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► **To cite this version:**

M. Ernoult, X Doligez, Nicolas Thiollière. Advanced Tools for Uncertainties Visualization and Analysis in Fuel Cycle Simulations. M&C 2023 - The International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, American Nuclear Society; Canadian Nuclear Society, Aug 2023, Niagara Falls, Canada. hal-04291910

HAL Id: hal-04291910

<https://hal.science/hal-04291910>

Submitted on 17 Nov 2023

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Advanced Tools for Uncertainties Visualization and Analysis in Fuel Cycle Simulations

M. Ernoult¹, X. Doligez¹, and N. Thiolliere²

¹IJCLab, Paris-Saclay University, CNRS/IN2P3, 91405 Orsay, France

²Subatech, University of Nantes, IMT Atlantique, CNRS/IN2P3, Nantes F-44307, France

ernoult@ijclab.in2p3.fr

ABSTRACT

Fuel cycle scenarios are “boundary objects” providing an opportunity to bring together different communities of stakeholders, with various knowledge and different, and sometimes opposing, interests in order to compare their visions for the future, organize their strategies and even cooperate. Uncertainties analysis is often difficult to discuss during this boundary interactions. A new method has been developed to calculate easily and represent uncertainties linked to our fuel cycle studies, representing the evolution of uncertainties with times and full distribution of outputs. The application of this method to a scenario closely inspired by the historical French fleet allows showing limited impact of uncertainties on global output like global plutonium inventory, but a significant one for inventories in specific stocks like UOX or MOX spent fuel stockpiles. Used as a support to the analysis of the impact of a new model for reactor evolution, the method confirms the significant of results from previous studies, notably those for the global plutonium inventory, the evaluation of the average value and the range of uncertainties are really similar for the two studied models. However, for the inventories in stocks, even when taken into account the large uncertainties associated, the differences appear to be significant.

KEYWORDS: nuclear fuel cycle, uncertainties, visualization

1. INTRODUCTION

Facilities of the nuclear fuel cycle have long operation time of several decades and the time between their design and the start of their operation is often also more than a decade. To be able to compare designs and sizing of those facilities that will allow future strategies, fuel cycle simulation tools have been developed [1,2]. They allow the simulation of the evolution of materials in the fuel cycle. Thanks to them, when a set of strategies for possible fuel cycle transitions is considered, the performance and possible outcomes can be evaluated through scenario studies. These Scenario studies are not at all necessarily simulations of a coherent futures, but more importantly, thought experiments to generate and observe potential consequences of possible future orientations of interest. However, even with the most care and study, the simulation of a transition strategy is necessarily subject to numerous uncertainties.

The majority of the scenarios developed by nuclear institutions and industry players are operational proposals based on feedback from the nuclear industry. They rely on technologies already developed or in use and draw primarily on hypotheses supporting the continued use of nuclear energy, with an unchanged installed capacity [3]. The scenarios proposed by the research world can sometimes free themselves from obligation of practical possibility to explore futures that disrupt the current system. Examples include research carried out on transmutation in ADS (accelerator-driven reactors) [4], actinides recycling in MSR (molten salt reactors) [5], and studies on the thorium cycle [6].

Scenarios often act as “boundary objects” providing an opportunity to bring together different communities of stakeholders, with various knowledge and different, and sometimes opposing, interests in order to compare their visions for the future, organize their strategies and even cooperate. To facilitate this role of

scenario study as boundary objects, and embrace the part of this role that makes them object of communication, producers of scenarios have to pay attention to the method they use to present their results, keeping them intelligible to the other communities.

In depth analysis have been made of the different type of uncertainties in electro-nuclear scenario studies [7,8]. They have brought to light six families of uncertainties: Base Physics Data (including Nuclear data), Physics modeling, Historical data, The choice of parameter values for the future strategy, Formulation of criteria to satisfy, allowing to figure out the relevant trajectories and strategies of interest as well as Hypotheses in the political, economic, industrial and societal decisions that may impact the nuclear fleet. [7] has represented the uncertainties of nuclear data can be, for the major part of nuclide decays and nuclear reactions in electro-nuclear scenario studies, and analyzed their propagation. The Fit Project [9] has started to tackle the question of uncertainties of physics modeling caused by essential simplifications or approximations in the resolutions of equations made to achieve acceptable computational costs. Several work dedicated to one specific modeling assumption have also be done in this direction [10,11]. [12] has studied the uncertainties of historical data. And [13] and [8] have developed new methods and tools to take into account uncertainties of external decision and evaluate their impacts. All theses analysis either present their result using complex mathematical objects, like Sobol indices or chaos polynomial coefficients [14,12], or using a very long series of one-to-one comparisons [15]. They allow in-depth understanding of interaction of uncertainties with scenario study results, but are not easy to share with other stakeholders and used as a basis of fruitful exchanges. The indices ask for a math background that is rare in communities without a strong scientific background, and the length series of dual figures are difficult to digest for strategic actors that have less time. Both are not easy to share with other stakeholders and used as a basis of fruitful exchanges. This lead to uncertainties not being well communicated during discussion with different communities of stakeholders and often not taken into consideration as much as their level would require.

We therefore developed dedicated associated tools to calculate easily and represent uncertainties linked to our fuel studies inspired by the graph with colored area used in IPCC summaries for policy-makers.

2. NEW TOOLS FOR VISUALIZATION OF UNCERTAINTIES

To help the calculation and representation of uncertainties, a new tool has been developed. It takes the form of a python package, providing many easy-to-use function for launching of post-treatment scripts for the fuel cycle simulation tool. Currently only CLASS [1] is supported, but the functions have been designed with modularity in mind and other simulation codes would be easy to plug as long as their input files are available in text form.

This package can read an input file created for the fuel cycle simulator and auto-extract the variable. It can then change them depending on the need of the user or the algorithm and launch the simulation or just produce a new input file to be launched by the user. The new values for the variable can be explicitly given or sampled following a random distribution. Most common random distributions are available, notable uniform, normal, triangle and log-normal. With those integrated functions, a whole script of analysis takes only a few lines. Once the calculations are done, outputs from a large number of simulations coming from the same initial input are easily visualized together, and distribution and statistical indicators are available. All figures presented in this paper are a direct result of the package.

3. APPLICATION TO HISTORICAL FRENCH FLEET SIMULATION

3.1. Characterization of uncertainties

To demonstrate the capabilities of this tool, we applied it on the last published scenario study made with CLASS, the simulation of a scenario closely inspired by the history of the French Fleet from [16]. This study is a relatively precise simulation of the deployment of a fleet of PWR using first only UOX fuel and starting later to use MOX fuel recycling plutonium from spent UOX assemblies. This scenario is closely inspired by the French nuclear fuel cycle from its start to 2021, and takes into account individual reactor and the specific fuel management strategies that have been used in each of them in the past and does every

simulation using both MLP [17], and DONJON [18] physics models in order to check if the result are still significant when considering uncertainties.

An input based on [16] has been created with options for MLP and DONJON physics models. The auto-analyze from the package found the 321 variables. Uncertainties about a lot of these variables have then been characterized. For example, the initial input used the nominal burn-up for each campaign in each reactor, but data show that there is variation of the burn-up between irradiation cycles. For example, uncertainty has been associated with all burn-up following a triangular distribution peaking at the nominal and using the minimum and maximum observed burn-up in the campaign as limits. Uncertainties on load factors that are subject to the need of the electricity network have been modeled by a normal distribution with the observed averaged and a relative standard deviation of 0.015 allowing to reach the most extreme observed annual value. However due to limitation in CLASS, load-factors are only sampled once per reactor and kept constant during the whole life of the reactor. The parameters of the physics models have also been associated with uncertainties coming from the comparison of these simplified model with reference calculation. For example, the reactivity margin (threshold k) for UOX fuel has been associated with a normal distribution of average 1.034 and stdev of 0.005 coming from the result of [19]. Uncertainties have also be associated with starting and stopping date of reactor to represent the fact that in reality, reactor do not start at full power from day one like we do in our CLASS models.

In total 260 of the 321 variables have been attributed uncertainties.

3.2. Visualization of operational parameter uncertainties

After the application of the package to extract and replace the variables with sampled one, 100 fuel cycle simulations have been done with the MLP physics models. The agglomeration of the result allowed to produce the figure 1 in which we can see the evolution of the plutonium inventory in the total cycle, in the storage for spent UOX fuels and spent MOX fuels. The middle line represent the average value and the colored area the standard deviation calculated on the 100 simulated trajectories and the total range observed in these trajectories. The figure shows that the uncertainty on the global plutonium inventory is small but the one for individual stock is far higher, up to 50% for the UOX spent fuel at some time. By looking at the value of an output at a set time, we get distributions that represent visually the level of knowledge extracted from the simulation. Outside of the average, standard deviation and limits that were also visible in figure 1, the distribution of figure 2 allows this way to see that the distribution is asymmetric and that the average is not the most probable value.

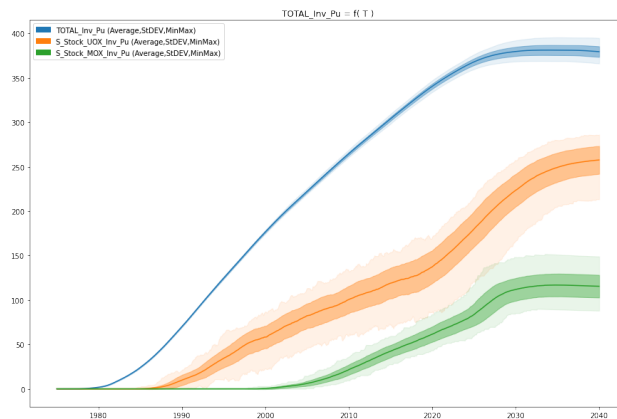


Figure 1: Representation of plutonium inventory evolution with the associated uncertainty
Blue : Total Inventory, Orange : Inventory in UOX Spent Fuel storage, Green : Inventory in MOX Spent Fuel storage

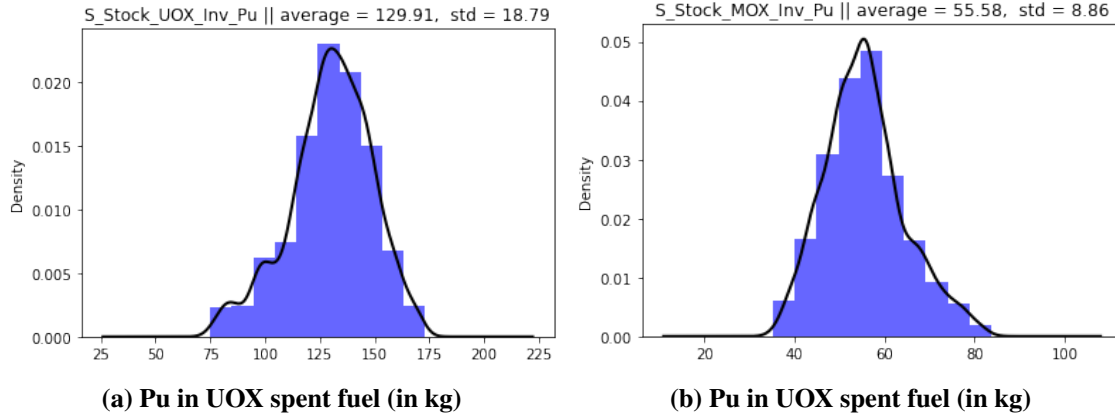


Figure 2: Plutonium mass in spent UOX and MOX fuel : distribution due to uncertainties

3.3. Uncertainties on plutonium isotopy

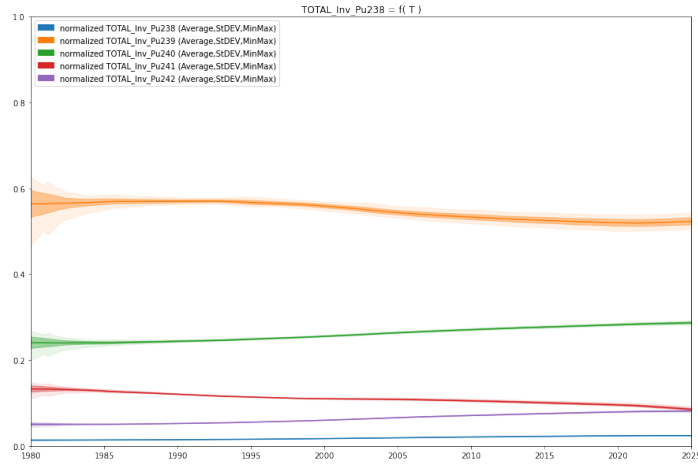
The same tools providing easy access to uncertainties on plutonium inventories presented in the previous section can provide, by adjusting an option, the distribution of plutonium isotopic composition in various places. Figure 3 shows the agglomeration of such isotopic composition in the total cycle, in the storage for spent UOX fuels and spent MOX fuels. In this section, compared to previous figures, the times after 2025 are cut out because after this date the simulated fleet does not represent any realistic trajectory. Our scenario inspired by the Historic French fleet start to phase out, but no new reactors are build. For accumulation of inventories, this quick decrease in active nuclear power-plant had little impact because almost new spent fuel is created, but time without active reactor have an impact on isotopic composition of plutonium that is not of interest for fuel cycle analysis.

In the figure, we can see that after a couple of initial year during which the relative uncertainties are really high due to some different synchronization of the first spent fuel discharge, the uncertainties on isotopic composition averaged on all the plutonium present in the fuel cycle is very low, but when looking as the isotopic composition of the plutonium in specific spent fuel storages the uncertainty, even if it tends to decrease with time, stay high during the whole simulation. The uncertainty is specially high for the content of lighter plutonium isotopes with the standard deviation on the plutonium 239 in the plutonium inside the UOX spent fuels being close to 10% in 2020. This high uncertainty leads plutonium qualities that could go from 40 to 80%, a huge difference that would definitely impact which recycling strategies are applicable to these spent fuel or not. For plutonium in spent MOX fuel, uncertainties are slightly lower once the spent MOX fuel start to be available in reasonable number after 2010, but the standard deviation on the plutonium 239 and plutonium 240 in its plutonium is still higher than 5%, opening the way at very high (over 60%) and very low (under 40%) quality of plutonium. Designing a recycling strategy working for this kind of large range, would be really challenging, so reducing uncertainties on this aspect would really help future fuel cycle studies.

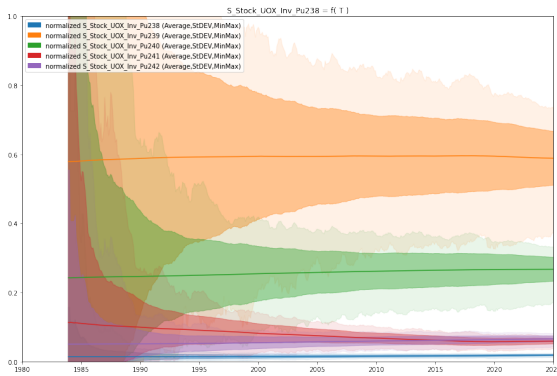
3.4. Inputs uncertainties with impact on plutonium-239 inventories

In the tools presented in this paper, several statistical tools are included to quickly and easily analyze the set of trajectory obtained exploring the uncertain values of inputs.

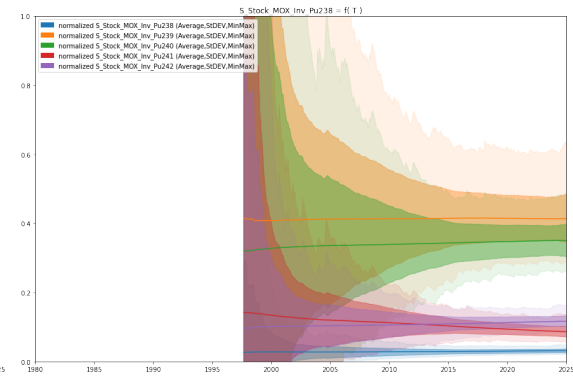
By calculating correlation between the change of each input and the change of one output of interest, Pearson coefficients have been determined help to determine the uncertainties of which input we need to decrease if we want to decrease on the output. An example of such result in table 1 which show the ten inputs (out of the 260 considered) contributing the most to the uncertainties on the total inventory of plutonium-239 in the whole cycle in 2020. In these output, association of city name with number represent French reactor. The city name is the city next to which the power plant site lies and the number is the place



(a) Pu isotope in the whole cycle



(b) Pu isotope in UOX spent fuels



(c) Pu isotope in MOX spent fuels

Figure 3: Ratio of each plutonium isotopes to the global plutonium inventory, for the full cycle, the stocks of spent UOX Fuel and the stock of spent MOX fuels
Blue : Pu238, Orange : Pu239, Green Pu240, Red : Pu241, Lila : Pu242

in chronological order of the construction of reactor in this power-plant. Fessenheim 2 is the second reactor built at Fessenheim power station. The error on correlation is here linked to the process of calculating the coefficient and is an algorithmic and statistical not, not an uncertainties like the the one presented in graphs elsewhere in this paper.

The MOX reactivity margin is used in our MLP-based models to compensate the fact only assembly-level simulation are used. In order to insure that the reactor could stay critical even with the neutron leakage that are not taken into account in these simulation, the model demands the capacity to maintain a multiplication factor slightly higher than 1, adding to it the MOX reactivity margin. A higher margin implies that more plutonium need to be loaded into the MOX assemblies, leading to an increase in plutonium burned. The uncertainty carried by this margin has thus logically an impact on the total plutonium-239 inventory in 2020

The MOX mass equivalence, is a compensation used in the current modeling of our scenario inspired by the historical French Fleet to adjust the total number of MOX assembly irradiated to take into account the fact this amount is lower than the initially planned one. It is lower than 1. The uncertainty carried by this factor directly impact the amount of MOX fuel loaded into reactor and such impacts the total plutonium-239 inventory in the cycle.

Uncertainties in cooling time will impact the minimum decay time of plutonium before being recycled.

Table 1: Correlation between change of values in inputs within their uncertainties and change in total plutonium-239 inventory in 2020 : 10 most impactful inputs

Input	Pearson Coeff.	Error on Pearson Coeff.
MOX reactivity margin	-0.71	2E-16
Cooling Time	-0.33	7E-4
MOX mass equivalence	-0.31	2E-3
Load factor of Bugey 4	0.28	4E-3
Start of Bugey 4	-0.28	0.01
Start of Fessenheim 1	0.26	0.01
Load Factor of Paluel 3	0.25	0.01
Start of Paluel 2	0.24	0.02
Start of mixing at Dampierre 3	-0.23	0.02
Start of Blayais 1	-0.22	0.03

Plutonium with less decay time have higher quality and lead to lower amount loaded in MOX assemblies.

Load factor and starting date impact the amount of energy produced by the reactor because no reactor have reached the end of their lifetime in 2020.

All these links between inputs and the plutonium inventory can be expected, but their ranking is not obvious because of the interaction of the sensibility of the output to each input and the size of the uncertainty associated with it. The new tools give access to these value with minimal human work for any trajectories implemented with the CLASS code.

3.5. Impact of Missed loadings of MOX fuels

During the simulation of the fuel cycle, it happens that the simulation code is not able to build a MOX fuel according to fulfill the expressed needs. It usually happens when the quantity or the quality of the available plutonium is too low. These failure to build the wanted fuel lead to missed loadings of MOX fuels [20].

Some of the trajectories simulated by our new tool to explore the space of uncertainty of the inputs have experience these kind of missed loadings. This happened in 19% of the explored space. This percentage does not means in any way that there were 19% of chance to have missed loadings in the historically planned French fleet and that the French nuclear sector took the bet. Indeed our scenario inspired by the historical French fleet consider uncertain a lot of factors that would be known by people managing a real nuclear fleet. Furthermore in a real fuel cycle, if no acceptable plutonium is available to build MOX fuel for a reactor, adaptation can be made, either by using mixes of plutonium or by using UOX assemblies, to ensure that the reactor is loading and is able to produce the electricity it should. However these adaptations lead to a difference in the effective MOX fraction and missed loading are an indicator to easily detect that.

When detecting missed loading, we could put constraint on input, and check which uncertainties we should reduce to ensure that the fuel cycle will be able to support the planned MOX assemblies. To do that we could use our tools and repeat analysis done on plutonium-239 and presented in the previous section but changing the output of interest to be the number of missed loading in the trajectory. The selection and representation of the data could be done as easily, however the statistical tools would need adaptation because they have been developed for continuous outputs and the number of missed loadings is a discrete one, specifically a

discrete one where many trajectory will have the same value. Due to the need of tools adaptation, this study has yet to be done.

Another concern that these missed loading raise is the bias they can cause in our other and previous analysis. All analysis done before have been done using all trajectories, including those with missed loading and therefore not respecting the wanted power history and MOX fraction. To evaluate the bias that the inclusion of these particular trajectories in our analysis, we've redone it using only the 81% without missed loading and compared the result.

Most result are indistinguishable, specifically the graphs. How ever we observed some discrepancies in the evaluation of the impact of singular inputs that are presented in table 2.

Table 2: Change in calculated correlation depending of inclusion or exclusion of trajectories with missed loadings
(only changes with error on the change of correlation correlation below 100%)

Input	Change of Pearson Coeff.	Error on the change
Cooling Time	-0.12	0.05
Start of Paluel 2	-0.07	0.02
Start of Blayais 1	0.05	0.04
Load Factor of Bugey 4	0.05	0.04
Load Factor of Paluel 3	-0.04	0.02
Start of Blayais 4	-0.03	0.03
MOX mass equivalence	-0.02	0.01

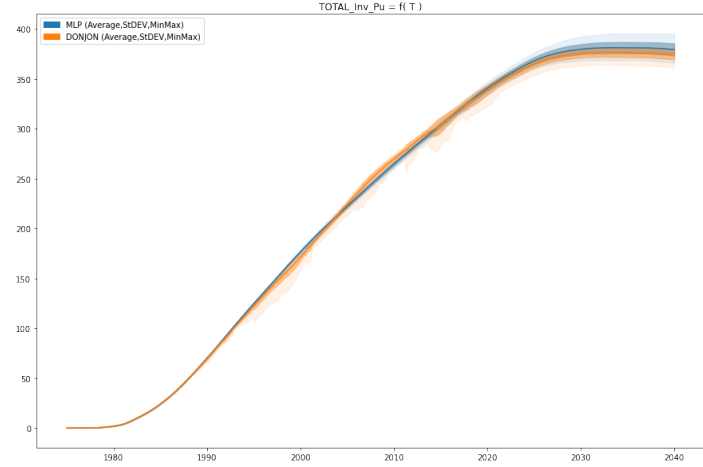
This table present the change in the correlations calculated with the two sets of trajectories, the one with all the trajectories and the one where the trajectories with missed loadings have been removed. The only change with a effect higher than three standard deviation is the change on the observed cooling time link with the plutonium-239 inventory, probably linked to an over selection of shorter cooling time in the set where the trajectories with missed loadings have been removed.

3.6. Visualization of the impact of model choice

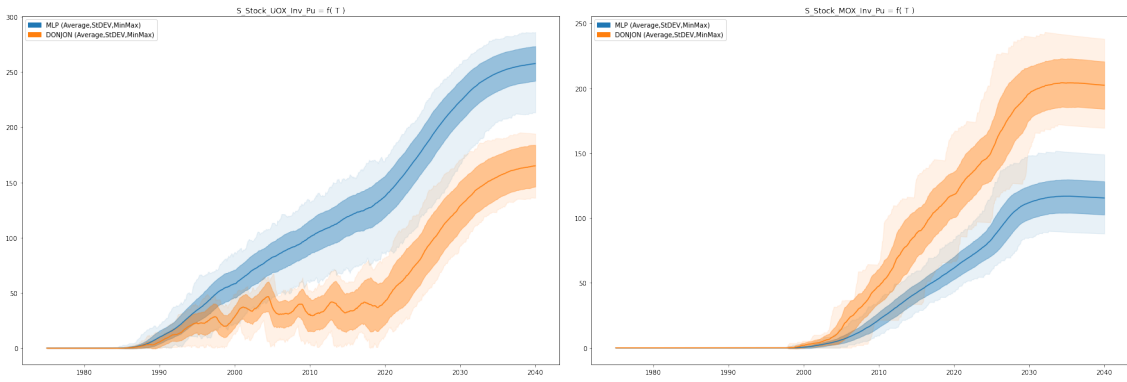
To compare directly and visually the result of two while taking into account their uncertainties. In this section we use this opportunity to check is the result of [16] and the difference they saw between the two models are still significant when uncertainties are considered. We created a new input differing only by the use of DONJON-based physics models and uses the newly developed package with the same characterization of uncertainties to run 30 sampled fuel cycle simulations. And two sets of outputs have been compared with the visualization tools. Figure 4 present inventories of plutonium to result presented in figure 1 but with one color per model, blue for MLP and orange for DONJON. We see that for the global plutonium inventory, the evaluation of the average value and the range of uncertainties are really similar with both models. However for the inventories inside the stocks, even when taken into account the large uncertainties associated, the differences observed in [16] are significant.

4. CONCLUSIONS

Fuel cycle scenarios are “boundary objects” providing an opportunity to bring together different communities of stakeholders. These decision-maker can have various knowledge and different, and sometimes opposing, interests. Scenarios can help them to compare their visions for the future, organize their strategies and even cooperate. Uncertainties analysis is often difficult to discuss during this boundary interactions.



(a) Impact on total Pu inventory



(b) Impact on Pu inventory in UOX spent fuels (c) Impact on Pu inventory in MOX spent fuels

Figure 4: Impact of model choice on plutonium inventory in stocks with the associated uncertainty
Blue : using MLP Assembly-based models, Orange : Using DONJON core-based models

New tools have been developed allowing calculating easily and represent uncertainties linked to our fuel cycle studies in a an easy to read fashion. It also allows representing evolution of uncertainties with times and full distribution of outputs. The application of this method to a scenario closy inspired by the historical French fleet allows showing limited impact of uncertainties on global output like global plutonium inventory, but a significant one for inventories in specific stocks like UOX or MOX spent fuel stockpiles. Used as a support to the analysis of the impact of a new model for reactor evolution, the method confirms the significant of results from previous studies, notably those for the global plutonium inventory, the evaluation of the average value and the range of uncertainties are really similar for the two studied models. However for the inventories inside the stocks, even when taken into account the large uncertainties associated, the differences observed are significant.

ACKNOWLEDGEMENTS

We would like to express our gratitude to the NEEDS program of the Energy Unit of the CNRS for the financial support through the CINEASTE project. We also thank Dr. Baptiste Mougnot, for his major work as the main developer of the fuel cycle simulator CLASS

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