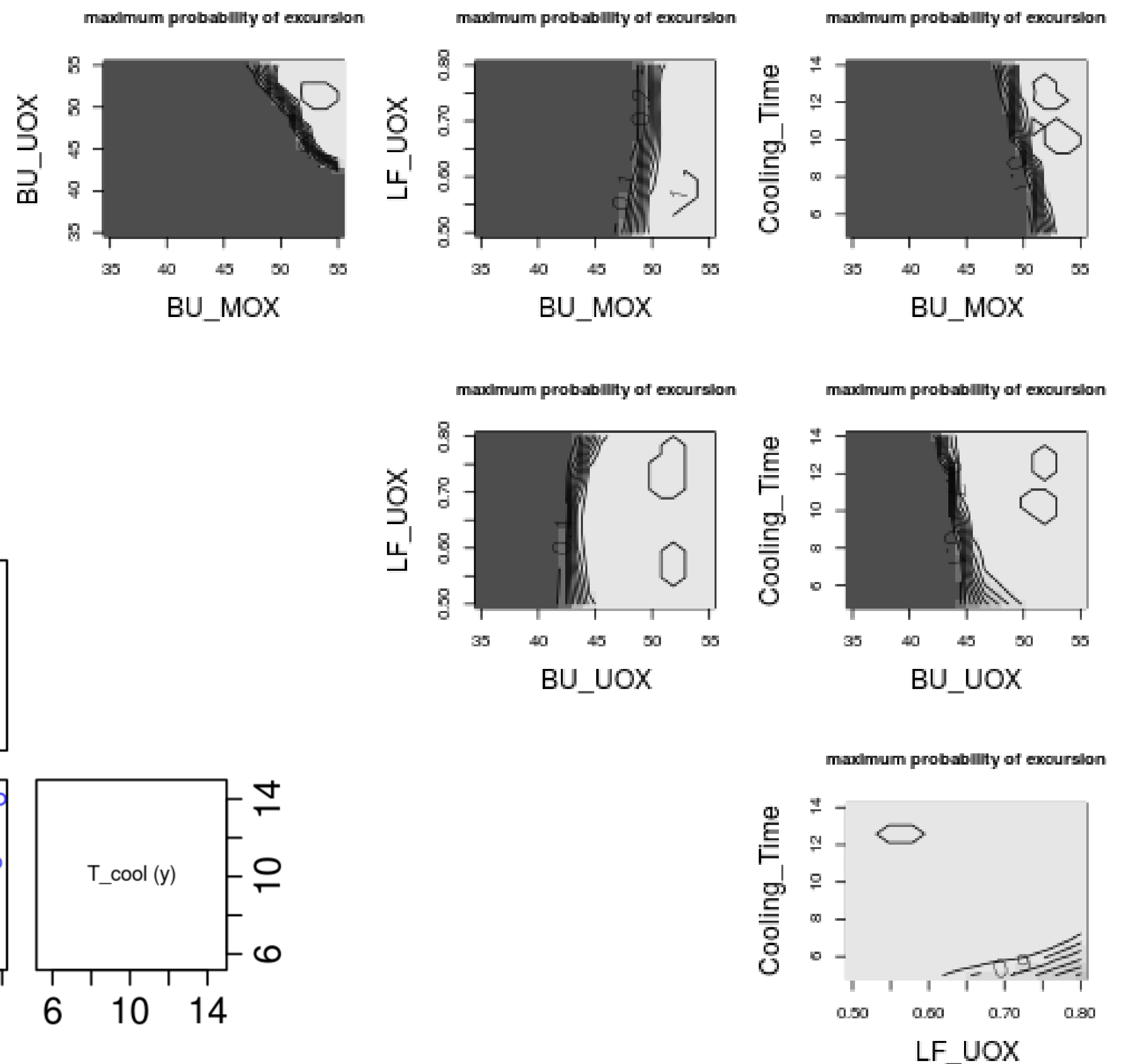
- BU_{UOX}, BU_{MOX} ~ [35 , 55] GW.d/t
- LF_{UOX} ~ [0.5 , 0.8]
- T_{cool} ~ [5 , 14]
- C_{Pu} = 10 %

BU_{UOX} and LF_{UOX} concern all PWR using UOX
The 4 parameters are independent.
LF_{MOX} stays constant (= 0.75).

Using the SUR algorithm

Which sets of the 4 parameters respect the fuel constraint?





Distribution of the calculation points

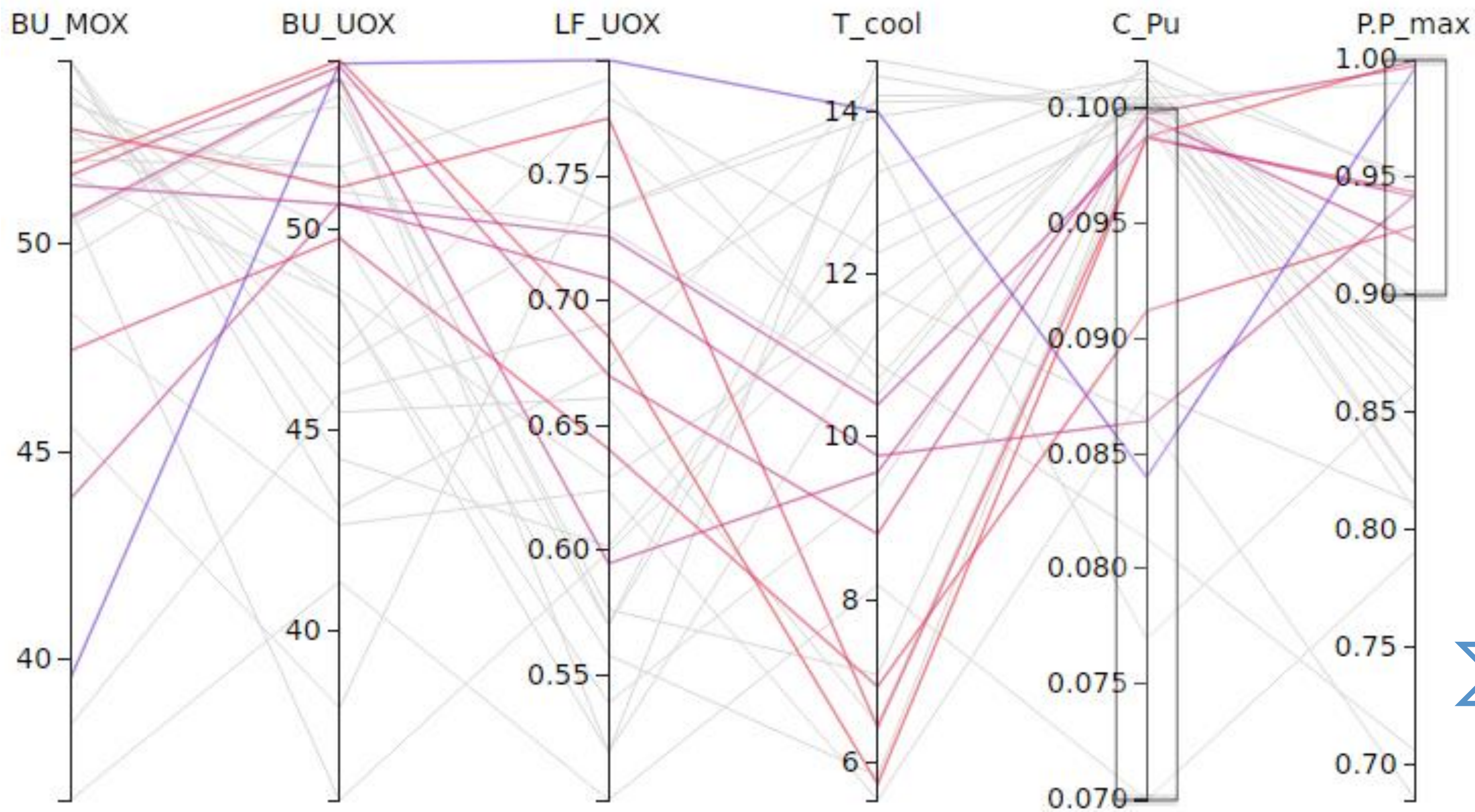
Contour lines of the results

↗ Using the SUR algorithm

Which sets of the 4 parameters respect the fuel constraint ?
What about the power production ?

Comment:

- In the simulation if the PWR-MOX hasn't any more of Pu, the reactor doesn't run. And try to restart at the next expected reactors fuel cycle.
- P.P_max is the sum of the power produce divide by the maximum value of all the simulation.



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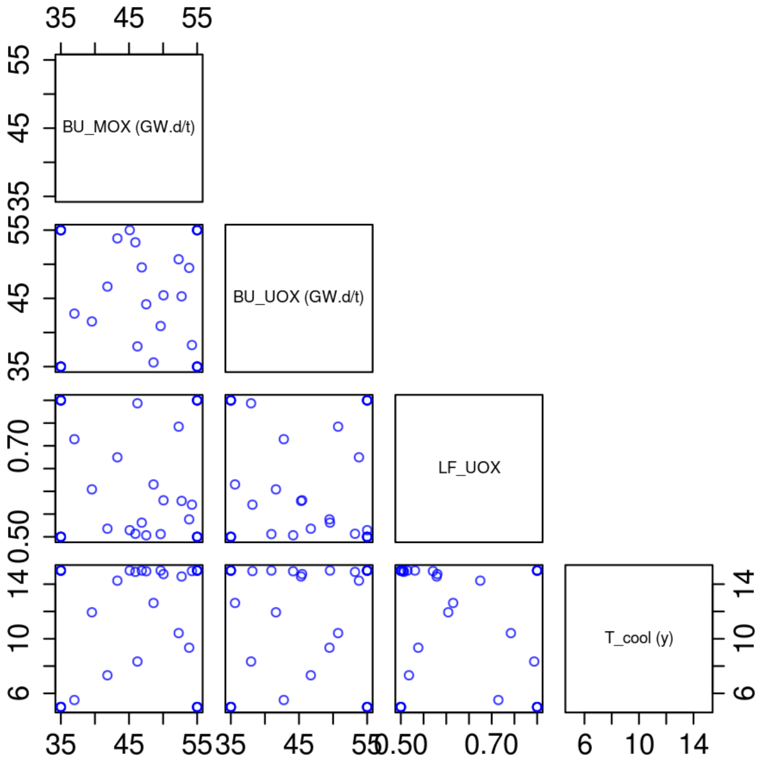
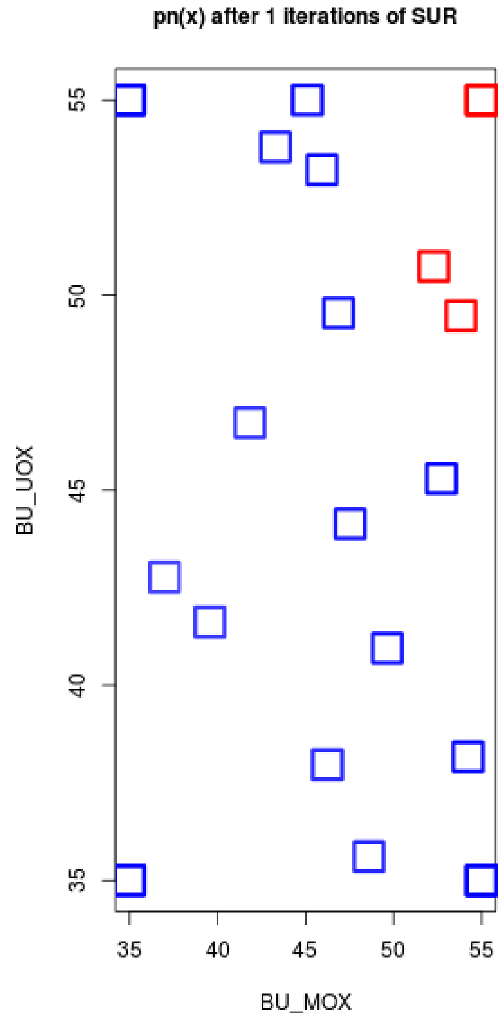
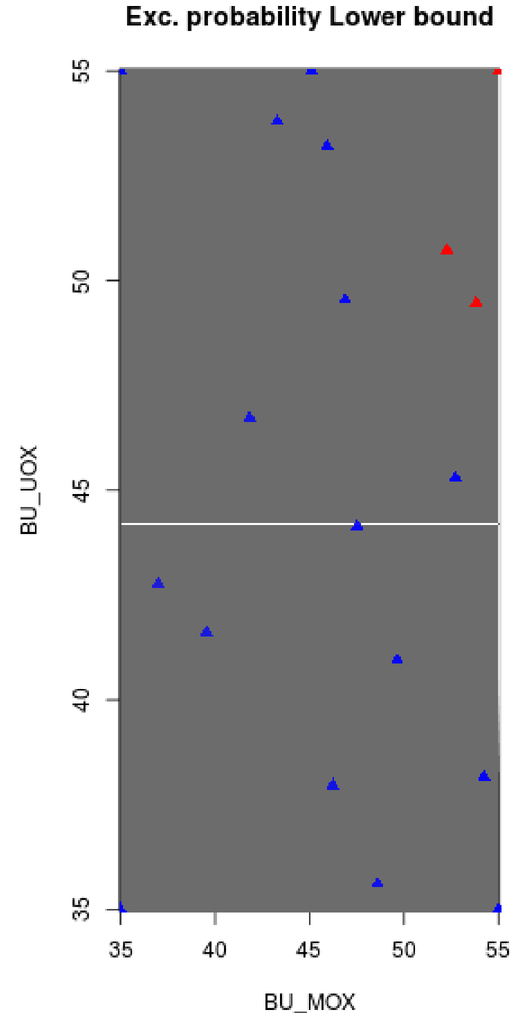
↗ Using the RSUR algorithm

If LF_{UOX} and T_{cool} are the penalizing parameters,
what are the sets of the BU_{UOX} and BU_{MOX} that respect the fuel constraint C_{Pu}?



Distribution of the calculation points





Calculation points with $C_{Pu} < 0.1$

Calculation points with $C_{Pu} > 0.1$

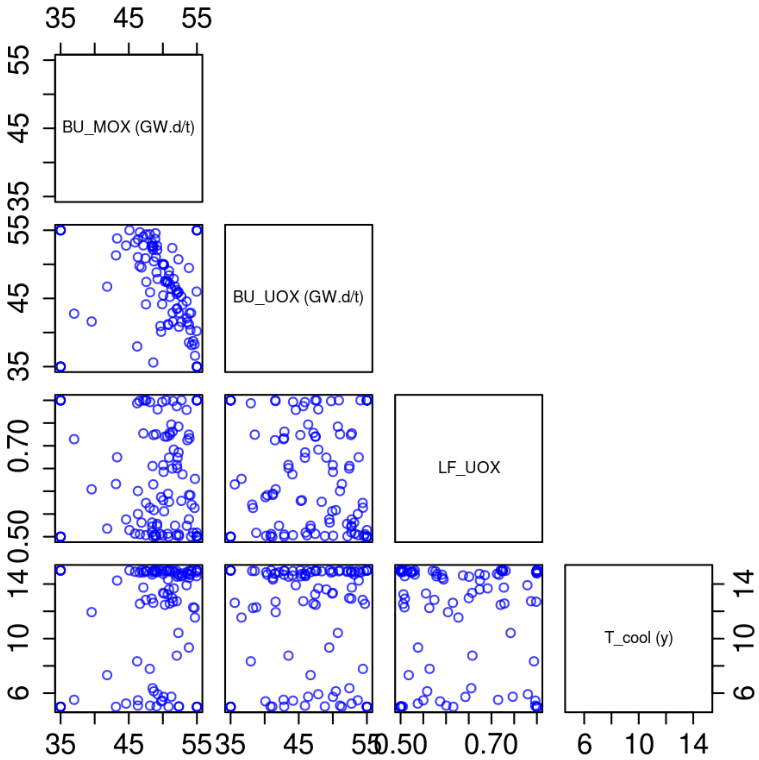
Probability than :

$C_{Pu} < 0.1$

$C_{Pu} > 0.1$

Using the RSUR algorithm

If LF_{UOX} and T_{cool} are the penalizing parameters, what are the sets of the BU_{UOX} and BU_{MOX} that respect the fuel constraint C_{Pu}?



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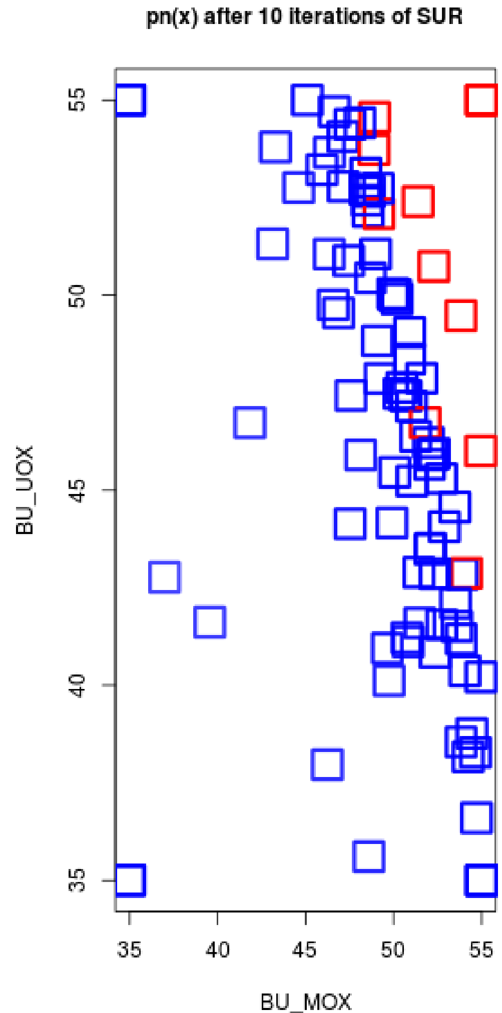

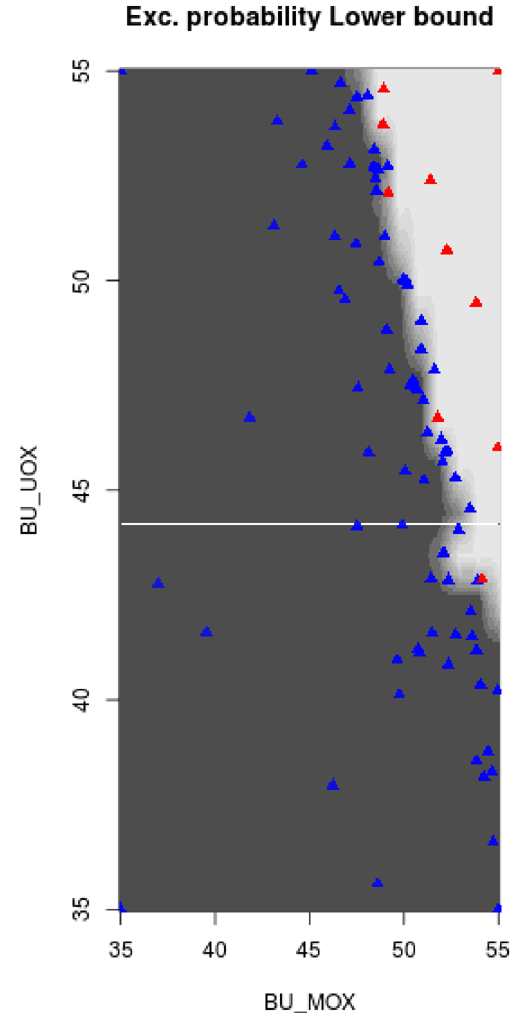

Calculation points with $C_{Pu} < 0.1$

Calculation points with $C_{Pu} > 0.1$

Probability than :

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↗ Using the RSUR algorithm

If LF_{UOX} and LF_{MOX} are the penalizing parameters,
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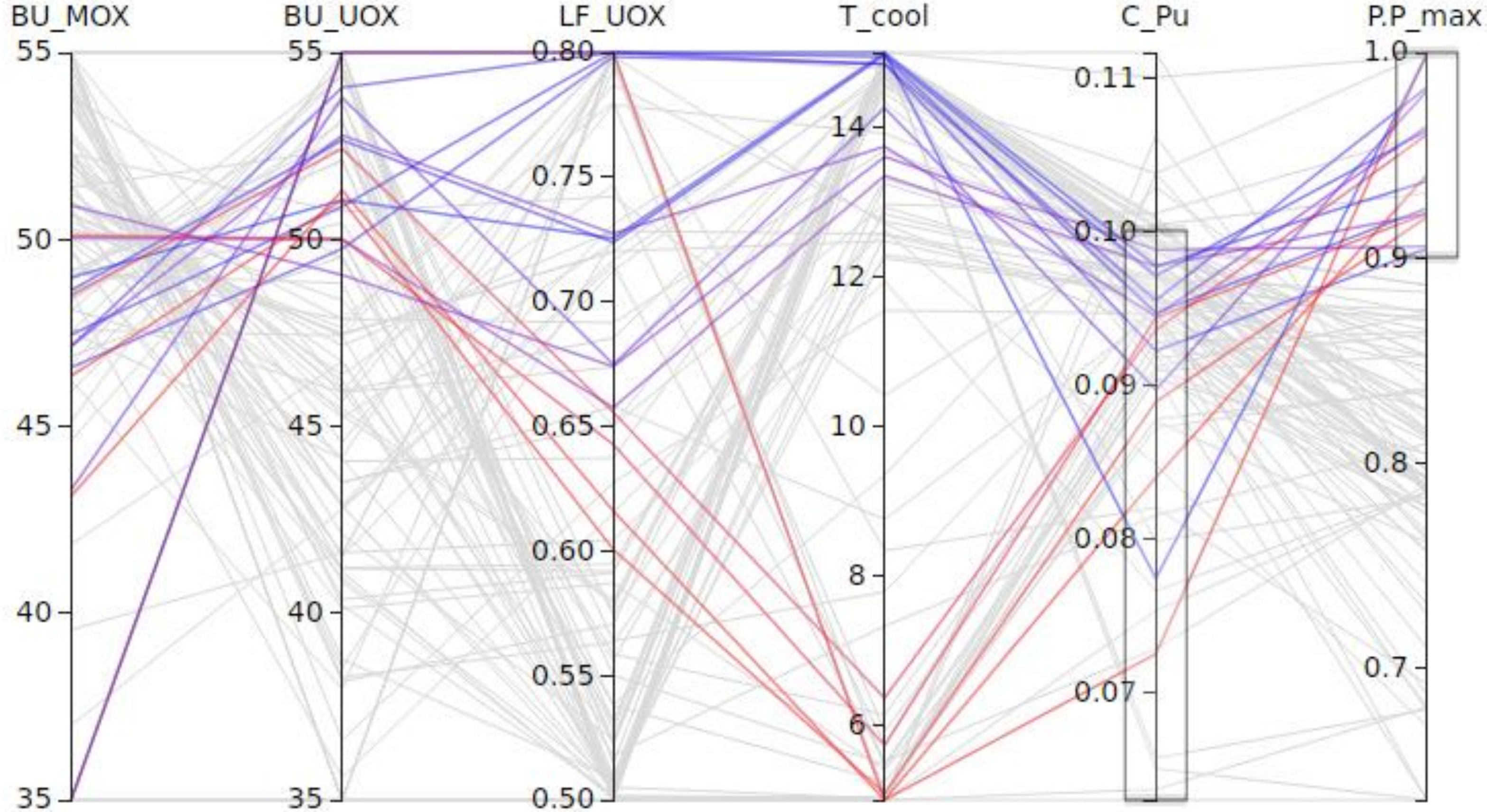
What about the power production ?



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Conclusions

- The fuel cycle scenarios studies require a parameterization approach
- Using algorithms can help to investigate the various options
- 2 examples of algorithm are presented: SUR and RSUR
  - Application with the CLASS and PROMETHE coupling
  - Determination of the subspace of parameters that respect a target value
  - For SUR approach all parameters are investigate without difference
  - For RSUR approach some parameters are define like uncontrolled or penalized parameters

Thank you for your attention

Questions?

Have a nice lunch!