Proceedings of the 19th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New Orleans, LA, USA

CASK LOADING PERFORMANCES: COMBINED DATA MINING AND SHIELDING INEQUALITIES

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Abstract

The IAEA recommendations (see Ref. 1) request that, under routine conditions of transport, shielding analyses consider loading plans with the maximum radioactive contents. In parallel, storage's regulators request now to define generic loading plans.

Thus, cask designers are facing a challenge to implement a method defining maximum generic loading plans without restrictions on new cask design or cask license renewal. To avoid unnecessary restrictions of the authorized content characteristics while still meeting the new requirements, Orano TN has adapted its licensing process and developed a very elaborated shielding analysis method (see Ref. 2).

The result of this method, part of certificates, is expressed under the shape of a linear inequalities system allowing to optimize efficiently the cask capacity by normalizing with reference loadings while still meeting the radiation criteria. Major advantages of this approach include the following: dose rate calculation is not required at each loading; it provides a high loading flexibility for the customers.

In the frame of the design approval of the dual-purpose TN®24 E package by the German authorities (BfE, TÜV) this method has been validated. Furthermore, in the frame of the design approval of the transport casks TN®G3 and TN®17 MAX, and in the frame of the license renewals of the TN®24 BH, TN®24 SH, TN®24 DH, TN®24 XLH and TN®9-4 package, this method has been also implemented and validated by the French authorities (ASN, IRSN).

The so determined linear inequalities system ensures the transport acceptance of any radioactive content regarding the regulation and allows using highly heterogeneous loading plans. The use of this validated method is decisive to give the cask user the maximum flexibility for an optimized management of its cask loading plans on the long term.

Indeed, using algorithms from data science, an optimization analysis of the cask loading plan solutions can be performed to get well-defined "best loading plan". These solutions must maximize the total residual thermal loaded and in parallel minimize the radiation levels around the cask.

This paper will describe the approach and the tool developed by Orano TN and its positive outcomes.

Introduction

A cask for the transport of spent fuel assemblies is a multiphysical system under 4 fields of stresses, that are (see Figure 1):

- the prevention of criticality: no development of fission reaction generation is allowed,
- the mechanical stresses: cask body and basket designs present a high mechanical resistance to guarantee the containment of the radioactive content,
- the control of the external radiation levels (Dose Rates): the steel body shields gamma emissions from spent fuels and the resin compound shields neutron emissions from spent fuels,
- the prevention of damages caused by heat: residual thermal power (P) from spent fuels must be controlled to keep cask components below their critical temperatures (T^{max}).

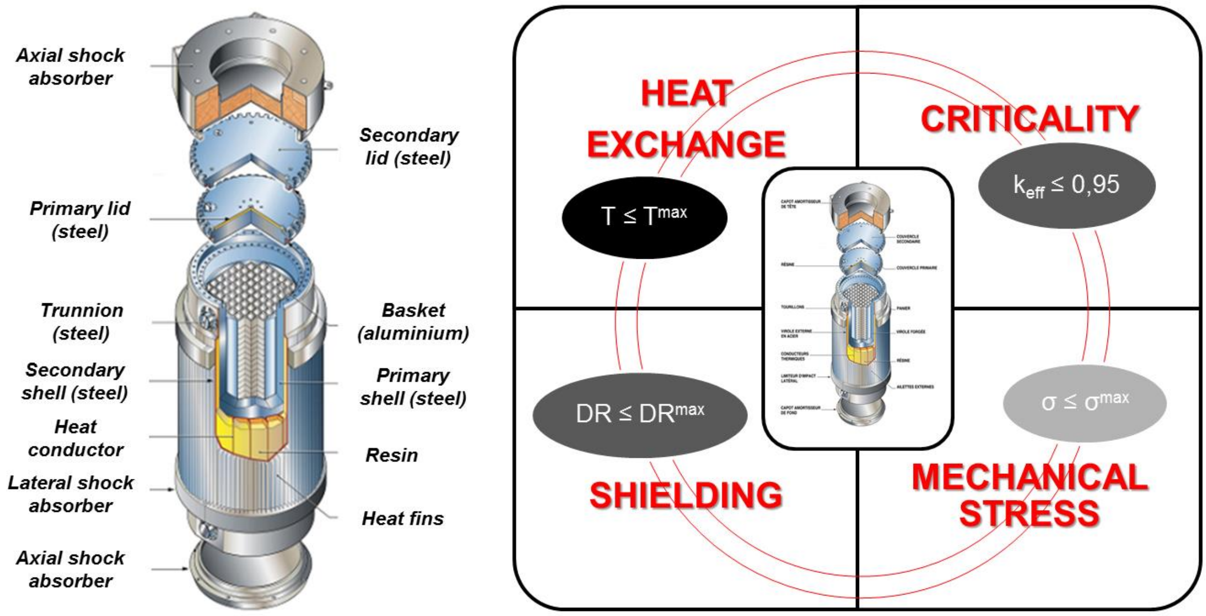

Figure 1: Cask components and multi field of stresses

All these fields have cross interactions that produce a complicated cask design in which each component is part of several safety functions. For example, regarding the thickness of the cask body a compromise must be found between the control of the external radiation levels and of the mechanical stresses. Also, the chemical composition of the resin compound must be qualified to support high temperatures generated by the residual thermal power from spent fuel assemblies.

In term of general behavior, the 4 fields of stresses could be classified in two categories:

- the operational stresses, composed of the heat exchange and the radiation shielding,
- the system stresses, composed of the criticality and the mechanical stresses.

System stresses are fixed with the cask design. On the contrary, operational stresses must be managed with attention for each loading plan. Indeed, the cask loading management must provide admissible loading plans of spent fuel assemblies.

Cask loading management – Constraints Satisfaction Problem

An admissible loading plan involves a selection of spent fuel assemblies and their layout in the cask basket (see Figure 1). In first step, a selection of fuel assemblies, presenting a residual thermal power below the threshold authorized in each basket lodgment, is carried out. Then, a layout allowing to fulfill both shielding and thermal requirements, must be defined. This key step is deeply time consuming.

Indeed, to validate a loading plan, the standard calculation sequence involves

- to solve the Bateman equations for each selected fuel assembly considering its depleted characteristics (enrichment (E), burnup (BU) and cooling time (CT)),
- to convert isotopic inventories in neutron emissions (N), gamma emissions (G), thermal power (P),
- then separately, heat exchange equilibrium is calculated using a 3D finite elements model and radiation levels around cask vicinity are calculated using a 3D radiation transport model (see Ref. 2).

As a compromise must be found to fulfill both radiation shielding and thermal requirements, many iterations are necessary. For example, in Figure 2, considering in parallel the thermal and radiation shielding field of stresses could lead to define two inconsistent loading plans for the same selection of spent fuel assemblies (FA). On one hand, to stay below the critical component temperatures, the fuel assembly layout will favor a loading of the "hot" individuals in the peripheral basket lodgments closed to the cask body. With this layout, the radiation levels will probably exceed regulatory limits.

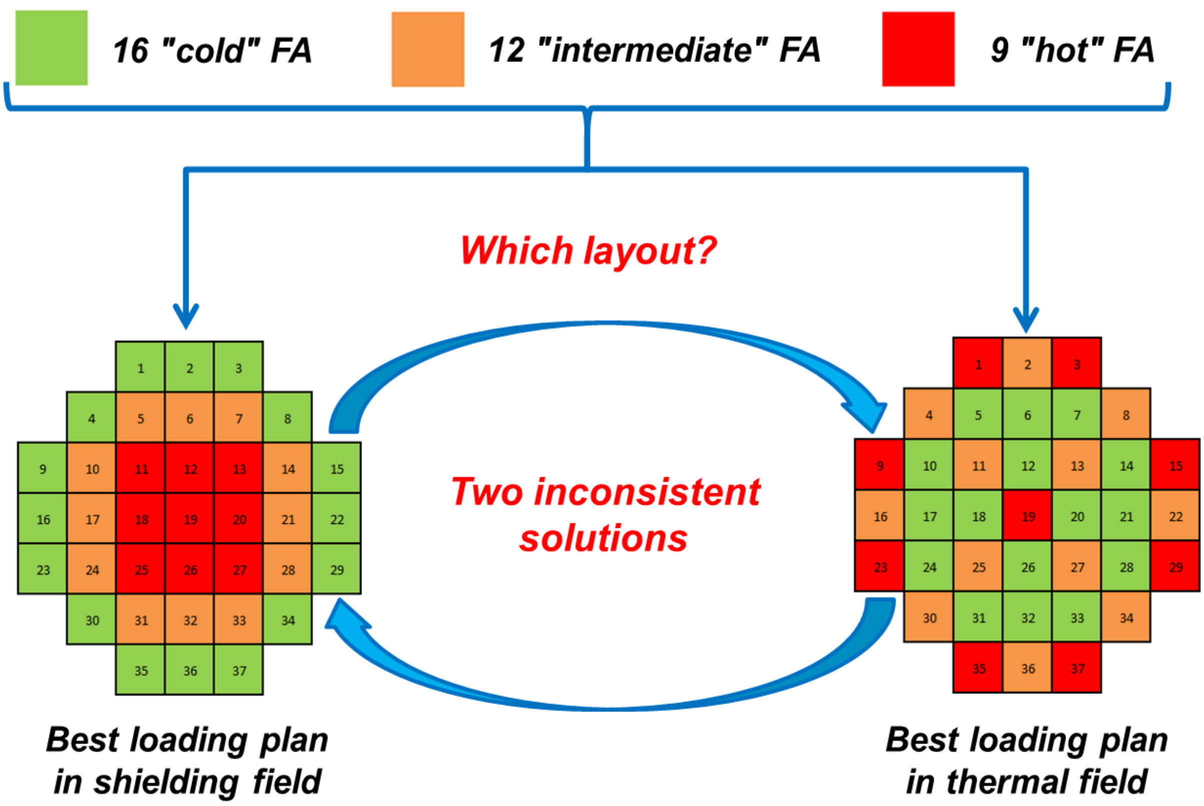

Figure 2: Cask loading management – Constraints Satisfaction Problem

On the other hand, to control the external radiation levels, the fuel assembly layout will favor a loading of the "hot" individuals in the central basket lodgments. With this layout, the critical temperatures in the basket center area will probably be exceeding. This example shows that the cask loading management belongs to the class of Constraints Satisfaction Problem (see Ref. 3). To reduce the time actually needed to define an admissible loading plan, Orano TN develops workflows combining several dynamic algorithms coming from data science.

Cask loading management – Optimization workflow

To explore in a very short time a large domain of feasible solutions, it is interesting to create a digital twin of the standard calculation sequence using numerical surrogate models (NSM). In the case of the depletion calculation sequence, such work requires first to detect the dependences between the residual thermal power (*P*) - neutron emissions (*N*) - gamma emissions (*G*) of a fuel assembly and its depleted characteristics (enrichment (*E*), burnup (*BU*) and cooling time (*CT*)). According to Figure 3, smooth and continue behaviors are present.

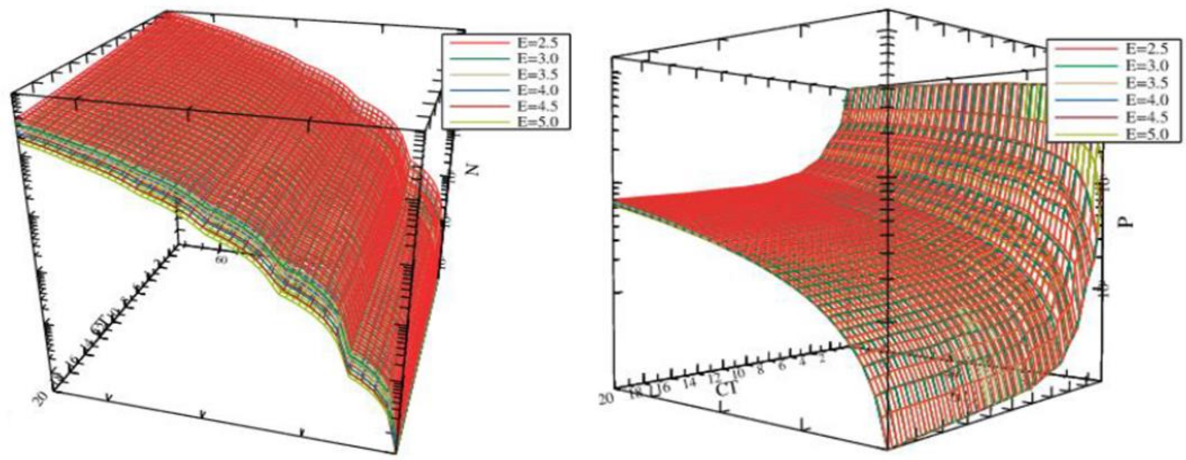

Figure 3: Dependences analysis

Then, based on an adapted design space exploration software, several workflows are defined to build the cask answer function ($\vec{F}$) regarding the operational stresses. Using algorithms from data science, Orano TN performs optimization analyses of the cask loading solutions to get well-defined "best loading plans" (see Figure 4).

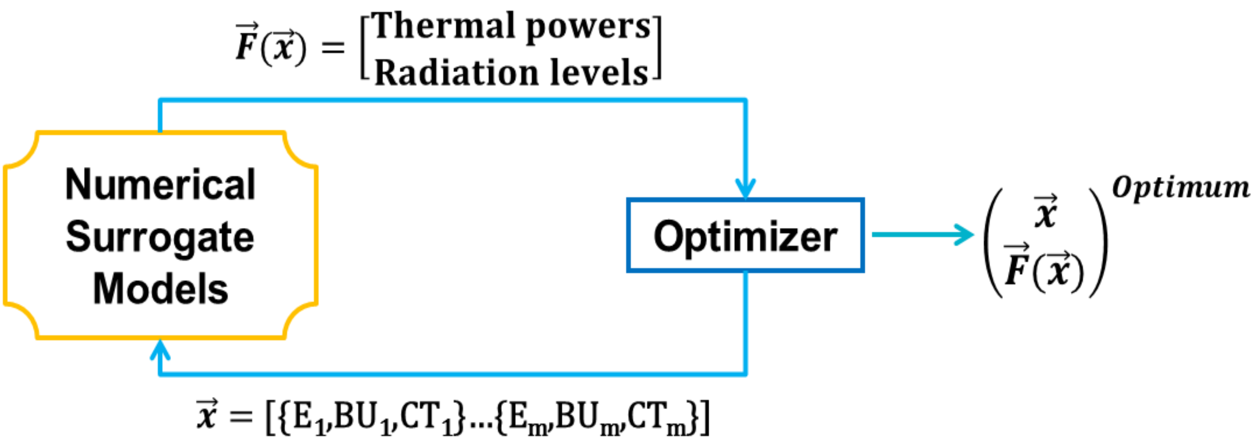

Figure 4: Optimization workflow for well-defined "best loading plans"

These solutions must maximize the thermal power loaded and in parallel fulfill the radiation level criteria. In general, this problem might have either none or multiple solutions.

To illustrate the capacity of the optimization workflows developed by Orano TN, in Figures 5 and 6 are plotted loading plans allowing to optimize the loading of a dual-purpose cask (transport and storage cask). In this example, the cask basket is designed to load 20 UOX spent fuel assemblies.

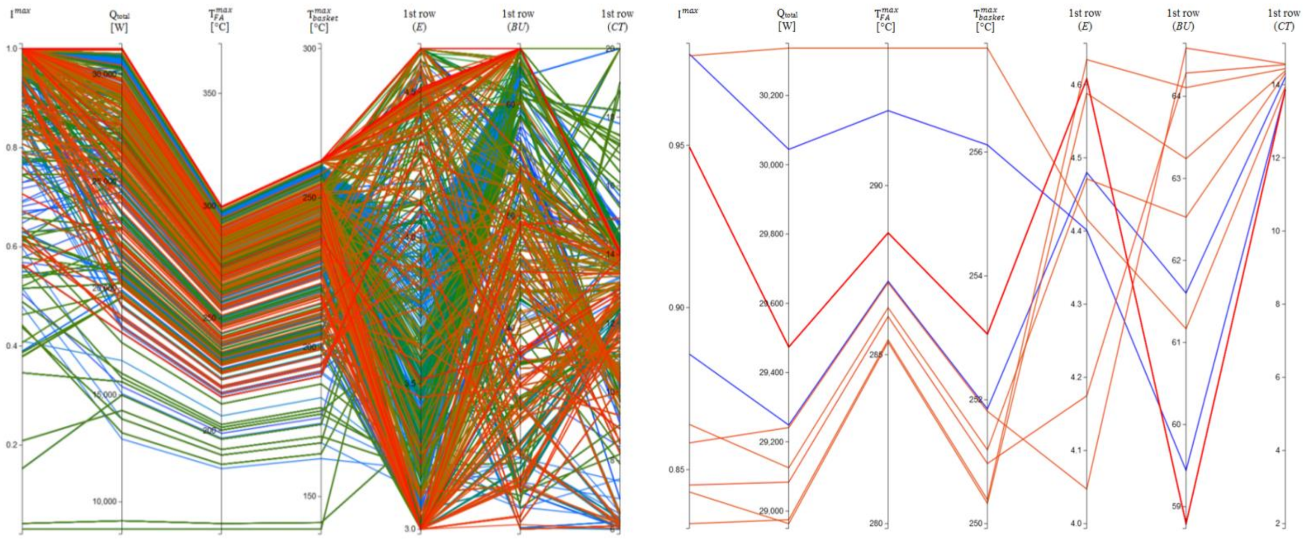

Figure 5: Optimized loading plans – 1 Loading row

In Figure 5 (left side) are plotted all the possible loading plans if the cask is fully loaded with spent fuel assemblies presenting the same depletion characteristics (*E*, *BU*, *CT*). For this cask loading strategy, whatever these depletion characteristics, the maximum fuel and basket temperatures are always lower than respectively 300°C and 270°C, within radiation level criteria fulfilled ($I^{max} \leq 1$). The radiation level criteria limit the maximum achievable thermal power loaded (Q^{total}) to 30,3 kW.

In Figure 5 (right side), the loading plan possibilities are reduced to respect specific ranges for depletion characteristics (*E*, *BU*, *CT*). With this cask loading strategy, a minimum cooling time of 14 years is required, and the radiation levels are always higher than 80% of the criteria. So, such strategy is not compatible to load spent fuel assemblies with high burnups and low cooling times.

In the same way, in Figure 6 (left side) are plotted all the loading plans if the cask basket is divided in two rows and if the spent fuel assemblies loaded in a same row have the same depletion characteristics (*E*, *BU*, *CT*). In comparison with the previous strategy, this one allows to increase the maximum achievable thermal power loaded up to 35 kW within radiation level criteria fulfilled.

In Figure 6 (right side), the loading plan possibilities are reduced to respect specific ranges for depletion characteristics (*E*, *BU*, *CT*). With this cask loading strategy, the number of authorized loading plans is increased. Furthermore, in parallel of the ranges of useful depletion characteristics (*E*, *BU*, *CT*), the range of maximum radiation levels is widened. So, such strategy is compatible to load spent fuel assemblies with high burnups and low cooling times.

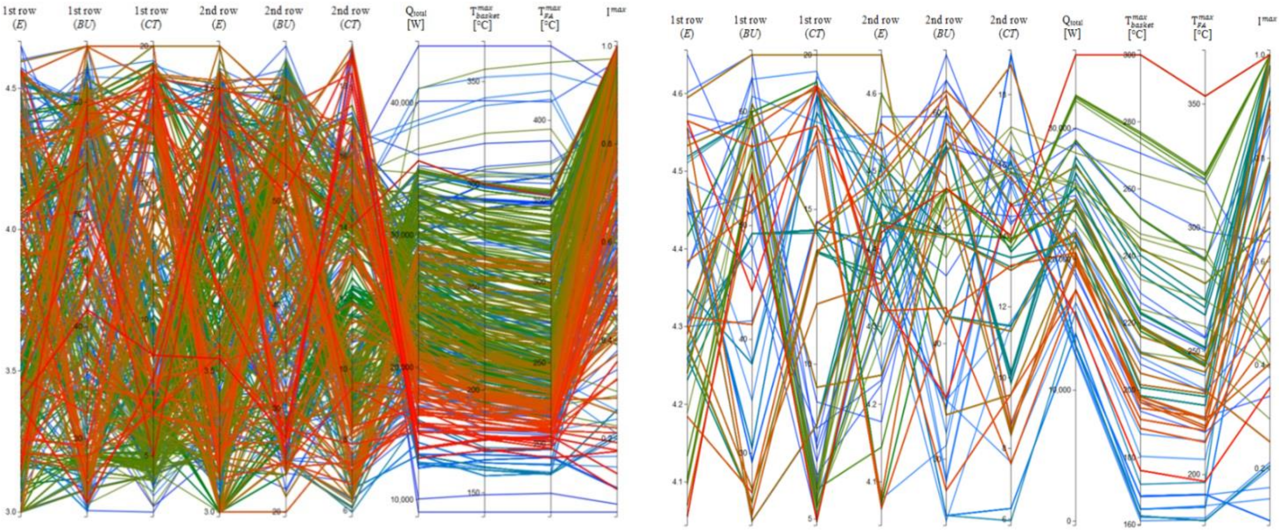

Figure 6: Optimized loading plans – 2 Loading rows

This example shows that such workflows allow to consolidate an efficient ratio between the number of “cold” spent fuels assemblies loaded and the number of “hot” spent fuels assemblies loaded. In long-term, the compromise to fulfill both shielding and thermal requirements stays achievable and the cask availability is strengthened (see Ref. 4)

Cask loading performances – “Best loading plan” selection

In the typical situation of a NPP spent fuel pool unloading, the use of such optimization workflows greatly simplifies the definition of an adapted cask loading strategy. Several optimized strategies can be offered according to customer needs in the short, medium and long term.

In this way, Orano TN has set-up his optimization workflows to answer to the two following problem formulations:

For a given set of fuel assemblies individuals and

- for a given number of casks of known types find feasible layouts, for which the total thermal power loaded ($\sum Q^{total}$) is maximal and radiation level criteria are fulfilled;
- for a given cask type, find an optimized layout sequence, for which all individuals are packed in admissible manner and required number of casks is minimal.

In this last problem formulation, the optimization workflows enable to calculate the time duration of the full loading sequence.

In Figure 7 is presented the optimization workflows. Optimization is conducted through blocks “Optimizer”, “Shielding” and “Formula”, which form closed cycle of workflow execution driven by the “Optimizer” block. In more details, the “Optimizer” block proposes layouts to be verified. Feasibility is checked (or degree of infeasibility is measured) in “Shielding” block, which returns evaluated radiation levels back to “Optimizer”, and in “Formula” block, which returns evaluated total thermal power back to “Optimizer”.

Depending on received responses, “Optimizer” block corrects its strategy and proposes new layouts for evaluation, thus closing the cycle.

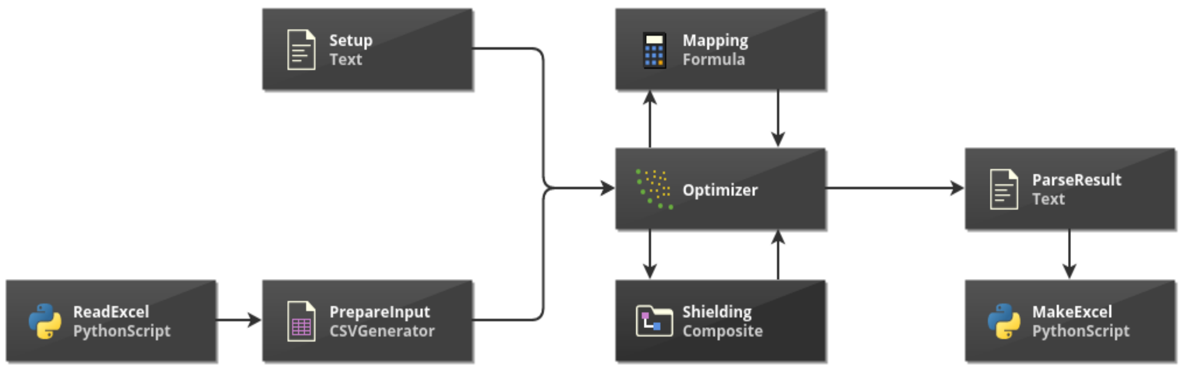

Figure 7: Structural scheme of the optimization workflows

Furthermore, to provide a user-friendly tool, a dedicated graphic user interface (GUI) has been developed. The top-level starting page of GUI is illustrated on Figure 8 and contains the following prime control fields:

- "Problem statement": selection of problem type to be solved, followed by the definition of relevant cask types and numbers together with validation text field, in which diagnostic messages appear;
- "Run settings": some run-time options could be specified;
- "Fuel elements": allows to define initial fuel elements population and their depletion characteristics (*E*, *BU*, *CT*).

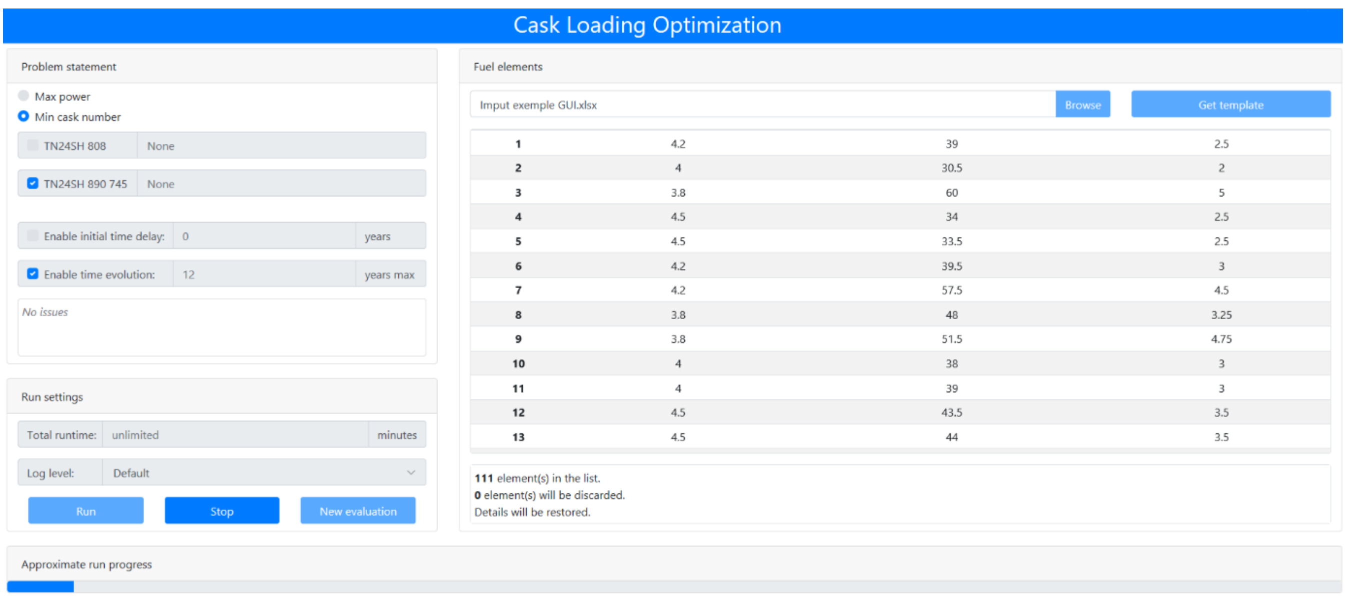

Figure 8: Top-level (starting) page of the GUI

When problem setup is finished, "Run" button allows to conduct the solution, completion of which changes GUI window to the one presented on Figure 9. It lists the solution summary information (left top panel) and the evolution of the required number of cask for a full loading sequence regarding the time duration (right top panel). For the selected loading strategy chosen, it shows also the graphs of

- thermal power distribution among the different casks,
- the normalized radiation level values (A to N values) for all casks (see Ref. 2).

Additional buttons appear on the GUI window. In particular, "Export to Excel" button allows to download full solution details in Excel format, while "Show details by cask" button brings additional GUI pages, graphically revealing the structure of obtained solution for each cask.

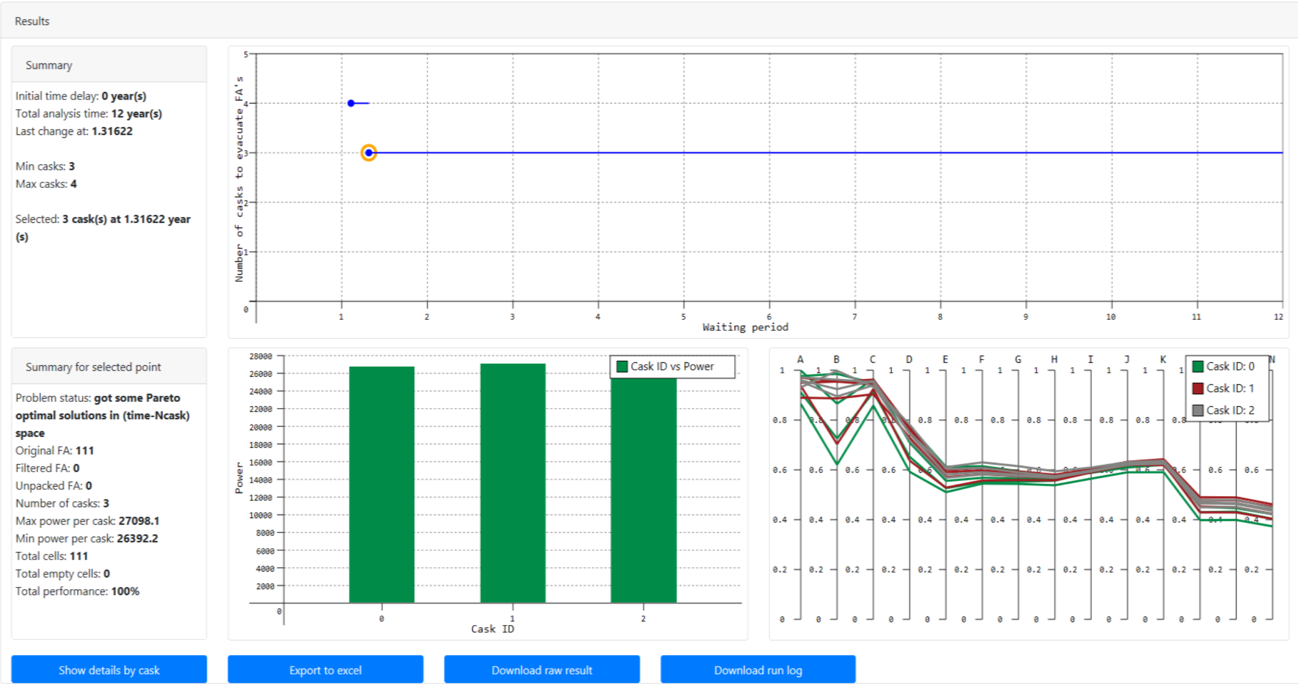

Figure 9: GUI window upon completion of the solution

For instance, Figure 10 exemplifies properties of the solution for the cask "ID 1", including:

- general information: total thermal power and summary of cask basket occupation;
- table of the normalized radiation level values (A to N values) in each relevant shielding area and for each cask quarter (see Ref. 2);
- graphical views of FA layout, including the arrangement of FA depletion characteristics and thermal power.

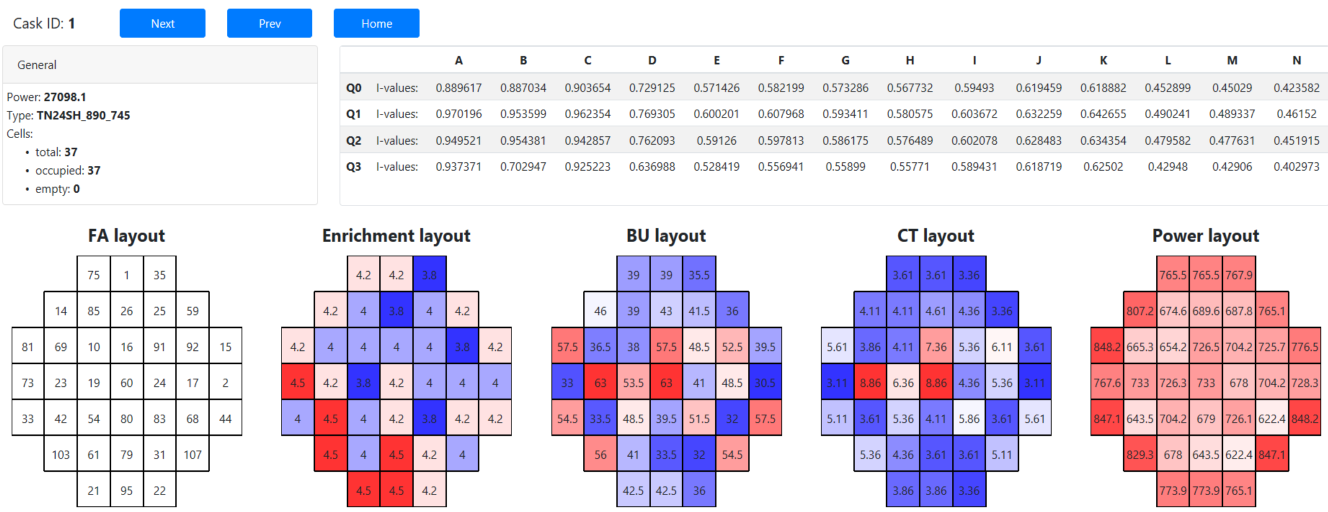

Figure 10: Details of solution for each cask in the GUI window

Conclusion

Fuel assembly characteristics are evolving to improve performance of reactor operations. As a result, enrichment is increasing as well as burnup that leads to challenge the unload of the spent fuel pools in a short time. Indeed, for every cask loading, a compromise must be found to fulfill both shielding and thermal requirements.

Because cask loading management belongs to the class of Constraints Satisfaction Problem, Orano TN develops workflows combining several dynamic algorithms coming from data science. These workflows are set-up to answer to two problem formulations:

For a given set of fuel assemblies individuals and

- for a given number of casks of known types find feasible layouts, for which the total thermal power loaded is maximal and radiation level criteria are fulfilled;
- for a given cask type, find an optimized layout sequence, for which all individuals are packed in admissible manner and required number of casks is minimal.

In this last problem formulation, the workflows optimize the time duration of the full loading sequence and enables to significantly decrease the total radiation exposures according to ALARA objectives (see Ref. 5).

To provide a user-friendly tool, a dedicated graphic user interface has been also developed. Such full solution greatly simplifies the definition of optimized pool unloading strategies and associated campaigns according to customer needs in the short, medium and long term.

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