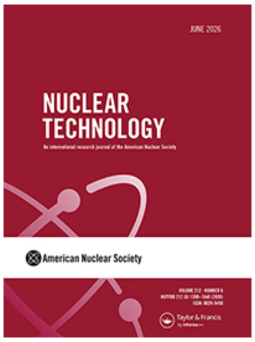

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Loading Optimization Algorithm for Solving Assembly Assignment Problems with Uncertainties in Decay Heat Powers in the Final Disposal of Spent Nuclear Fuel in Finland

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Abstract — *In Finland, spent nuclear fuel assemblies are placed in copper-iron canisters that are disposed of in a deep underground disposal facility in Olkiluoto. The decisions on which fuel assemblies to assign to which disposal canisters can be determined by formulating and solving a mathematical optimization problem, which is called an assembly assignment problem. New requirements have emerged, implying new objectives, constraints, and data for the problem.*

In this paper, the heuristic disposal canister loading optimization algorithm is developed further to solve the refined problem. One major advancement in the new version of the algorithm is that it takes into account the uncertainty of the decay heat power of a disposal canister. This uncertainty is due to the uncertainties in the decay heat powers of the fuel assemblies assigned to the disposal canister and possible dependencies between these uncertainties.

The other major advancement is that the new version of the algorithm manages the spent nuclear fuel interim storage efficiently according to new requirements. To get a prediction of how the disposal of all fuel assemblies for a certain fuel type can succeed, the new version of the algorithm is capable of simulating the loading of all disposal canisters with the current data by assigning fuel assemblies to the disposal canisters iteratively one batch of the encapsulation plant at a time. In Finland, the safe and cost-efficient assignment of fuel assemblies to disposal canisters is facilitated by the developed loading optimization algorithm.

Keywords — *Spent nuclear fuel assemblies, uncertainties in decay heat powers, interim storage, multi-objective optimization, disposal canister loading optimization algorithm.*

I. INTRODUCTION

At the moment, there are two nuclear power plants in Finland: one in Olkiluoto, which is owned by Teollisuuden Voima Oyj, and the other in Loviisa, which is owned by Fortum Power and Heat Oy. Nuclear waste management is essential to the sustainability and acceptability of nuclear power. Finnish legislation makes the companies operating nuclear power plants responsible for disposing of their nuclear waste. For the final disposal of the spent nuclear fuel (SNF) Posiva Oy, owned by afore mentioned companies, was founded in 1995. Posiva submitted an operating license application for a SNF encapsulation plant (EP) and a disposal facility, the first in the world, to the Finnish Government in 2021. Posiva aims to start final disposal in mid the 2020s. The final disposal of fuel assemblies (FAs) is based on the KBS-3 concept, where the FAs are placed in copper-iron canisters, which are disposed of deep underground.

In this paper, we consider which FAs should be inserted into which disposal canisters (DCs). There are three different

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fuel types to consider: OL1-2 fuel produced by the Olkiluoto 1 and Olkiluoto 2 boiling water reactors, LO1-2 fuel produced by the Loviisa 1 and Loviisa 2 Russian pressurized water reactors, and OL3 fuel produced by the Olkiluoto 3 European pressurized water reactor. The FAs of the different fuel types differ by mass, dimension, and shape among other things, and hence, there are three different DC types.

The decisions on which FAs to assign to which DCs can be determined by formulating and solving a mathematical optimization problem, which is called an assembly assignment problem. Recently, Eronen et al. [1] developed a new version of the loading optimization algorithm to solve an assembly assignment problem. The developed loading optimization algorithm considers the DCs disposed of in the current batch of the EP, which are to be disposed of in the near future, more carefully than the rest of the DCs. The current batch of the EP may, e.g., consist of all those DCs that are to be disposed of in a single disposal tunnel.

In any case, for the DCs to be disposed of in the current batch, the DC powers are determined beforehand through planning. Hence, the user of the algorithm needs to give goal heat powers (GHPs) to the DCs to be disposed of in the current batch. The algorithm tries to match FAs to these DCs such that the decay heat powers of these DCs are under their GHPs and within a given accuracy. For the rest of the DCs, the maximum DC power is minimized. This gives a rough idea of the decay heat powers of these DCs. With disposal schedules without troubles, the decay heat powers of the DCs without GHPs will be rather even.

Any FA cannot be assigned to any DC, and a feasible solution needs to satisfy several constraints. For dechannelled FAs, which do not contain fuel channels surrounding the actual fuel bundle, a feasible solution satisfies a given disposal pace. Some FAs could be banned, implying that these FAs will not be assigned to the DCs with GHPs. In addition, FAs can be preassigned, in which case the user specifies to which DC these FAs will be assigned.

Lids over pools in the Olkiluoto SNF interim storage were considered as well. The pool lids were opened to fetch FAs for each transfer cask separately, and the goal was to minimize the number of times the pool lids are lifted. The developed loading optimization algorithm was implemented in Posiva's SNF database Kaapo.

The investigation reported by Eronen et al. [1] is the continuation of long-term optimization research on the efficiency of the final disposal of SNF in Finland. A two-stage hierarchical method was developed by Ranta [2] to optimize the efficiency of the final disposal process: (1) plan an efficient disposal schedule and (2) plan an efficient assignment of FAs to DCs according to the disposal schedule.

In Ref. [2], a disposal scheduling problem was formulated as a single-objective mixed-integer linear programming model that minimizes the total cost of the final disposal of SNF in Finland within constraints ensuring the safety aspects. Montonen et al. [3,4] further developed the disposal scheduling model into a multi-objective mixed-integer nonlinear programming model.

Ranta [2] and Ranta and Cameron [5] formulated a minimax canister formation problem and developed a loading optimization algorithm to solve the problem. In the minimax canister formation problem, a final disposal schedule for a certain fuel type is given, and the task is to assign FAs to DCs such that the maximum decay heat power of all DCs is minimized. The maximum DC power was close to the theoretical lower bound, implying that the loading optimization algorithm was successful. An applied study on the minimax canister formation problem was shown for the LO1-2 FAs by Kuopanportti and Lahtinen [6] that utilized the loading optimization algorithm developed in Refs. [2,5].

Multiple aspects of the final disposal of SNF have been studied using optimization. Several studies have investigated the loading optimization of DCs [7–13]. The optimization of SNF cask loading was studied in Refs. [14,15]. In Ref. [16], the scheduling of final disposal was investigated. Several other studies related to the final disposal of SNF have utilized optimization [17–27].

In this paper, the recent investigation by Eronen et al. [1] is continued. Thereafter, new requirements have emerged, implying new objectives, constraints, and data for the assembly assignment problem. The new requirements are created in collaboration with Posiva and the power companies. The aim of this investigation is to develop the loading optimization algorithm further to solve the refined problem.

One major advancement is that the new version of the loading optimization algorithm takes into account uncertainties in the decay heat powers of the FAs. Specifically, the choices of which FAs to insert into a DC should consider dependencies between these uncertainties and avoid increasing the DC power unnecessarily due to these dependencies.

The other major advancement in the new version of the algorithm is that it manages the SNF interim storage efficiently according to new requirements. Suppose that some positions in the SNF interim storage are wanted to be empty. In the new version of the algorithm, the FAs in those positions can be set as prioritized and the algorithm decides which of the FAs, if any, will be assigned to the DCs with GHPs and to which DC. In the new version of the algorithm, SNF interim storage pools can be emptied by given times, and as well, enough free space can be guaranteed in certain pools after the FAs assigned to the DCs with GHPs are transferred to the EP. Moreover, the new version of the algorithm has three main ways to control which pools are open in the SNF interim storage when FAs are transferred to the EP to be disposed of in the DCs with GHPs. In the new version of the algorithm, adjusting the DC powers can be done for the DCs without GHPs by weighting coefficients. To get a prediction of how the disposal of all FAs for a certain fuel type can succeed, the new version of the algorithm is capable of simulating the whole disposal with the current data by assigning FAs to DCs iteratively one batch of the EP at a time.

The new version of the loading optimization algorithm is implemented in Posiva's SNF database Kaapo. Kaapo software collects data on SNF from the Finnish nuclear power plant operators. It then uses these data to optimize, with the loading optimization algorithm, the selection of FAs and their configurations in the DCs based on safety boundary conditions with uncertainties in the decay heat powers. The database has been built so that it performs the nuclear material accounting and provides the necessary nuclear safeguards reports for the state regulatory authority, the European Commission, and the International Atomic Energy Agency.

This paper is organized as follows. Sec. II describes the FAs' journey from a nuclear reactor to the disposal facility. Sec. III is devoted to the uncertainties in the decay heat powers of the FAs and how these affect the uncertainty of the decay heat power of a DC. In Sec. IV, different assembly assignment problems are described. In Sec. V, a concise description of the loading optimization algorithm to solve the different assembly assignment problems is presented. Computational results from loading simulations performed with the algorithm based on an example scenario are shown in Sec. VI. Sec. VII discusses the developed loading optimization algorithm. Finally, Sec. VIII summarizes the conclusions of the loading optimization algorithm.

II. SNF DISPOSAL PROCESS IN FINLAND

A part of the FAs in a nuclear reactor are removed from the reactor and replaced with fresh ones annually. For OL3, eventually the user experience will define if the removals are done annually or biennially. In this investigation, we assume that the OL3 removals are done biennially. After the removal, the spent FAs produce a large amount of decay heat and radiation. Before the FAs can be transferred to the SNF interim storage, they cool down for a few years in the water pools of the reactor hall. Thereafter, the FAs are transferred with a transfer cask to the SNF interim storage located in the corresponding nuclear power plant area.

Here two SNF interim storages are considered: one in Olkiluoto storing OL1-2 and OL3 FAs and the other in Loviisa storing LO1-2 FAs. The SNF interim storage is formed by several water pools where the FAs are stored in racks. There are lids over the water pools in the Olkiluoto SNF interim storage. Whenever FAs are added or removed from a water pool, then the lid of the water pool must be open. In order to guarantee radiation safety, the minimum cooling time of a FA, i.e., time after shutting down the reactor for the removal, is ensured before the FA is disposed of. However, the FAs are usually stored much longer before disposal.

After a suitable cooling time in the SNF interim storage, the FAs are transferred to the EP in Olkiluoto in transfer casks, with the fuel types having an individual cask with the different number of positions for the FAs. The FAs are loaded into copper-iron DCs in the EP. Each fuel type has its own DC type with a different height and capacity, i.e., the number of positions for FAs in a DC. Each DC must meet the safety criteria related to, e.g., decay heat power, radiation dose rate, and criticality safety.

A suitable selection of the FAs needs to be chosen such that the DC power, including the uncertainties in the decay heat powers of the FAs, is within the limits. Sometimes it may be cost efficient to even leave a position empty in a DC. This can allow for loading a DC with hotter FAs than usual, with a suitable minimum cooling time for each FA guaranteeing the low dose rate for the DC that obeys radiation safety. In addition, the criticality safety criteria are verified for all DCs, including nonregular FAs.

The nonregular fuel is defined as fuel that does not meet all the fuel criteria, e.g., OL1-2 dechannelled FAs and FAs containing one or more failed, i.e., leaking fuel rods. Dechannelled FAs do not contain fuel channels surrounding the actual fuel bundle because in the past, the channels were recycled in the irradiation of the FAs. The dechannelled FAs have different dimensions than the regular FAs. The dechannelled FAs, therefore, are nonregular FAs, but with proper technical solutions they can be disposed of with regular FAs. However, it would maximize safety if there were a constant number of these in a transfer cask and a DC, i.e., the handling procedures can be fixed.

A leaking fuel rod is a fuel rod whose cladding has been breached allowing for radioactive fission products to escape. Basically, the leakage is exhausted, but nevertheless, we call it the leaking fuel rod. Only a small fraction of all fuel rods are leaking. The FAs containing leaking fuel rods require additional DC-specific considerations. Nevertheless, failed fuel rods can be disposed of either within the host FA or with a device ensuring the long-term safety properties.

Another thing to consider in a FA selection includes the position where the FA is located in the SNF interim storage. Suppose that some positions in the SNF interim storage are wanted to be empty. This can be achieved by disposing of the FAs in these positions or by transferring the FAs to some other positions. In the case of the OL1-2 FAs and OL3 FAs, a pool where the FA is located in the Olkiluoto SNF interim storage needs to be considered in a FA selection. There can be only a certain number of FAs in total in the pools that are open in the Olkiluoto SNF interim storage when FAs are transferred to the EP.

Furthermore, the OL1-2 pools need to be empty by certain times to be able to store OL3 FAs in them. This implies that the OL1-2 FAs in a given pool are preferred to be disposed of before this time or they need to be transferred to the other pools. Furthermore, it may be preferred that FAs from the reactor halls be transferred to certain pools in the Olkiluoto SNF interim storage. To be able to have enough free space in these pools may require disposing of FAs from these pools or transferring FAs from these pools to the other pools.

Once the FAs are encapsulated into DCs in the EP, the last part of the FAs' journey toward the permanent disposal begins when the DCs are transferred to the deep underground disposal facility in Olkiluoto. The disposal facility consists of disposal tunnels that are connected with central tunnels. Each fuel type has its own disposal tunnel type. The DCs are deposited into disposal holes drilled into the floor of a disposal tunnel.

For the proper layout of the disposal facility, it is crucial that the thermal dimensioning of the disposal facility be taken into account. The temperature at the outer surface of a DC should not exceed its maximum allowed value. This is controlled by defining spacings between the DCs and disposal tunnels together with the DC powers for each fuel type separately.

As the final disposal progresses, new disposal tunnels and central tunnels are excavated. The disposal tunnel is filled with bentonite and clay at the same time when the DCs are deposited into the disposal holes. After all the DCs in a disposal tunnel have been deposited, the disposal tunnel is sealed with a plug. Finally, for the purposes of the long-term safety, the central tunnels are filled with bentonite and clay, and the disposal facility is sealed.

III. DC DECAY HEAT POWER UNCERTAINTY CONSIDERATION

Here we consider the uncertainty of the decay heat power of a DC, which is due to the uncertainties in the decay heat powers of the FAs assigned to the DC and the dependencies between these uncertainties.

III.A. Uncertainties in FA Decay Heat Powers

The power companies have specified the uncertainty factors of the FA decay heat powers for the OL1-2, LO1-2, and OL3 FAs. The uncertainty factors of the FA decay heat powers are related to the actual or estimated physical conditions, including, e.g., FA design properties with tolerances, FA irradiation history, and calculations using SNF programs and libraries with varying assumptions (see Ref. [28]). A more specific physical explanation for the uncertainty factors of FA decay heat powers is not public information.

Here we assume that there are four uncertainty factors for the OL1-2 and OL3 fuel and that each of them has a normal distribution. For the LO1-2 fuel, we assume that there are six uncertainty factors. The first four have a uniform distribution, and the other two have a normal distribution. All the distributions of the uncertainty factors have the mean value of 0 W.

In addition to the decay heat power of each FA, the time-dependent data include the relative standard deviation and relative bias of each FA for each uncertainty factor. These are given in percentage. For example, if the relative standard deviation of a FA for an uncertainty factor at a time is 2% and the decay heat power of this FA at that time is 50 W, then the standard deviation of this FA for this uncertainty factor at that time is 1 W. A notable thing is that we assume that for all OL1-2 and OL3 FAs, the relative bias is 0% for all the uncertainty factors at all times.

The power companies have specified a correlation list for each fuel type and for each uncertainty factor. These lists contain pairs of FAs if their uncertainties of corresponding uncertainty factor are not independent because there has been some sort of relationship between the FAs depending on the uncertainty factor concerned. A more specific physical explanation for the correlation between the uncertainties of FAs' decay heat powers of the corresponding uncertainty factor is not public information.

The data for OL1-2 and OL3 fuel contain correlations regarding the forecasted FAs, too. The data for LO1-2 fuel do not contain correlations regarding the forecasted FAs. What makes it important is that if a DC contains one or more FAs without correlations, then its DC power will be underestimated in the algorithm. As an approximative solution, we have used artificial imputations for missing correlations regarding the forecasted LO1-2 FAs in this paper.

III.B. Uncertainty in DC Decay Heat Power

When the uncertainties are added in the calculation of a DC power, the DC power becomes a random variable with a distribution instead of a number. Consider a DC with C number of FAs inserted into it. Suppose each FA has U uncertainty factors, each having a distribution with zero mean value and a known standard deviation. The decay heat power of FA i at the time when the DC is disposed of can be written as

$$P_i^{\mathrm{FA}} = p_i^{\mathrm{FA}} + \sum_{j=1}^{U} B_{ij}^{\mathrm{FA}} + \sum_{j=1}^{U} \varepsilon_{ij}^{\mathrm{FA}} \ , \tag{1}$$

where p_i^{FA} is the decay heat power of FA i without uncertainties, B_{ij}^{FA} is the bias of FA i related to uncertainty factor j, and $\varepsilon_{ij}^{\mathrm{FA}} \sim dist\left(0, \sigma_{ij}^{\mathrm{FA}}\right)$. The biases do not have distributions, and they can be considered like the decay heat powers. Then the DC power can be written as

$$P^{\mathrm{DC}} = \sum_{i=1}^{C} p_i^{\mathrm{FA}} + \sum_{i=1}^{C} \sum_{j=1}^{U} B_{ij}^{\mathrm{FA}} + \sum_{i=1}^{C} \sum_{j=1}^{U} \varepsilon_{ij}^{\mathrm{FA}} \ . \tag{2}$$

When the uncertainties are taken into account, the DC power is defined to be the upper bound of the one-sided 95% confidence interval. In other words, the 95th percentile of the distribution. Finding the distribution of P^{DC} requires knowledge of the marginal distributions of $\varepsilon_{ij}^{\mathrm{FA}}$ and the dependency structure between different $\varepsilon_{ij}^{\mathrm{FA}}$. An approximated marginal distribution is known for each uncertainty factor and for each fuel type. The known part of the dependency structure is that $\varepsilon_{i_1 j_1}^{\mathrm{FA}}$ and $\varepsilon_{i_2 j_2}^{\mathrm{FA}}$ are independent if $j_1 \neq j_2$. Otherwise, the dependency structure is not known.

To be able to approximate P^{DC}, we assume that whenever $\varepsilon_{i_1 j}^{\mathrm{FA}}$ and $\varepsilon_{i_2 j}^{\mathrm{FA}}$ may be dependent, they are linearly dependent, i.e., the Pearson correlation coefficient between them is one out of the possible values [−1,1]. Otherwise, $\varepsilon_{i_1 j}^{\mathrm{FA}}$ and $\varepsilon_{i_2 j}^{\mathrm{FA}}$ are independent, implying that the Pearson correlation coefficient between them is zero. There is no proof that this is a conservative assumption in the sense that the 95th percentile would be overestimated due to the assumption unless the distribution of P^{DC} is normal.

In any case, this approximation overestimates the standard deviation of P^{DC}, which is the justification for using it. However, this approximation is not enough to define the approximated distribution of P^{DC}. If the correlation matrix between the FAs contains only the values zero and one, it needs to be transitive in order to be a valid correlation matrix. That is, if for some uncertainty factor the correlation between FA 1 and FA 2 is one and the correlation between FA 2 and FA 3 is one, then the correlation between FA 1 and FA 3 needs to be one as well. Thus, to be able to define the approximated distribution of P^{DC}, the correlation matrix of each uncertainty factor between the FAs in a DC will be made transitive by changing zero to one when needed.

For the OL1-2 and OL3 fuels, the distributions of all four uncertainty factors are normal. With the approximated dependency structure, this results in P^{DC} having a normal distribution regardless of the number of the correlating pairs of the uncertainty factors. For the LO1-2 fuel, the four uncertainty factors have a uniform distribution and the other two have a normal distribution. Since both the uniform and the normal distribution are symmetric and variables $\varepsilon_{ij}^{\mathrm{FA}}$ are modeled to be either linearly dependent or independent, the formula for P^{DC} consists of the sum of the independent symmetric distributions. Also, in this case, it is assumed that the distribution of P^{DC} is close enough to normal distribution.

If the distribution of P^{DC} is normal, then the upper bound of the one-sided 95% confidence interval can be calculated approximately by the formula

$$\sum_{i=1}^{C} p_i^{\mathrm{FA}} + \sum_{i=1}^{C} \sum_{j=1}^{U} B_{ij}^{\mathrm{FA}} + \Phi(0.95)\sigma^{\mathrm{DC}} \ . \tag{3}$$

Throughout this study we use the approximation of $\Phi(0.95) \approx 1.645$. The standard deviation of P^{DC} can be calculated by the formula

$$\begin{aligned} \sigma^{\mathrm{DC}} &= \sqrt{Var\left(\sum_{i=1}^{C} \sum_{j=1}^{U} \varepsilon_{ij}^{\mathrm{FA}}\right)} \\ &= \sqrt{\sum_{i=1}^{C}\sum_{j=1}^{U} Var\left(\varepsilon_{ij}^{\mathrm{FA}}\right) + 2\sum_{i=1}^{C-1} \sum_{k=i+1}^{C} \sum_{j=1}^{U} Cov\left(\varepsilon_{ij}^{\mathrm{FA}}, \varepsilon_{kj}^{\mathrm{FA}}\right)} . \end{aligned} \tag{4}$$

The covariances are zero if $\varepsilon_{ij}^{\mathrm{FA}}$ and $\varepsilon_{kj}^{\mathrm{FA}}$ are linearly independent and

$$\sqrt{Var\left(\varepsilon_{ij}^{\mathrm{FA}}\right)Var\left(\varepsilon_{kj}^{\mathrm{FA}}\right)}\ , \tag{5}$$

if they are linearly dependent. Thus, to calculate the standard deviation of a DC's decay heat power it suffices to know the variance of each uncertainty factor for each FA in the DC and for each uncertainty factor and each pair of FAs in the DC if they are linearly dependent or not.

IV. PROBLEM DEFINITION

Recently, Eronen et al. [1] presented an assembly assignment problem. New requirements have emerged affecting the problem definition. Specifically, the uncertainty in the decay heat power of a DC needs to be considered. Furthermore, there are new requirements for how to manage the SNF interim storage. In the following, we describe the requirements for loading optimization created in collaboration with Posiva and the power companies. These form objectives and constraints for the different assembly assignment problems whose mathematical formulations are given in Appendix A.

The most important outcome of loading optimization is the assignment of FAs to DCs in the current batch of the EP, i.e., in the near future. However, there are certain things that are not specifically considered in loading optimization and should be carried out externally. These include verification of the safety criteria related to the radiation dose rate and criticality safety, what exact place in the DC the FAs are inserted into, which FAs are transferred in which transfer cask from the SNF interim storage to the EP, what exact place in the transfer cask the FAs are inserted into, which FAs are transferred between the SNF interim storage pools if any, and which FAs are transferred from the reactor pools to the SNF interim storage and to which pool, among others.

IV.A. Different Assembly Assignment Problems

Each fuel type has its own problem, which is considered separately. For a single assembly assignment problem, we need data, objectives, and constraints. Compared to the recent investigation [1], one major difference is that the uncertainty of the decay heat power of a DC needs to be taken into account. The DC power needs to be calculated as the upper bound of the one-sided 95% confidence interval, as shown in Sec. III. The data related to the FAs include the decay heat powers of each FA, the relative biases of each uncertainty factor for each FA, and the relative standard deviations of each uncertainty factor for each FA given monthly from the start of the disposal. For each pair of FAs and for each uncertainty factor, a correlation is needed. All these data are needed for each FA that will be disposed of, including the forecasted ones.

An important piece of data is the disposal schedule, which should include the disposal date of each DC. The number of DCs in the disposal schedule should be at least the number of FAs divided by the capacity of a DC for that fuel type. There may be more DC slots than there are FAs.

The production of the EP proceeds in batches. Since the data on the forecasted FAs, the FAs in the interim storage pools, the GHPs, and the disposal schedule will change, all determined assignments will not be final ones. Therefore, we divide all the DCs into the DCs to be disposed of in the current batch and the rest of the DCs, as was done in Ref. [1]. The DCs in the current batch of the EP will be disposed of in the near future.

The current batch of the EP may consist of, e.g., all those DCs that are to be disposed of in a single disposal tunnel. The assignments for the DCs in the current batch of the EP are supposedly final, and they are considered more carefully than the rest of the DCs. Furthermore, the decay heat powers of the DCs to be disposed of in the current batch have been planned beforehand. Thus, for each DC disposed of in the current batch, a GHP needs to be given; these DCs are also called DCs with GHPs.

Compared to Ref. [1], the other major difference is that the SNF interim storage needs to be managed according to the new requirements. To be able to set FAs that are preferred to be disposed of in the DCs with GHPs as prioritized is one of the new requirements. For example, the FAs can be set as prioritized based on their position in the SNF interim storage to avoid additional transfers of FAs. This is not a hard constraint, and thus, the number of prioritized FAs disposed of in the DCs with GHPs is an objective of the assembly assignment problem.

In the Olkiluoto SNF interim storage, there are lids over the water pools, and thus, the pools for OL1-2 and OL3 have been modeled. Emptying the OL1-2 pools by given times is another requirement. Without this requirement, the OL1-2 pools are emptied quite evenly and a lot of rearrangement of the OL1-2 FAs in the Olkiluoto SNF interim storage is needed to empty one pool for the OL3 fuel.

Another pool-related requirement is to guarantee that after the disposal of the DCs with GHPs, there is enough free space in certain pools to transfer the FAs from the reactor halls. This requirement is useful, e.g., to make sure that there is free space in such pools that will not be emptied before the FAs transferred from the reactor halls can satisfy their minimum cooling time criterion. Otherwise, the FAs transferred from the reactor halls will later be transferred to another pool to continue cooling.

Recently, pool lids were opened to fetch FAs for each transfer cask separately, and the goal was to minimize the number of pool lids lifted [1]. However, according to the new requirements, all the FAs assigned to the DCs with GHPs are transferred to the EP from the same pools, and those pools are kept open for as long as the transfer takes, implying a much smaller number of the pool lids will be lifted. Moreover, the number of FAs in the open pools needs to be lower than the maximum allowed number when the FAs are transferred to the EP.

In order to consider the new requirements for open pools in the Olkiluoto SNF interim storage when FAs are transferred to the EP, three main ways to control open pools are introduced. The first one, also called batch task 1, is to let optimization determine which pools are open for the DCs with GHPs, and thus, we do not have to specify which pools are open. The second way to control the pools, called batch task 2, is to specify the open pools beforehand for the DCs with GHPs, and thus, optimization does not determine them. These pools are called loading pools.

In the third way, called batch task 3, the open pools for the DCs with GHPs are specified beforehand as well. However, some of the pools are loading pools and some are transfer pools. The FAs from the transfer pools are transferred to the loading pools before they are transferred to the EP for encapsulation.

To illustrate the usefulness of batch task 3, suppose that the number of FAs in the open pools can be two times the maximum capacity of a single pool and at some year pools 1, 2, and 3 have more FAs than this limit. Suppose we transfer the FAs that are to be disposed of from pool 3 to pool 1, then all the FAs to be disposed of are located in pools 1 and 2, which both can be open as long as needed. In this example case, pools 1 and 2 are loading pools and pool 3 is a transfer pool. There are no pool lids in the Loviisa SNF interim storage, and thus, no pools for LO1-2 have been modeled. We call the way of considering pools with LO1-2 fuel as batch task 0.

In the following, we consider the requirements for a good solution to the assembly assignment problem. Compared to Ref. [1], requirements (2) and (9) through (14) are new, requirements (1), (3), (5), and (8) are changed, and requirements (4), (6), and (7) are the same. Most of these imply a need for new data and constraints for the problem, but some will also imply new objectives:

1. *Minimize the maximum difference from the GHPs for the DCs with GHPs*. The most important objective of the assembly assignment problem is to get the DC powers of the DCs with GHPs close to the GHPs while being under the GHPs. Compared to Ref. [1], the uncertainties in the decay heat powers of the FAs assigned to the DC and the possible dependencies between these uncertainties need to be taken into account in the calculation of the DC power.

2. *Maximize the number of prioritized FAs disposed of in the DCs with GHPs*. The second most important objective is to maximize the number of prioritized FAs disposed of in the DCs with GHPs. There can be FAs that are preferred to be disposed of in the DCs with GHPs, but it is not that important that they need to be preassigned. For example, the FAs can be set as prioritized based on their position in the SNF interim storage to avoid the additional transfers of FAs. By setting the FAs as prioritized, optimization decides which of the FAs, if any, are assigned to the DCs with GHPs and to which DC; thus, we do not have to specify these.

3. *Minimize the maximum weighted DC power of the DCs without GHPs*. Another objective is to minimize the maximum weighted DC power of the DCs without GHPs. This gives a rough idea of the decay heat powers of these DCs. Compared to Ref. [1], weighting coefficients are given to DCs without GHPs. This makes it possible to have different DC powers for DCs without GHPs. The basis for different DC powers comes from the disposal scheduling problem, where GHPs for all the DCs are determined.

4. *Guarantee that the capacity of a DC is not exceeded*. Each fuel type has its own DC type with its maximum capacity. For OL1-2 and LO1-2, this is 12 FAs, and for OL3, this is 4 FAs. The number of DCs in the disposal schedule should be at least the number of FAs divided by the capacity of a DC of that fuel type. There may be more DC slots than there are FAs. In the assembly assignment problem, we assume that these empty slots are modeled as FAs with zero decay heat powers, biases, and variances.

5. *For OL1-2 guarantee the required number of dechannelled FAs in each DC*. For OL1-2 fuel, there are dechannelled FAs that have different dimensions than

the FAs with a channel. This implies that there will be an additional block of material both in a transfer cask and in a DC at the slot where a dechannelled FA is inserted into. In this paper, it is assumed that the dechannelled FAs will be disposed of starting from the second disposal tunnel. To facilitate the disposal process, there will be a constant number of dechannelled FAs in a transfer cask and in a DC until there are no dechannelled FAs left. To make consideration of the dechannelled FAs flexible in the optimization problem, it is required to give the number of dechannelled FAs for each DC, unlike in Ref. [1]. The number of FAs that are dechannelled must match the total number of the dechannelled FAs needed for the DCs.

6. *Guarantee that certain FAs are not in the DCs with GHPs*. There can be several reasons why a specific FA is not wanted to be disposed of in the DCs with GHPs. One obvious reason is that the FA is not in the SNF interim storage at the time when the DCs with GHPs are disposed of. To consider this case, we need to know if a FA is in the SNF interim storage or not. Other reasons can be that the FA contains a leaking fuel rod and some preparations are needed before disposal or that the FA is stuck in its place in the SNF interim storage and cannot be moved for some time. To avoid disposing of a certain FA in the DCs with GHPs, the FA can be set as banned.

7. *Guarantee that certain FAs are in certain DCs*. There can also be FAs that are wanted to be disposed of at a certain time. For this, a FA can be preassigned to a certain DC. This means that optimization does not determine to which DC the FA is inserted into, but that the DC is given beforehand. There are few leaking fuel rods. How these leaking fuel rods are disposed of will be determined later. These leaking fuel rods are assumed to be bundled together to form FAs. The FAs containing leaking fuel rods will be disposed of at some point in time, and with the preassignments, the DC where these will be disposed of can be specified accurately. Another use for the preassignments is to specify which DCs will have empty slots, if there are any.

8. *Guarantee that each FA satisfies the minimum cooling time criterion*. Each FA needs to satisfy the minimum cooling time criterion provided by the radiation safety. The minimum cooling time is given to each FA separately, implying that different FAs may have different minimum cooling times unlike in Ref. [1]. To be able to take the minimum cooling time criterion into account the date when the cooling has started is required for each FA. If FA j has not cooled down for its minimum cooling time at the time of disposal of DC i, then FA j cannot be disposed of in DC i.

9. *For OL1-2 and OL3 guarantee that certain pools are emptied by certain times*. The OL1-2 pools need to be emptied if OL3 fuel is stored in them. A date should be given by which a given pool needs to be empty. Furthermore, a given number of FAs can be left in a pool after the date it should be empty. These will be transferred to another pool.

10. *For OL1-2 and OL3, guarantee that there is at least the required amount of free space in certain pools after the disposal of the DCs with GHPs*. It may be preferred that FAs from the reactor halls be brought to certain pools. To guarantee that there is enough free space in these pools after the disposal of the DCs with GHPs, a set of pools where free space is required needs to be given, as well as the amount of required free space.

11. *For OL1-2 and OL3 with batch task 1, guarantee that only FAs from certain pools, which can be open or are required to be open, are assigned to the DCs with GHPs*. The lids over the pools in the Olkiluoto SNF interim storage somewhat restrict which FAs can be disposed of at a certain time. In this research, there is a lid over each pool, and the lid needs to be open if FAs are taken from or brought to the corresponding pool. Three main ways to control the pools are introduced. The first one, also called batch task 1, is to let optimization determine which pool lids are opened. In this case, we need to set which pools can be open and which pools are required to be open.

12. *For OL1-2 and OL3 with batch task 1, guarantee that the number of FAs in the open pools is lower than the maximum allowed number when FAs are transferred to the EP*. In batch task 1, we need to set the maximum allowed number of FAs in the open pools when FAs are transferred to the EP, which restricts the solution. Here we assume that on a regular basis, the number of FAs in the open pools can be two times the maximum capacity of a single pool.

13. *For OL1-2 and OL3 with batch task 2, guarantee that only FAs from the loading pools are used in the DCs with GHPs*. The second way to control the pools, also called batch task 2, is that the pools that are open are given beforehand, and thus, optimization does not determine them. These pools are called loading pools. When

setting the loading pools, the number of FAs open should be considered among others.

14. *For OL1-2 and OL3 with batch task 3, guarantee that only FAs from the loading pools and transfer pools are used in the DCs with GHPs*. In the third way, also called batch task 3, the open pools are given beforehand, as well. However, some of the pools are loading pools and some are transfer pools. The FAs from the transfer pools are transferred to the loading pools before they are transferred to the EP for encapsulation. When setting the loading pools, the number of FAs open should be considered among others.

V. LOADING OPTIMIZATION ALGORITHM

In this section, the algorithm to solve the different assembly assignment problems is presented. This algorithm is a new version of the loading optimization algorithm derived by Eronen et al. [1], and likewise, is implemented in Posiva's SNF database. Given the large number of binary variables, the problem is solved heuristically, as was done in Ref. [1]. The problem has three objectives, and hence, there are several mathematically equally good solutions, which are called Pareto optimal solutions [29]. However, there is some hierarchy between the different objectives, and therefore, a lexicographic approach can be used in the solution process [29].

The first and the most important objective is to get the DC powers of the DCs with GHPs close to the GHPs, while being under the GHPs. The second objective is to maximize the number of prioritized FAs disposed of in the DCs with GHPs, which is the second most important. The third objective is to minimize the maximum weighted DC power of the DCs without GHPs, which is the third most important. This gives a rough idea of the decay heat powers of these DCs.

One of the most important parameters of the algorithm is the accuracy, which specifies how close to the GHPs the DC powers are required to be. This is given in percentage of DC power. For example, if the GHP of a DC is 1700 W and the accuracy is 0.1%, then the algorithm determines that the DC power is in the GHP within the given accuracy if the DC power is between [1698.3 W, 1700.0 W].

V.A. Loading Simulation

The production of the EP proceeds in batches. The DCs in the current batch of the EP will be disposed of in the near future. The process for determining the assignments for the DCs in the current batch of the EP, by solving an assembly assignment problem, is called loading optimization. When the assignments for the DCs are determined in practice, multiple assembly assignment problems will be solved with updated data. This process can be simulated by solving multiple assembly assignment problems with the current data. The process of determining the assignments for the DCs by solving several assembly assignment problems with the current data is called loading simulation. In loading simulation, a single instance of an assembly assignment problem is called a batch.

In this sense, loading optimization can be seen as loading simulation with a single batch. Note that there are two kinds of batches: a batch of the EP and a batch of the loading simulation. The batch of the EP relates to DCs disposed of within a certain time, while the batch of the loading simulation relates to a single instance of the assembly assignment problem that is solved in order to determine the assignments for the DCs disposed of in the corresponding batch of the EP. Thus, in addition to the DCs with GHPs, which are disposed of in the corresponding batch of the EP, DCs without GHPs also are contained in the batch of the loading simulation.

The algorithm is also capable of doing loading simulation. One purpose of loading simulation is to get a prediction of how the disposal of all FAs for a certain fuel type can succeed based on the current data. In loading simulation, the assignments for DCs are simulated with the current data by doing loading optimization iteratively, one batch of the EP at a time. Compared to loading optimization, where the maximum weighted DC power is minimized for the DCs not in the current batch of the EP, this loading simulation takes additional objectives and constraints into account for these DCs in the corresponding batch, but also requires more input data from the user.

For example, the criteria related to pools are taken better into account in the loading simulation. To be able to do this, each FA needs to be in the interim storage at some point. For this we need to know when each FA is transferred to the interim storage. Furthermore, several parameters are batch dependent and need to be provided for each batch. These include a batch task, an accuracy, the number of DCs disposed of in a batch and their GHPs, pools where free space is required and the amount of free space, batch–task–specific information on the pools, the pools' capacity, banned FAs, and prioritized FAs, among others.

V.B. Flowchart of the Loading Optimization Algorithm

In Fig. 1, the flowchart of the optimization algorithm is given. There are 10 steps in the loading optimization algorithm, of which some are relevant only for specific

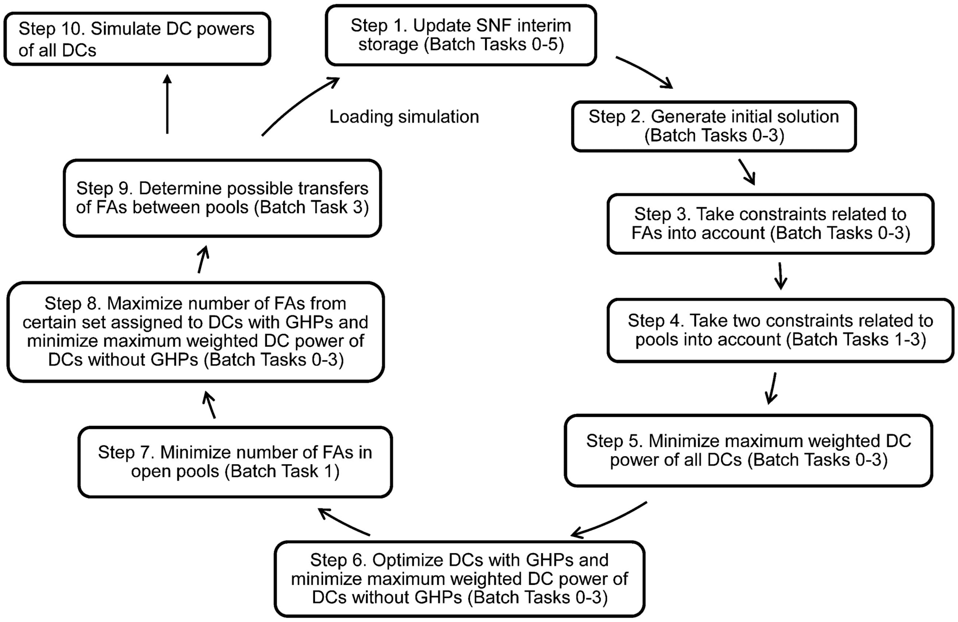

Fig. 1. Flowchart of the loading optimization algorithm.

batch tasks. Loading optimization will go through steps 1 through 9, which are relevant for the current batch, and thereafter, will end in step 10 if the user has so decided.

Loading simulation will go through steps 1 through 9, which are relevant for each batch, and finally, after the last batch will end in step 10 if the user has so decided.

There are six possible batch tasks 0 through 5 for each batch. Batch tasks 0 through 3, defined earlier, are for batches where some DCs are disposed of, i.e., for batches where there are DCs with GHPs. Batch tasks 4 and 5 are for batches where no DCs are disposed of and only the SNF interim storage is updated. The possible batch tasks depend on the fuel type. Batch tasks 1 through 4 are used for OL1-2 and OL3, while batch tasks 0 and 5 are used for LO1-2.

In step 1, the SNF interim storage is updated. Determining which FAs are transferred to the SNF interim storage in that batch, is necessary for the loading simulation, as we cannot dispose of FAs that are not in the SNF interim storage. For the OL1-2 and OL3 FAs, the pools to which the FAs are transferred to also need to be considered. These are determined with simple heuristics in the batch, with the real decisions on which pools the FAs should be brought to needing to be made outside the algorithm with proper planning.

In step 2, an initial solution is generated by assigning each FA to a single DC such that the capacity of the DC is not exceeded. After finding an initial solution, we will alter the solution with 1–1 or 2–2 exchanges. In a 1–1 exchange, two FAs from different DCs are exchanged. In a 2–2 exchange, two pairs of FAs from different DCs are exchanged. We use the 2–2 exchanges only in steps 5 and 6. In step 3, 1–1 exchanges are used to make the solution satisfy constraints related to dechannelled FAs, preassigned FAs, banned FAs, and the minimum cooling time criterion.

In step 4, two constraints related to the pools are considered. The user can require that a certain pool be empty or contain at most a certain number of FAs after a given pool emptying date. The user can also require that there is at least a certain amount of free space in a certain set of pools after the batch. The procedures in steps 3 and 4 make sure that certain constraints are satisfied in a solution. In order to keep the solution feasible, we need to check that these constraints remain satisfied whenever we alter the solution with 1–1 or 2–2 exchanges.

In step 5, the maximum weighted DC power of all the DCs is minimized using 1–1 exchanges, and also 2–2 exchanges, if the user has chosen to do so. In step 6, the DCs with GHPs are optimized within the accuracy of their GHPs. If no improving 1–1 exchanges are found anymore, then improving 2–2 exchanges are searched for if the user chooses to do so. Finally, we minimize the maximum weighted DC power of the DCs without GHPs.

In step 7, the number of FAs in the open pools is sought to be below the limit on how many FAs can be in the open pools in the batch. Alternatively, the algorithm can lower this value even further, if so wanted in the batch. The number of open pools is decreased by going through steps 3 through 6, with all FAs from certain pools banned. When decreasing the number of the pools open in the batch, the solution quality might deteriorate a bit. Therefore, the user should give the relaxed accuracy for minimizing the number of FAs in the open pools in the batch to specify what is still acceptable. For step 7, the user can require that some pools be open in the batch. Furthermore, the user needs to give which pools can be open in the batch.

In step 8, the number of FAs from two sets assigned to the DCs with GHPs are maximized. In batch tasks 2 and 3, this set can be the set of FAs being in certain pools. In batch tasks 0 through 3, this set can be the set of the prioritized FAs. Finally, we minimize the maximum weighted DC power of the DCs without GHPs.

In step 9, transfers of FAs from the transfer pools to the loading pools are determined. This needs a routine, as there can be more than one loading pool, implying that the transfers are not unique. Furthermore, the loading pools may be so full that there is no room for the FAs to transfer. In this case, we need counter transfers where we transfer some FAs from the loading pools to the transfer pools. This includes the decision about which FAs from the loading pools to transfer and to which transfer pools they are to be transferred. All these are determined heuristically in the batch in step 9. While the algorithm needs to determine the transfers, and especially the counter transfers for the loading simulation, the real transfers need to be specified outside the algorithm with proper planning.

In step 10, for each DC, its DC power is simulated a given number of times. This step makes it possible to compare the simulated DC power with the DC power calculated by the algorithm. In a good case, these are close to each other and there are no outliers having simulated DC powers greater than the DC powers calculated by the algorithm.

The description of each step in the loading optimization algorithm is presented in Appendix B.

VI. COMPUTATIONAL RESULTS

In this section, loading simulations are performed with the algorithm based on a disposal schedule optimized for an example scenario using certain conditions and decisions. One purpose of the loading simulation is to get a prediction of how the disposal of all FAs for a certain fuel type can succeed. It should be noted that the solution for the next batch of the EP might vary when the data change even a little. Because the current data change constantly during the final disposal, the solution from the loading simulation cannot be repeated. During the final disposal, the next batch of the EP is repeatedly optimized using updated data.

VI.A. Example Scenario

Each fuel type has its own FAs and data related to them. The data format is similar for all fuel types. The data include forecasted FAs, and thus, consist of all FAs to be irradiated. For LO1-2, the forecasts are estimated by the current fuel usage. For each FA, the date when cooling has started, i.e., the date when irradiation has ended, is given.

The example scenario investigated in this paper corresponds to the case of the current plan in 2022 for OL1-2, +23, and +20 operation years for the Loviisa 1 and Loviisa 2 reactors, respectively, and the current plan in 2022 for OL3. Table 1 sums up the data on the number of FAs for each fuel type in this scenario. We do not take the FAs of LO1-2 that were transferred outside Finland in the early years into account.

There are time-dependent data, such as the decay heat power of a FA. All the time-dependent data for a FA are given at the beginning of each month, starting from the year following the year at which the irradiation of the FA has ended. For all the fuel types, there are monthly data for roughly 100 years.

In Fig. 2, the decay heat powers of all the OL1-2, LO1-2, and OL3 FAs without uncertainties are visualized. In Fig. 3, illustrative decay heat powers without uncertainties as a function of time for the OL1-2, LO1-2, and OL3 FAs are

TABLE 1

Data on the Number of FAs for the Different Fuel Types in the Example Scenario

Fuel Type	Operation Years	Year of the First Removal	Year of the Last Removal	Number of FAs
OL1-2	1979–2038	1981	2038	14 056
LO1-2	1977–2050	1989	2050	11 046
OL3	2023–2081	2023	2081	3 756

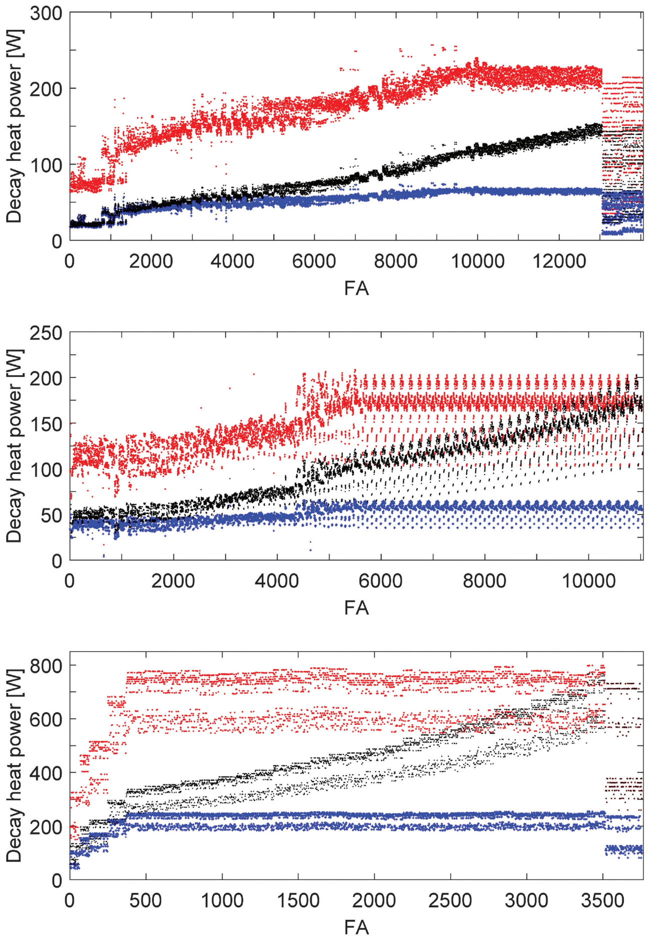

Fig. 2. FA decay heat powers without uncertainties for (top) OL1-2, (middle) LO1-2, and (bottom) OL3 in the example scenario. The values are given after 20 years of cooling (red dots), after 99 years of cooling (blue dots), and when the last FAs have cooled 20 years (black dots). The last FAs will have cooled 20 years in June 2058, June 2070, and June 2101 for OL1-2, LO1-2, and OL3, respectively.

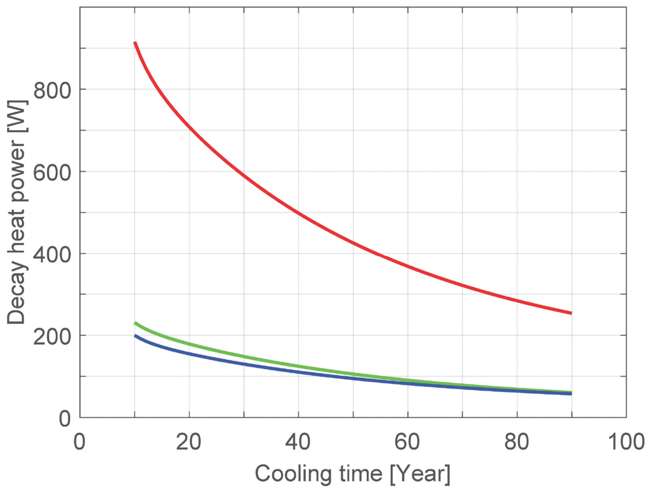

Fig. 3. Illustrative FA decay heat powers without uncertainties as a function of time for OL1-2 (green), LO1-2 (blue), and OL3 (red).

shown. To compute the illustrative decay heat powers, we first selected 10 FAs for each fuel type, such that their decay heat powers after 20 years of cooling were closest to the median decay heat power for that fuel type after 20 years of cooling, i.e., closest to the median of the red dots for that fuel type in Fig. 2. Then we computed the average decay heat power for these FAs at different cooling times. In Finland, UO_2 fuel matrices are currently in use, resulting in decay heat that behaves similarly among the fuel types. The main factors that contribute to decay heat power are burnup and uranium mass.

Summarized data on the uncertainties for the OL1-2, LO1-2, and OL3 FAs are given in Table 2.

Reactor pools store spent FAs before they are transferred to the SNF interim storage. The FAs in the reactor pools are the FAs whose irradiation has been stopped and that are not yet in the SNF interim storage. The FAs that are in the SNF interim storage at the end of year 2021 have been given for each fuel type. From this, and the time when the irradiation of each FA has been stopped, we can determine which FAs are in the reactor pools.

The rule about how many FAs are transferred from the reactor pools to the SNF interim storage each year depends on the fuel type. In this paper, the common rule for all fuel types is that the FAs to be transferred to the SNF interim storage are determined by the FIFO (first-in, first-out) principle. The oldest FAs in the reactor pools are transferred first. In this paper, it is assumed that there are currently four pools dedicated to OL1-2 and two pools dedicated to OL3 in the Olkiluoto SNF interim storage.

VI.A.1. Disposal Schedules, GHPs, and Pool Allocations Derived from the Disposal Scheduling Problem

The optimized disposal schedules for each fuel type for the example scenario using certain conditions and decisions are derived from the disposal scheduling problem. One multiobjective version of the model was presented by Montonen et al. [3]. The GHPs for all the DCs are derived from the disposal scheduling problem, as well. The GHPs are given in Table 3. The years when each pool is allocated for OL1-2 and OL3 are obtained from the disposal scheduling problem, as well.

It should be noted that the solutions obtained from the disposal scheduling model are scenario dependent. With different conditions or decisions, we obtain different disposal schedules, GHPs, and pool allocations from the disposal

TABLE 2

Summarized Data on Each Uncertainty Factor for the OL1-2, LO1-2, and OL3 FAs in the Example Scenario

Fuel Type	Uncertainty Factor	Distribution	Average Relative Standard Deviation in June 2058, June 2070, and June 2101 for OL1-2, LO1-2, and OL3, Respectively (%)	Trend in Relative Standard Deviation	Average Relative Bias in June 2058, June 2070, and June 2101 for OL1-2, LO1-2, and OL3, Respectively (%)	Trend in Relative Bias	Proportion of Correlating Pairs of FAs (%)
OL1-2	1	Normal	0.77	Increasing	0.00	–	10.25
OL1-2	2	Normal	0.58	Decreasing	0.00	–	0
OL1-2	3	Normal	1.63	Decreasing	0.00	–	0
OL1-2	4	Normal	0.36	Increasing	0.00	–	0.89
LO1-2	1	Uniform	2.98	Decreasing	0.33	Decreasing	25.54
LO1-2	2	Uniform	0.16	Decreasing	0.13	Decreasing	17.20
LO1-2	3	Uniform	0.49	Increasing	0.69	Increasing	3.36
LO1-2	4	Uniform	0.44	Increasing	0.00	–	2.32
LO1-2	5	Normal	1.61	Decreasing	0.00	–	0
LO1-2	6	Normal	2.00	Constant	0.00	–	0
OL3	1	Normal	0.89	Increasing	0.00	–	22.11
OL3	2	Normal	0.58	Decreasing	0.00	–	0
OL3	3	Normal	1.63	Decreasing	0.00	–	0
OL3	4	Normal	0.36	Increasing	0.00	–	2.00

TABLE 3

GHPs for All the DCs for the Example Scenario

	OL1-2	OL1-2	OL1-2	LO1-2	OL3
DCs	1 to 172	173 to 452	453 to 1172	1 to 921	1 to 939
GHP (W)	1700.0	1656.5	1595.0	1369.2	1830.0

scheduling model. In addition, the final disposal is a century long process, and thus, the current data, which were a best estimate in 2022, will change in time. The decisions in the final disposal process should be revised when new data are available. For these reasons, the disposal schedules, GHPs, and pool allocations used in the actual loading optimization could differ from the examples used in this paper.

VI.A.2. Simulation Setup

In these loading simulations, each batch of the EP corresponds to the DCs disposed of in a year in the optimized disposal schedule. For each fuel type, the last batch of the EP corresponds to the DCs disposed of in the last year of the disposal.

There are several parameters that affect the solution of the loading simulation, and the most important ones are given here. There are no banned FAs or prioritized FAs for any fuel type. In this paper, it is assumed that there are approximately 850 dechannelled FAs for the OL1-2 fuel and that they will be disposed of at pace two dechannelled FAs/DC starting from the second disposal tunnel. There are no preassigned FAs, other than FAs modeling empty slots in the DCs. The minimum cooling time for all the FAs is 20 years for the OL1-2, LO1-2, and OL3 fuels.

The DC power is defined as in Sec. III, i.e., the coefficient for the standard deviation is 1.645, which corresponds to the upper bound of the one-sided 95% confidence interval if the distribution is normal. The accuracy is 0.1% for all fuel types. The relaxed accuracy for minimizing the number of FAs in the open pools is 0.2% for the OL1-2 and OL3 fuel types with batch task 1.

In the loading simulation, a single instance of the assembly assignment problem is called a batch. In each batch of the loading simulation, GHPs are given only for DCs disposed of in the corresponding batch of the EP. However, we give weighting coefficients for the DCs without GHPs in each batch of the loading simulation so that possibly different GHPs for these DCs can be taken into account to some extent by minimizing the maximum weighted DC power.

The basis for the different DC powers comes from the disposal scheduling problem, where GHPs for all the DCs are determined. For example, for OL1-2, the GHP is 1700.0 W for DCs 1 to 172, 1656.5 W for DCs 173 to 452, and 1595.0 W for DCs 453 to 1172. Hence, for OL1-2, we set the weighting coefficients to one for DCs 1 to 172, to $1700.0/1656.5 \approx 1.0263$ for DCs 173 to 452, and to $1700.0/1595.0 \approx 1.0658$ for the rest of the DCs. Note that we have weighting coefficients for every DC, which is necessary in step 5 of the algorithm.

The minimization of the maximum weighted DC power of all the DCs in step 5 of the algorithm implies that the weighting coefficients have an effect on the assignment of the FAs to DCs with GHPs in each batch. Moreover, the minimization of the maximum weighted DC power of the DCs without GHPs in steps 6 and 8 of the algorithm implies that the weighting coefficients have a direct effect on the assignment of FAs to DCs without GHPs in each batch. However, in this paper, all the batches of the EP are simulated, hence there are no DCs without GHPs in the last simulated batch.

In the loading simulations for the OL1-2 and OL3 fuels, we use batch task 1 at first, where we do not have to specify the loading pools. In batch task 1, we try to open the pools so that the number of FAs in the open pools is under certain values for OL1-2 and for OL3. Here, we assume that this value can be two times the maximum capacity of a single pool. Based on this result, we do the loading simulation again with batch task 2, and the loading pools are set based on the solution obtained when using batch task 1. It should be noted that the solutions from batch tasks 1 and 2 are not identical. Especially, the number of FAs in the open pools might be over the limit in batch task 2. In the studied scenario, this effect did not occur.

For OL1-2, zero FAs are allowed to be in a pool that should be empty. However, in batch task 1, any pool that is not required to be empty at a certain year can be open at that year. It is enough that the limit of the number of FAs in the open pools is undercut. In batch task 2, we do not maximize or minimize the FAs taken from certain pools.

For OL3, the pools are not required to be emptied until the last disposal year. In batch task 1, all the pools can be open at any year and no pool is required to be open. However, there can be only a certain number of FAs in the pools that are open at a certain time. In batch task 1, we try to have as few FAs as possible in the open pools. In batch task 2, we do not maximize or minimize the FAs taken from certain pools.

For the OL1-2 and LO1-2 fuels, only 1–1 exchanges were used when minimizing the maximum weighted DC power. For the OL3 fuel, 2–2 exchanges also were used. With OL3, other parameters were also used to improve a solution when minimizing the maximum weighted DC power. When finding exchanges, we preferably wanted to find a change that does not increase the covariances. After minimizing the maximum weighted DC power, we continued to minimize the second largest weighted DC power and so on. After minimizing the 10th largest weighted DC power, we moved on. These parameters were not used with the LO1-2 or OL1-2 fuels.

The loading simulations took a long time with OL1-2. Due to this, 2–2 exchanges were not used when getting the decay heat powers of the DCs with GHPs to their GHPs within the accuracy for OL1-2. In addition, the covariances were allowed to increase for OL1-2 when finding exchanges in the procedure that empty the pools by given times.

VI.B. Loading Simulation Results

The OL1-2 fuel turned out to be the trickiest for the loading simulation, and several options to speed up the solving process were needed. Furthermore, some batch–task–specific adjustments were made to improve the solutions. With batch task 1, this is setting the pools that are certainly open in some batches. With batch task 2, these are requiring at least a certain amount of free space in a certain pool for a certain batch and closing a certain pool for a certain batch, even if it was open with batch task 1.

Even then, there are unexpected effects, like not being able to empty pools completely without transfers between the pools or some DCs that are not in their GHPs. Part of the reason that the OL1-2 fuel is tricky is that we require that some pools will be empty after a certain time. This requirement follows from the disposal schedules of the example scenario, where some

OL1-2 pools are emptied for the OL3 fuel. To prevent the algorithm from stopping, the emptying of the pools is done weakly, meaning that the algorithm can exceed the number of FAs that can be in a pool after it is emptied. These OL1-2 FAs are transferred to other pools to make the pool empty. The algorithm transfers these FAs at the start of the next batch. The cause for the unexpected results is somewhat related to the disposal schedule of the example scenario. Such a disposal schedule, where after emptying a pool the remaining pools must be full or near full, seems to be tricky.

The DC powers for OL1-2 with batch tasks 1 and 2 are presented in the top left and top right images, respectively, in Fig. 4. For OL1-2 with batch task 1, the covariances increase the DC power by 1.5 W on average, and the uncertainties increase the DC power by 18.7 W on average. With batch task 2, the corresponding values are 1.7 W and 18.9 W. The spike in the OL1-2 DC power is related to the disposal schedule used. In the disposal scheduling model, the FAs are modeled as continuous variables, with each removal having its own decay heat power, and the decay heat uncertainties and correlations are taken into account, increasing the decay heat powers by a percentage. By changing this percentage appropriately in the disposal scheduling model, the disposal schedule can be improved.

In the disposal scheduling model, the pool where a FA is located and the dechannelled FAs do not restrict the solution, whereas in the loading simulation, these need to be considered appropriately. These should cause the DC powers in the loading simulation to be somewhat higher than the DC powers in the disposal scheduling model.

The accuracy used also contributes to having a spike in the DC powers. The closer we require the DC powers to be to their GHPs, the more exchanges are done to the solution obtained from minimizing the maximum weighted DC power. The disposal schedule should be revised during the final disposal when new data are available.

For the LO1-2 and OL3 fuels, the results are not as surprising. The DC powers for LO1-2 with batch task 0 are presented in the middle left image in Fig. 4. For LO1-2, the general pattern is that almost all the DC powers are in the GHPs within 0.1%, except for the last batches. For LO1-2 with batch task 0, the covariances increase the DC power by 2.5 W on average, and the uncertainties increase the DC power by 42.0 W on average. The biases increase the LO1-2 DC power by 11.3 W on average, which is included in the 42.0 W. For LO1-2, the two levels for the DC powers in the last batch are related to the disposal schedule used.

The DC powers for OL3 with batch tasks 1 and 2 are presented in the bottom left and bottom right images, respectively, in Fig. 4. For OL3, there are some DCs that are not in the GHPs within 0.1% in most batches. However, for OL3, all the DC powers are in the GHPs within 0.2%, except for the last batch, where the DC powers are under the GHPs. For OL3 with batch task 1, the covariances increase the DC power by 0.9 W on average, and the uncertainties increase the DC power by 32.5 W on average. With batch task 2, the corresponding values are 0.8 W and 34.2 W.

The decay heat powers of each FA in each DC without uncertainties are presented in Appendix C.

In Table 4, information about the results of the loading simulations performed with the algorithm based on the disposal schedule optimized for the example scenario is given. The total number of FAs transferred from the pools that should be empty refers to the total number of FAs that are left in the pools that should be empty after transferring FAs to the EP for disposal. This can be nonzero only for OL1-2 fuel.

The total number of times the pool lids are opened was calculated by the following rules. When FAs are transferred from the reactor pools to the SNF interim storage, the lids of the pools where the FAs are placed are opened. When the FAs are transferred from the SNF interim storage to the EP, the lids of the pools where the FAs are, needs to be opened. If a pool needs to be open in two consecutive years, it remains open in those years to avoid the lifting of the lid. For OL3, transfers to the SNF interim storage occur biennially, implying that pool lids are closed between consecutive transfers. This results in a large number of lifting of the lids for OL3.

All the uncertainty factors for OL1-2 and OL3 are normally distributed. With the approximated dependency structure, this results in DC power having a normal distribution regardless of the number of the correlating pairs of the uncertainty factors. Thus, the differences between the calculated values and the simulated values calculated in step 10 of the algorithm are purely due to randomness in the sampling. These differences could be made as small as wanted by increasing the sample size used in step 10. For LO1-2, the distributions of the DC powers are not normal, since two uncertainty factors have a uniform distribution.

In Fig. 5, the differences between the simulated DC powers and the algorithm's calculated DC powers are presented for LO1-2. The sample size to approximate

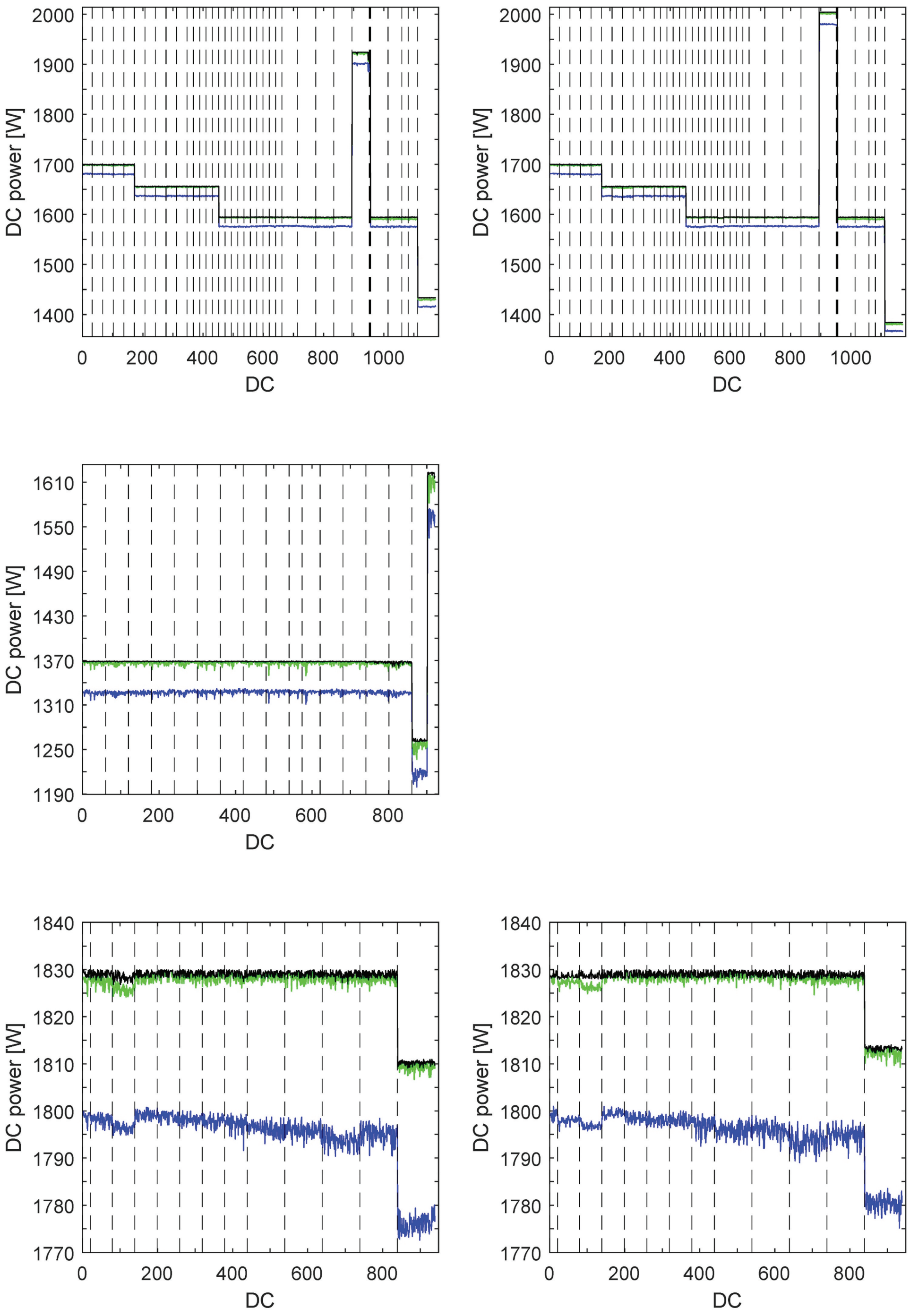

Fig. 4. DC powers for (top left and top right) OL1-2 with batch tasks 1 and 2, for (middle) LO1-2 with batch task 0, and for (bottom left and bottom right) OL3 with batch tasks 1 and 2. The curves represent DC power with uncertainties (black), DC powers if the correlation matrices were identity matrices (green), and DC powers without uncertainties and biases (blue). The dashed lines separate the batches, and the bolded dashed line indicates that there is a hiatus in the OL1-2 disposal at that point.

the distribution of the DC power is 75 000. There are some outliers with the algorithm's calculated DC powers greater than the simulated ones. Thus, in the clear outlier cases, the algorithm's calculated DC powers are conservative.

VII. DISCUSSION

A new version of the loading optimization algorithm that assigns FAs to DCs in Finland has been developed. One major advancement in the new version of the

TABLE 4

Loading Simulation Results for the Example Scenario

	OL1-2	OL1-2	OL1-2	OL1-2	OL1-2	OL1-2	LO1-2	OL3	OL3
Batch task	1	1	1	2	2	2	0	1	2
Number of DCs in GHPs within the accuracy of 0.1%	172	280	599	172	280	578	812	806	816
Number of DCs not in GHPs within the accuracy of 0.1%	0	0	121	0	0	142	109	133	123
GHP (W)	1700.0	1656.5	1595.0	1700.0	1656.5	1595.0	1369.2	1830.0	1830.0
Average DC power with uncertainties (W)	1699.4	1655.8	1608.8	1699.5	1655.9	1611.5	1369.3	1827.0	1827.3
Average DC power if the correlation matrices were identity matrices (W)	1698.3	1654.8	1606.9	1698.1	1654.4	1609.7	1366.8	1826.1	1826.5
Average DC power without uncertainties (W)	1680.7	1636.9	1590.1	1680.5	1636.4	1592.8	1327.3	1794.5	1794.9
Total number of FAs transferred from pools that should be empty	0	0	85	0	0	0	—	—	—
Number of times pool lids are opened for transferring FAs from the SNF interim storage to the EP for disposal	3	2	3	3	2	2	—	12	12
Number of times pool lids are opened just for transferring FAs to the SNF interim storage or transferring FAs from pools that should be empty	2	0	5	2	0	5	—	35	35
Total number of times pool lids are opened	5	2	8	5	2	7	—	47	47

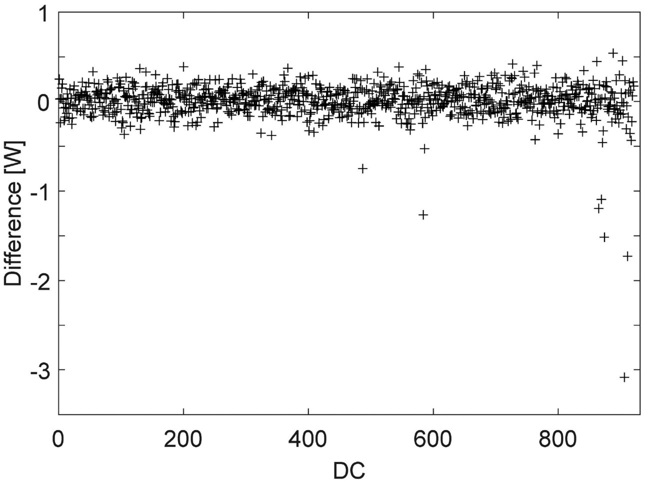

Fig. 5. Differences between the simulated DC powers and algorithm's calculated DC powers for LO1-2.

algorithm is that it takes into account uncertainties in the decay heat powers of the FAs and the dependencies between these uncertainties when assigning FAs to DCs. Due to the uncertainties, the DC power of a DC is the upper bound of the one-sided 95% confidence interval of the distribution of the decay heat power of the DC.

The other major advancement in the new version of the algorithm is that it manages the SNF interim storage efficiently according to new requirements. Suppose that some positions in the SNF interim storage are wanted to be empty. In the new version of the algorithm, the FAs in those positions can be set as prioritized, and the algorithm decides which of the FAs, if any, are assigned to the DCs with GHPs and to which DC. A date by which a pool in the Olkiluoto SNF interim storage should be empty can be set, as well as how much free space is required in certain pools in the Olkiluoto SNF interim storage after the FAs assigned to the DCs with GHPs are transferred to the EP.

Moreover, the new version of the algorithm has three main ways to control which pools are open in the Olkiluoto SNF interim storage when FAs are transferred to the EP to be disposed of in the DCs with GHPs. One way is to let the algorithm decide which pools are open. Another way is to give the loading pools from which the FAs to be disposed of in the DCs with GHPs will be transferred to the EP. In the third way, the loading pools are given, but also transfer pools are given. FAs from these transfer pools that are disposed of in the DCs with GHPs will be transferred to the loading pools before they are transferred to the EP.

Like the recently developed loading optimization algorithm, the new version considers banned, dechannelled, and preassigned FAs. Furthermore, FAs that are preferred to be disposed of in the DCs with GHPs can be set as prioritized in the new version. This is not a hard constraint, and thus, the number of prioritized FAs disposed of in the DCs with GHPs is an objective of the new version. For the DCs to be disposed of in the near future, GHPs need to be given. In addition, weighting coefficients need to be given for every DC in the new version. This makes it possible to have different DC powers for DCs without GHPs.

The algorithm seeks to get the DC powers of the DCs with GHPs under their GHPs and within a given accuracy. In addition, the algorithm seeks to maximize the number of prioritized FAs disposed of in the DCs with GHPs. For the DCs without GHPs, the algorithm seeks to minimize the maximum weighted DC power. This gives a rough idea of the decay heat powers of these DCs. The assignments for the DCs with GHPs are supposed to be final, whereas the assignments for the other DCs may change as the data change. To get a prediction of how the disposal of all FAs for a certain fuel type can succeed, the new version of the algorithm is capable of simulating the whole disposal iteratively, one batch of the EP at a time with the current data.

The new version of the loading optimization algorithm was presented. Loading simulations were performed with the algorithm for an example scenario. In these loading simulations, the assignments for all DCs were determined by doing loading optimization iteratively, one batch of the EP at a time according to the disposal schedules, GHPs, and pool allocations derived from a disposal scheduling problem. The developed loading optimization algorithm succeeded in taking the uncertainties in the decay heat powers of the FAs into account. In loading simulations with the current data, the correlations increased the average DC power by 1.5 to 1.7 W for OL1-2, 2.5 W for LO1-2, and 0.8 to 0.9 W for OL3. In total, the uncertainties increased the average DC powers by 18.7 to 18.9 W for OL1-2, 42.0 W for LO1-2, and 32.4 to 32.5 W for OL3.

In the loading simulation, making sure that the OL1-2 pools were empty when needed turned out to be challenging in the example scenario. With the aid of some batch–task–specific adjustments, no additional transfers were needed to empty the OL1-2 pools by the given times with batch task 2. With batch task 1, a few additional transfers were needed, even when the batch–task–specific adjustments were made to improve the solution. This could be alleviated by using slightly lower than actual capacities for the OL1-2 pools in the disposal scheduling model. This would encourage more FAs to be disposed of earlier, and therefore, after emptying a pool, the remaining pools would not be full or near full.

The loading optimization algorithm can be developed further when new requirements emerge. It is known that the loading optimization algorithm may not find a feasible solution, although such a solution exists. This possibility could be reduced by taking constraints on the FAs and pools into account already in the routine that generates an initial solution. The routine that determines what pools will be opened may not find the optimal solution. If there is a solution where GHPs are attained if pools 1 and 4 are open, it may not be found if pool 4 is closed first before pools 2 and 3. If emptying pools or/and requiring free space in certain pools is done weakly, they are treated as objectives rather than constraints. How these objectives are prioritized could be revisited. Currently emptying pools is prioritized over the required free space, even if the requirement of free space is not weak.

The new version of the loading optimization algorithm has been implemented in Posiva's SNF database Kaapo. Kaapo software is the first of its kind in the world, since most of nuclear power countries are still in the early stages in their planning for nuclear waste disposal. The final test for the software will be performed as part of the trial run of the final disposal, which is ongoing during the writing of this paper, and also the loading optimization algorithm is used in the trial run of the final disposal, providing optimal FAs into the DCs.

In the trial run of the final disposal, encapsulation and final disposal test is carried out with the facilities, machinery, organization, and procedures, which will be used in the operation phase: fuel transports, encapsulation, final disposal, retrieval of a damaged canister, description of the design and construction of the disposal tunnel and holes. In the trial run of the final disposal, the only difference to the actual disposal is that the spent FAs are represented by dummy FAs similar to spent FAs but containing no SNF. For testing the loading optimization, the Olkiluoto interim storage's SNF inventory is used in the calculations, and by expert decision, the actual SNF data is combined with the dummy FAs.

VIII. CONCLUSIONS

A new version of the loading optimization algorithm that assigns FAs to DCs in Finland has been developed. The algorithm succeeded in taking the uncertainties in the decay heat powers of the FAs into account. In loading simulations with the current data, the uncertainties increased the average DC powers by about 1.2%, 3.2%, and 1.8% for OL1-2, LO1-2, and OL3, respectively. The SNF interim storage can be efficiently managed with the algorithm.

APPENDIX A

MATHEMATICAL FORMULATIONS FOR DIFFERENT ASSEMBLY ASSIGNMENT PROBLEMS

In this appendix, we give the mathematical formulation for each assembly assignment problem. First the optimization problem is given for the OL1-2 fuel with batch task 1. The other problems are derived based on this problem.

Define the following sets:

$\mathcal{I}$	set of DC indices
$\mathcal{J}$	set of FA indices
$\mathcal{U}$	set of uncertainty factors
$\mathcal{R}$	set of DCs with GHPs
$\mathcal{F}$	set of prioritized FAs
$\mathcal{B}$	set of banned FAs that cannot be assigned to the DCs with GHPs
$\mathcal{P}$	set of pairs (i,j) that indicates that the preassigned FA j should be assigned to DC i
$\mathcal{W}$	set of pools where FAs are held in the interim storage
$\mathcal{Q}$	set of pools that can be open
$\mathcal{O}$	set of pools that are required to be open
$\mathcal{M}$	set of pools where free space is required

The mathematical model has the following parameters:

G_i	GHP of DC i
C	capacity of DC
A_{ij}	decay heat power of FA j at the time when DC i is disposed of
B_{iju}	relative bias of uncertainty factor u in decay heat power of FA j at the time when DC i is disposed of
V_{iju}	variance in the uncertainty factor u in the decay heat power of FA j at the time when DC i is disposed of
C_{jku}	correlation between FAs j and k with respect to uncertainty factor u
D_j	indicator whether FA j is dechannelled or not
E_i	how many dechannelled FAs are wanted to be disposed of in DC i
W_{rj}	indicator whether FA j is in pool r
P_r	capacity of pool r
F	free space that is required in pools in set $\mathcal{M}$
T_r	order number of the DC that is disposed of last before pool r needs to be empty. There are no timestamps in the mathematical model. To be able to empty pool r by the given time, we use the order number of the DC that is disposed of last before pool r needs to be empty.
N_r	number of FAs in pool r
N^{max}	maximum allowed number of FAs in open pools
M_r	number of FAs that can be left in pool r after the date it should be empty
K	coefficient of standard deviation in the formula for DC power
H_i	weighting coefficient for DC power of DC i

The mathematical model has the following continuous variables:

h_i	decay heat power of DC i

The mathematical model has the following binary variables:

w_r	1, if the lid of pool r is needed to be open when filling DCs in set $\mathcal{R}$
x_{ij}	1, if the FA j is assigned to DC i
c_{jkul}	auxiliary variables to get the DC-specific correlation matrices transitive
a_{jkmul}	auxiliary variables
b_{jkul}	auxiliary variables.

In the continuation, we use the following notations:

Notation	Symbol	Description
Belongs to	$x \in A$	Element x belongs to set A if it is included in set A.
Difference	$A \backslash B$	Returns a new set that contains all the elements that belong to set A but not to set B.
Curly brackets	$\{\}$	Defines a set that contains all the elements inside the curly brackets.
Cardinality	$\|A\|$	Returns the number of elements in set A.
Union	$A \cup B$	Returns a new set that contains all the elements that belong to set A, or set B, or both sets.

The considered assembly assignment problem can be formulated as the following multi-objective optimization problem.

The model has the following objectives:

$$\min\left(\max_{i\in\mathcal{R}}\,(G_i - h_i)\right) \,, \tag{A.1}$$

$$\max\left(\sum_{i\in\mathcal{R}}\sum_{j\in\mathcal{F}} x_{ij}\right) \,, \tag{A.2}$$

$$\min\left(\max_{i\in\mathcal{I}\setminus\mathcal{R}} H_i h_i\right) \,. \tag{A.3}$$

Variables in the model are subject to the following constraints:

$$\sum_{j\in\mathcal{J}} x_{ij} = C, \quad i\in\mathcal{I} \,, \tag{A.4}$$

$$\sum_{i\in\mathcal{I}} x_{ij} = 1, \quad j\in\mathcal{J} \,, \tag{A.5}$$

$$\sum_{j\in\mathcal{J}} A_{ij}\left(1+\sum_{u\in\mathcal{U}} B_{iju}\right)x_{ij} + K\sqrt{\sum_{u\in\mathcal{U}}\sum_{j\in\mathcal{J}}\sum_{k\in\mathcal{J}} c_{jku(C-1)}x_{ij}x_{ik}\sqrt{V_{iju}}\sqrt{V_{iku}}} = h_i, i\in\mathcal{I} \,, \tag{A.6}$$

$$c_{jku1} = C_{jku}, j\in\mathcal{J}, k\in\mathcal{J}\setminus\{j\}, u\in\mathcal{U} \,, \tag{A.7}$$

$$c_{jmul}x_{ij}x_{im} + c_{kmul}x_{ik}x_{im} - 1 \le a_{jkmu(l+1)}, i\in\mathcal{I}, j\in\mathcal{J} \,, \quad k\in\mathcal{J}\setminus\{j\}, m\in\mathcal{J}\setminus\{j,k\}, u\in\mathcal{U}, l=1,\ldots,C-2 \,, \tag{A.8}$$

$$c_{jmul}x_{ij}x_{im} + c_{kmul}x_{ik}x_{im} - 1 \ge 2a_{jkmu(l+1)} - 1, i\in\mathcal{I}, j\in\mathcal{J} \,, \quad k\in\mathcal{J}\setminus\{j\}, m\in\mathcal{J}\setminus\{j,k\}, u\in\mathcal{U}, l=1,\ldots,C-2 \,, \tag{A.9}$$

$$a_{jkmu(l+1)} \le b_{jku(l+1)}, j\in\mathcal{J}, k\in\mathcal{J}\setminus\{j\}, m\in\mathcal{J}\setminus\{j,k\}, u\in\mathcal{U}, \quad l=1,\ldots,C-2 \,, \tag{A.10}$$

$$\sum_{m\in\mathcal{J}\setminus\{j,k\}} a_{jkmu(l+1)} \ge b_{jku(l+1)}, \quad j\in\mathcal{J}, k\in\mathcal{J}\setminus\{j\}, u\in\mathcal{U}, \quad l=1,\ldots,C-2 \,, \tag{A.11}$$

$$c_{jkul} + b_{jku(l+1)} \le 2c_{jku(l+1)}, \quad j\in\mathcal{J}, \quad k\in\mathcal{J}\setminus\{j\}, u\in\mathcal{U}, \ l=1,\ldots,C-2 \,, \tag{A.12}$$

$$c_{jkul} + b_{jku(l+1)} \ge c_{jku(l+1)}, \quad j\in\mathcal{J}, k\in\mathcal{J}\setminus\{j\}, \quad u\in\mathcal{U}, l=1,\ldots,C-2 \,, \tag{A.13}$$

$$c_{jju(C-1)} = 1, j\in\mathcal{J}, u\in\mathcal{U} \,, \tag{A.14}$$

$$h_i \le G_i, i\in\mathcal{R} \,, \tag{A.15}$$

$$x_{ij} = 0, i\in\mathcal{R}, j\in\mathcal{B} \,, \tag{A.16}$$

$$x_{ij} = 1, (i,j)\in\mathcal{P} \,, \tag{A.17}$$

$$\sum_{j\in\mathcal{J}} D_j x_{ij} = E_i, i\in\mathcal{I} \,, \tag{A.18}$$

$$x_{ij} \le 5000 - A_{ij}, i\in\mathcal{I}, \quad j\in\mathcal{J} \,, \tag{A.19}$$

$$\sum_{r\in\mathcal{M}}\left(P_r - \sum_{i\in\mathcal{I}\setminus\mathcal{R}}\sum_{j\in\mathcal{J}} W_{rj}x_{ij}\right) \ge F \,, \tag{A.20}$$

$$\sum_{i>T_r}\sum_{j\in\mathcal{J}} W_{rj}x_{ij} \le M_r, r\in\mathcal{W} \,, \tag{A.21}$$

$$\sum_{j\in\mathcal{J}}\sum_{i\in\mathcal{R}} W_{rj}x_{ij} \le C|\mathcal{R}|w_r, \quad r\in\mathcal{W} \,, \tag{A.22}$$

$$\sum_{r\in\mathcal{W}} N_r w_r \le N^{max} \,, \tag{A.23}$$

$$w_r = 0, \quad r\in\mathcal{W}\setminus(\mathcal{O}\cup\mathcal{Q}) \,, \tag{A.24}$$

$$w_r = 1, r\in\mathcal{O} \,. \tag{A.25}$$

The first objective (A.1) minimizes the maximum difference from the GHPs for the DCs with GHPs. With the second objective (A.2) the number of prioritized FAs disposed of in the DCs with GHPs is maximized. The third objective (A.3) minimizes the maximum weighted DC power among the DCs without GHPs. Constraint (A.4) ensures that there will be exactly C FAs assigned to each DC. The possible empty slots are modeled with FAs having zero in the corresponding elements of parameters A_{ij}, B_{iju}, and V_{iju}.

Constraint (A.5) ensures that each FA is assigned to a single DC. Constraint (A.6) determines the DC power of each DC. With the constraints (A.7) through

(A.14) the DC-specific correlation matrices used in (A.6) are ensured to be transitive. Constraint (A.15) makes sure that the DC powers are below the GHPs for the DCs with GHPs. Constraint (A.16) ensures that no banned FAs are assigned to the DCs with GHPs. Constraint (A.17) ensures that the preassigned FAs are assigned accordingly. Constraint (A.18) makes sure that there will be the correct number of dechannelled FAs in the DCs. Constraint (A.19) implies that each FA satisfies the minimum cooling time criterion since if FA j does not satisfy the minimum cooling time criterion at the time when DC i is disposed of, then we set $A_{ij} = 5000$ W, which is significantly larger than any reasonable DC power.

Constraint (A.20) ensures that there will be at least the required amount of free space in the given pools. Constraint (A.21) makes sure that the pools are emptied by given times. Constraints (A.22) and (A.23) ensure that the number of FAs in the open pools is lower than the maximum allowed number when the FAs are transferred to the EP. Constraint (A.24) implies that only FAs from certain pools, which can be open or are required to be open, are used in the DCs with GHPs. Constraint (A.25) ensures that the pools required to be open are open.

For the assembly assignment problem for the OL1-2 fuel with batch task 2, some changes are made to the optimization problem. The constraints (A.22) and (A.23) are omitted. Set $\mathcal{Q}$ is the same as set $\mathcal{O}$, which consists of the loading pools.

For the assembly assignment problem for the OL1-2 fuel with batch task 3, the constraints (A.22) and (A.23) are omitted. Set $\mathcal{Q}$ corresponds to the transfer pools and set $\mathcal{O}$ to the loading pools. To make sure that the transfer pools are open, we add a new constraint,

$$w_r = 1, r \in \mathcal{Q} \; . \tag{A.26}$$

For the OL3 fuel, the assembly assignment problems are similar, but the constraint (A.18) related to dechannelled FAs is omitted. For the LO1-2 fuel, none of the 3 batch tasks are used. We call the way of considering pools with LO1-2 fuel as batch task 0. In this case, the pools are not modeled. To formulate the assembly assignment problem with batch task 0, all the constraints related to pools are omitted. These include constraints (A.20) to (A.25). The constraint (A.18) is omitted, as well, since there are no dechannelled FAs for LO1-2.

APPENDIX B

DESCRIPTION OF EACH STEP IN THE LOADING OPTIMIZATION ALGORITHM

In this appendix, we present the description of each step in the loading optimization algorithm.

B.I. STEP 1. UPDATE SNF INTERIM STORAGE

The FAs that are chosen to be disposed of in the DCs with GHPs are transferred from the SNF interim storage to the EP. Hence, only the FAs that are located in the SNF interim storage can be disposed of in the DCs with GHPs. To be able to do a loading simulation of the whole production of the EP, each FA needs to be in the SNF interim storage at some point. Those FAs that are not currently in the SNF interim storage need to be brought to the SNF interim storage in some batch. The user specifies which FAs are brought to the SNF interim storage for each batch.

In the case of LO1-2, the FAs that are in the Loviisa SNF interim storage are updated in step 1. In the case of OL1-2 and OL3, the procedure to update the SNF interim storage in step 1 determines also to which pools these FAs will be transferred in the Olkiluoto SNF interim storage. Furthermore, if there are some FAs left in a pool that should be empty, this procedure determines new pools for those FAs. Ideally, when defining transfers to the SNF interim storage, we want to avoid the unnecessary opening of lids and situations where the only pools where we can make transfers are the ones that should be empty before the transferred FAs satisfy the minimum cooling time criterion.

At first, it is checked if there are FAs in the pools that should be empty. If there are, then those are added to the list of FAs that are to be transferred to SNF interim storage. The pools that are emptied next are considered more carefully. There can be more than one pool with the earliest date by which the pool should be empty; these pools are saved to list B. We do not want to transfer FAs to pools in list B unless necessary. If the number of FAs that is transferred to SNF interim storage before the next DC is disposed of can be stored completely in other pools than the ones in list B, then the free space in the pools in list B is set to zero. However, if this is not true, and there is enough room in the pools in list B for FAs that are to be transferred to SNF interim storage in the current batch, then the free space in the other pools is set to zero. Setting the free space to zero means that FAs cannot be transferred to those pools.

First, all the pools are ordered in the increasing order of free space. Then the order is changed such that the pools that have less free space than the number of FAs that are to be transferred to SNF interim storage in the current batch are set to last. Then the order is changed, such that the pools that are open are set to first.

An example of a pool where transfers from the SNF interim storage is prioritized would be one that is open and that has as little free space as possible but still enough such that all the FAs that need to be transferred can be transferred to that pool. In this procedure, the open pools consist of pools that are known to be open in the current batch and pools that were open in the previous batch. If the number of FAs that is transferred to SNF interim storage before the next DC is disposed of cannot be stored in pools other than the ones in list B, then the order is changed such that pools in list B are set first. The pools will be filled in the found order.

B.II. STEP 2. GENERATE INITIAL SOLUTION

The empty positions are modeled with FAs that have zero decay heat powers, biases, and variances at all times. These empty FAs are first assigned to DCs that are disposed of as late as possible with a rule that only one empty FA is assigned per DC if possible. The other FAs are ordered in the decreasing order of decay heat power at the time when the last DC is disposed of. In this order, each FA is assigned to a DC that will have the lowest weighted DC power after the allocation.

An initial solution can be influenced by two parameters. The first one is related to a covariance term of the DC power. The largest change in the covariance terms between two FAs in the DC after the allocation of a FA needs to be under a given threshold. This aims to avoid assigning FA i to a DC where there is already FA j that correlates with FA i with a big covariance term. The default value for this parameter is 1 W^2. If this constraint cannot be satisfied for a FA, then the constraint is neglected for that FA.

The other parameter is related to the decay heat power of a FA. If the decay heat power of FA i in DC j is greater than the given threshold, then FA i is not assigned to DC j. The default value for this parameter is high enough that it is a limiting constraint only if a FA does not satisfy the minimum cooling time criterion. If there are no DCs where the decay heat power of FA i is below the threshold, then FA i is assigned to a DC that is disposed of as late as possible.

B.III. STEP 3. TAKE CONSTRAINTS RELATED TO FAs INTO ACCOUNT

The constraints related to the FAs include the constraints on dechannelled FAs, preassigned FAs, banned FAs, and the minimum cooling time criterion. These constraints are considered in this order, as was the case in the recent investigation [1].

B.III.A. Take Constraints on Dechannelled FAs into Account

For the dechannelled FAs, the user gives for each DC how many dechannelled FAs are assigned to it. Initially array A is generated to which we collect allocations for the dechannelled FAs. Thereafter, the dechannelled FAs that are preassigned are allocated correspondingly in array A. Thereafter, the number of dechannelled FAs required in each DC is taken into account by updating array A. Dechannelled FAs that are banned cannot be allocated to DCs with GHPs.

Since there might be more than one dechannelled FA in a DC, the covariance of the dechannelled FAs in a DC is monitored. The dechannelled FA that is assigned to a DC with another dechannelled FA is chosen so that the covariance between the dechannelled FAs is as low as possible. Once each dechannelled FA is in array A, corresponding exchanges are made to satisfy array A. The non-dechannelled FAs participating in such exchanges are chosen to have as low a decay heat power as possible. The reasoning behind this is that the dechannelled FAs are supposed to be old and have a low decay heat power.

B.III.B. Take Constraints on Preassigned FAs into Account

If preassigned FA i is not in DC k where it is supposed to be, we need to exchange it with a non-preassigned and non-dechannelled FA from DC k. This FA is chosen so that the sum of the covariances of DC k and the DC, where FA i is currently, is minimized.

B.III.C. Take Constraints on Banned FAs into Account

Each DC with a GHP is checked in case there are banned FAs assigned to it. If banned FA j is assigned to DC i with a GHP, we need to search for a FA to exchange. All FAs are ordered in the increasing order of the absolute difference in the decay heat power from banned FA j at the time of disposal of DC i. This aims to find a FA with the decay heat power close to the decay heat power of banned FA j. To approve an exchange, almost all the constraints related to FAs need to be satisfied for both FAs that are exchanged. The only constraint that is not checked is related to the minimum cooling time criterion of FA j in the other DC.

The procedure also takes the covariances into account. If the covariances of the DCs do not increase, the exchange is approved. If such an exchange cannot be found, then the exchange where the covariance of DC i does not increase and the covariance of the other DC increases as little as possible is chosen. If we cannot find an exchange where the covariance of DC i does not increase, we try to find an exchange where the covariance increases as little as possible.

B.III.D. Take Constraints on Minimum Cooling Time into Account

If the minimum cooling time criterion is not satisfied for a FA at a time t_0, we know that it is not satisfied at a time t less than t_0 either. Hence, we can try to make all the DCs satisfy the minimum cooling time criterion, if the disposal schedule allows it, by going through the DCs in the order of increasing disposal time and making sure the criterion is satisfied for each FA in the DCs.

Suppose that there is FA j that does not satisfy the minimum cooling time criterion at the disposal time of DC i where it is currently assigned. Then we try to find FA k that will be exchanged with FA j. First, we try to find FA k such that both FAs j and k satisfy the minimum cooling time criterion and the constraints related to banned, dechannelled, and preassigned FAs after their exchange. If such an exchange cannot be found, we try to find FA k from the DCs that are disposed of after DC i such that FA k satisfies the minimum cooling time criterion at the time of the disposal of DC i and both FAs j and k satisfy the constraints related to banned, dechannelled, and preassigned FAs after their exchange. If such a FA k cannot be found, the minimum cooling time criterion cannot be satisfied for all FAs.

B.IV. STEP 4. TAKE TWO CONSTRAINTS RELATED TO POOLS INTO ACCOUNT

The two constraints related to the pools in this step include taking into account a date by which each pool needs to be emptied and trying to get free space in the given set of pools.

B.IV.A. Take Constraints on Emptying Pools into Account

The pools are ordered in increasing order according to the date by which they are required to be empty. Each pool is checked for FAs that are to be disposed of later than the pool should be empty. If such FA j is found in pool i, we go through each FA to find an exchange. FA k that could be exchanged needs to be assigned to a DC that will be disposed of earlier than pool i is emptied. The constraints related to FAs need to be satisfied after the exchange, and the pool where FA k is needs to be emptied later than pool i.

It should be noted that this procedure will try to empty the pools as much as it can. This holds true regardless of how many FAs are allowed to remain in a pool after the time it should be empty. If the procedure cannot find a solution with a less or equal number of FAs allowed to remain in the pool after the date of emptying, an error message is given. However, the user may set a parameter to allow for weak emptying, meaning that the error will not be given and the allowed number of FAs in a pool after the pool should be empty is set to be equal to the corresponding number in the current solution.

B.IV.B. Take Constraints on Free Space in Given Pools into Account

The idea is to make at least the given amount of free space in the given set of pools after the disposal of the DCs with GHPs. Thus, it is checked if there will be enough free space in the given set of pools. If not, the FAs from these pools that are not assigned to the DCs with GHPs are tried to be exchanged with FAs that are assigned to the DCs with GHPs and are not in the given set of pools. For an exchange to be approved, all the constraints related to FAs must be satisfied after the exchange.

Moreover, the number of FAs remaining in the pools where the FAs are, after the pools should be empty, are not allowed to increase. When enough exchanges are made to get enough free space, the procedure ends. There is a parameter to control what happens if a solution with sufficient free space is not found. One option is to end the algorithm with an error message. Another option, corresponding to weak free space, is to continue the algorithm even if the constraint is not satisfied and the amount of required free space is set to be equal to the corresponding number in the current solution. A warning message is given in this case.

B.V. STEP 5. MINIMIZE MAXIMUM WEIGHTED DC POWER OF ALL DCs

The procedure to minimize the maximum weighted DC power of all DCs is always applied first with 1–1 exchanges where two single FAs from different DCs are exchanged to improve a solution. With a parameter, the user can specify that the procedure is repeated with 2–2 exchanges as in Ref. [1]. In 2–2 exchanges, two pairs of FAs from different DCs are exchanged to improve the solution. The core of this procedure is to find improving exchanges that decrease the maximum weighted DC power or the number of DCs with the maximum weighted DC power, until none can be found.

One way to improve the solution is to minimize the second largest weighted DC power after exchanges to decrease the maximum weighted DC power cannot be found. In this case, the FAs in the DC with the maximum weighted DC power cannot be exchanged and the weighting coefficient for this DC is set to zero. The result is that the DC with the second largest weighted DC power will now have the maximum weighted DC power. Thus, applying the minimization of the maximum weighted DC power will result in minimizing the second largest weighted DC power. This trick can be further used to minimize the third largest weighted DC power, and so on. The user can give a parameter to what sequence number this is continued.

Minimizing the maximum weighted DC power may take a lot of time, especially if 2–2 exchanges are used. Therefore, there is a parameter that will make the procedure stop if the difference between the maximum weighted DC power and lowest weighted DC power is below a given value. Furthermore, there is a parameter that ends finding improving exchanges if a given time limit is surpassed. However, setting a time limit will make the algorithm nondeterministic in the sense that the solution cannot be repeated.

B.V.A. Find Exchange So That Maximum Weighted DC Power Is Decreased

An important part of the procedure to minimize the maximum weighted DC power is to find an exchange so that the maximum weighted DC power or the number of DCs with the maximum weighted DC power is decreased. In the procedure to find a 2–2 exchange, DC i with the maximum weighted DC power is searched. After that, the other DCs are gone through to find an improving exchange. Suppose that DC j is currently investigated. All pairs of FAs in DC i are gathered in list A and all pairs of FAs in DC j are gathered in list B. The pairs containing preassigned FAs are removed from the lists.

Each possible exchange of pairs between lists A and B is checked. The constraints related to FAs and pools need to be satisfied after the exchange. If an exchange is found where the maximum weighted DC power of the DCs is decreased, the possible exchanges from lists A and B are gone through, and the exchange with the largest decrease in the maximum weighted DC power of the DCs is returned. The procedure to find a 1–1 exchange is similar to the one for a 2–2 exchange. Instead of finding two pairs of FAs to exchange, only two single FAs are exchanged in that case.

There is a parameter that controls how big of a decrease in the DC power results in an approved exchange. It is supposed that increasing this parameter makes the algorithm faster, but the maximum weighted DC power will be higher. Another parameter is related to taking covariances more specifically into account. In this case, the improving exchange must not increase the covariances of DCs. If such an exchange cannot be found, a certain Pareto optimal exchange is chosen, where the objectives are the decrease in the maximum weighted DC power of the DCs and the largest of the increases in the covariances of the DCs.

B.VI. STEP 6. OPTIMIZE DCs WITH GHPs AND MINIMIZE MAXIMUM WEIGHTED DC POWER OF DCs WITHOUT GHPs

Optimizing the DCs with GHPs is divided into getting the DCs with GHPs below their GHPs, and after that, getting the DCs with GHPs within the accuracy of their GHPs, as was the case in Ref. [1].

B.VI.A. Get DCs with GHPs Under Their GHPs

The DCs with GHPs are checked to verify if the DC power is already below the GHP. If not, then an exchange that decreases the DC power is tried to find. FA j with the maximum decay heat power is tried to be exchanged. All the other FAs are ordered in the increasing order of the absolute difference of decay heat power from FA j. The first thing to check in a potential exchange is that the constraints related to FAs and pools are satisfied after the exchange. Additionally, the other FA needs to be in a DC without a GHP at this phase.

If, after the exchange, the DC power is below its GHP, attains its GHP within the accuracy, and the covariances of both DCs do not increase, the exchange is done. If such an exchange is not found, then the current best exchange is updated iteratively. The current best exchange is an exchange that is a compromise between decreasing the DC power of the DC with a GHP and not increasing the covariance terms.

This process to find exchanges and doing them continues until the DC with a GHP is below its GHP or improving exchanges are not found. If the DC with a GHP is still not under its GHP, we try to find exchanges between the DCs with GHPs. In those exchanges, the constraints related to FAs and pools need to be satisfied. Furthermore, the DC power of the other DC needs to be below its GHP and remain below the GHP after the exchange.

B.VI.B. Get DCs with GHPs Within the Accuracy of Their GHPs

The DCs with GHPs should have DC powers below their GHPs at this point. If this is not true for some DCs, then no exchanges are done with them in the procedure to get the decay heat powers of the DCs with GHPs to their GHPs within the accuracy. In the procedure, we try to find 1–1 exchanges between a DC with a GHP and a DC without a GHP to minimize the maximum difference between the DC powers and their GHPs. If no improving 1–1 exchanges are found anymore, then improving 2–2 exchanges are searched for if the user so chooses.

If the maximum difference between the DC powers and their GHPs is not within the accuracy after this step, then, if the user so chooses, the next largest difference is minimized and so on. This is done to avoid one DC whose DC power is not in the GHP from prohibiting other DCs from reaching their GHPs. The last step is to find improving exchanges between the DCs with GHPs in case the GHPs have not been reached within the accuracy.

B.VI.C. Find Exchange Between DCs With and Without GHP So That the Maximum Difference from GHPs Is Reduced

The procedure to find an improving exchange between DCs with and without GHP when getting the DC powers to their GHPs progresses rather similarly to the procedure where an exchange is to be found so that the maximum weighted DC power or the number of DCs with the maximum weighted DC power is decreased. For an exchange to be approved, the constraints related to FAs and pools need to be satisfied after the exchange.

Furthermore, after the exchange the DC power of the DC with a GHP needs to be under its GHP, the DC power should be increased at least the user-given percentage, and covariances should not be increased over the user-given value. For an ideal exchange, the DC power of the DC without a GHP is not increased. If such an exchange cannot be found, the exchange that increases the DC power of the DC without a GHP the least is accepted.

B.VI.D. Find Exchange Between DCs with GHPs So That the Maximum Difference from GHPs Is Reduced

The procedure to find improving exchanges between the DCs with GHPs when getting the DC powers to their GHPs is rather similar to the procedure where an exchange is to be found between DCs with and without GHP so that the maximum difference from the GHPs is reduced. For an exchange to be approved, the constraints related to FAs and pools need to be satisfied after the exchange.

Furthermore, after the exchange, the DC powers of both DCs need to be under their GHPs and the maximum difference from the GHPs should be reduced. This reduction needs to be greater than a user given percentage.

B.VI.E. Minimize Maximum Weighted DC Power of DCs without GHPs

Finally, the maximum weighted DC power of the DCs without GHPs is minimized. The procedure to minimize the maximum weighted DC power of the DCs without GHPs is quite similar to the procedure to minimize the maximum weighted DC power of all DCs, but now only the DCs without GHPs are of concern.

B.VII. STEP 7. MINIMIZE NUMBER OF FAs IN OPEN POOLS

Before this step, we will have a solution where FAs have been chosen for the DCs with GHPs. These FAs are taken from certain pools, thereby determining which pools need to be open when the transfers to the EP will be done. To reduce the number of FAs in the open pools, the pools are closed iteratively, and certain constraints are checked to determine if the solution is acceptable.

At first, the open pools are ordered in a certain way. The pools from which we will take the least number of FAs are ordered first. The pools where free space is required are ordered last. Then the pools that were open in the previous batch are ordered last as well. In this order, we ban the FAs from the considered pool, repeat steps 3 through 6, and accept the solution if it is good enough. The solution is good enough if the constraints related to the FAs and pools are met and the DCs with

GHPs are in their GHPs within the relaxed accuracy for minimizing the number of FAs in the open pools.

If a new solution is found, we continue to try to close the pools. This closing of the pools is stopped if the number of FAs in the open pools is below a given limit. However, the user may choose to continue the closing of the pools even after this criterion is met. In this case, the closing of the pools is stopped if we cannot find an acceptable solution after closing any of the remaining open pools.

It is possible that the limit of the maximum number of FAs in the open pools is not undercut. This happens if the algorithm cannot find a feasible solution if some of the open pools are closed and there are too many FAs in the open pools. Otherwise, the requirement of the maximum number of FAs in the open pools is met, potentially at the cost of not getting the DCs with GHPs to their GHPs.

The ideal solution is that the DC powers of the DCs with GHPs are in their GHPs within the relaxed accuracy for minimizing the number of FAs in the open pools. If such a solution is not found, the second best would be to have the DCs with GHPs below their GHPs. If even this kind of solution is not found, then we need to allow for the DC powers to surpass the GHPs.

B.VIII. STEP 8. MAXIMIZE THE NUMBER OF FAs FROM A CERTAIN SET ASSIGNED TO DCs WITH GHPs AND MINIMIZE MAXIMUM WEIGHTED DC POWER OF THE DCs WITHOUT GHPs

There are two sets from which we can maximize the number of FAs assigned to the DCs with GHPs. In batch tasks 2 and 3, this set can be the set of FAs in certain pools. In batch tasks 0, 1, 2, and 3, this set can be the set of the prioritized FAs. These sets are considered separately and in this order.

B.VIII.A. Maximize Number of FAs from a Certain Set Assigned to DCs with GHPs

First, we create list A of the FAs that are in the given set and not assigned to DCs with GHPs but can be assigned to those DCs. Then for each element in list A we go through each FA that is disposed of in the DCs with GHPs and check if the FAs can be exchanged. The exchange is possible if all the constraints related to FAs and pools are satisfied after the exchange. Most importantly, the DC with a GHP must remain within the accuracy of its GHP. If batch task 1 is used, this accuracy corresponds to the relaxed accuracy for minimizing the number of FAs in the open pools.

There are a few parameters related to this procedure. In the case of prioritized FAs, one can choose for batch tasks 1, 2, and 3 that exchanges be made with FAs from the same pool. This parameter is not in batch task 0, and the prioritized FAs can be exchanged with any FAs in the Loviisa SNF interim storage. There also exists a parameter that limits the increase in the DC power due to covariance.

B.VIII.B. Minimize Maximum Weighted DC Power of DCs Without GHPs

Like in step 6, finally, the maximum weighted DC power of the DCs without GHPs is minimized.

B.IX. STEP 9. DETERMINE POSSIBLE TRANSFERS OF FAs BETWEEN POOLS

Transfers are done in batch task 3 where FAs located in the transfer pools are transferred to the loading pools before they are transferred to the EP in the current batch. If there is not enough space in the loading pools, then counter transfers are needed where some of the FAs from the loading pools are transferred to the transfer pools. This affects the free space in the pools after the current batch, and thus, we need to consider in which pools free space is needed.

Specifically, we order the FAs that need to be transferred in a way that FAs from the transfer pools where free space is needed are first. We want to avoid making counter transfers to these pools. Otherwise, the FAs from the transfer pools where the least number of FAs are taken are ordered first. The loading pools are ordered according to the decreasing free space in the pool. This maximizes the possibility that all FAs are transferred to a single pool.

The FAs to be transferred are set to the loading pools until all the FAs are transferred or there is no more free space in the loading pools. If there was not enough free space for all of the transferred FAs, the algorithm starts to find counter transfers. These are searched first from the loading pools where free space is required. The FA for a counter transfer needs to be a FA that is non-dechannelled and is not disposed of in a DC with a GHP. Furthermore, the constraints related to the pools need to be satisfied after the counter transfer. If enough counter transfers are not found, a warning message is given, implying that some of the transfers were not done.

B.X. STEP 10. SIMULATE DC POWERS OF ALL DCs

The distribution of the DC power of each DC is simulated by sampling from the distributions of uncertainties a given number of times. The routine returns for each DC the simulated DC power corresponding to the *n*'th percentile of the DC's simulated distribution, where *n* is provided by the user. To take one sample of DC power for a DC, the expected decay heat power of each FA in the DC is summed first.

Standardized random numbers are generated for each FA and uncertainty factor, depending on the distribution of the uncertainty factor. Only

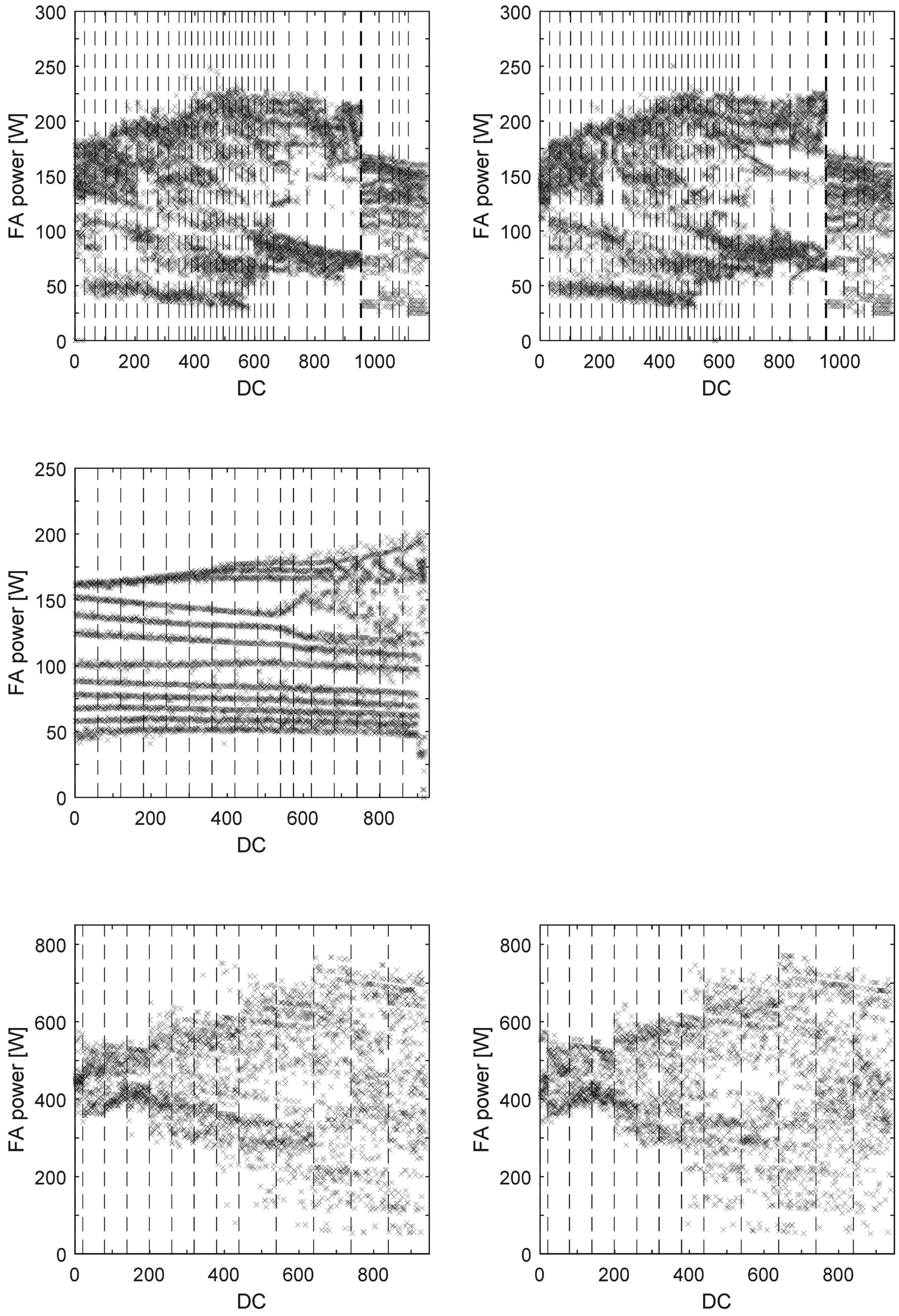

Fig. C1. Decay heat powers for each FA in each DC without uncertainties for (top left and top right) OL1-2 with batch tasks 1 and 2, for (middle) LO1-2 with batch task 0, and for (bottom left and bottom right) OL3 with batch tasks 1 and 2. The dashed lines separate the batches and the bolded dashed line indicates that there is a hiatus in the OL1-2 disposal at that point.

uniform and normal distributions can be used. For each uncertainty factor, a corresponding transitive correlation matrix of FAs in the DC is generated. If the correlation of two uncertainty terms is one according to these matrices, then the corresponding random numbers are equalized. The values are scaled based on the standard deviation and the distribution, and all of these are added to the sum of the expected values.

APPENDIX C

DECAY HEAT POWERS OF EACH FA IN EACH DC WITHOUT UNCERTAINTIES

The decay heat powers of each FA in each DC without uncertainties for all fuel types are shown in Fig. C1. Since for OL1-2 and LO1-2 there are 12 FAs in a DC, there are 12 points with a x-coordinate corresponding to a DC. For OL3, there are four FAs in a DC, and correspondingly, four points with a x-coordinate. There is a clear pattern for LO1-2 with the n'th hottest FAs in a DC forming bands. This structure is lost in the last disposal year. The empty slots for LO1-2 are in the last DCs, as they were preassigned.

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Author Contributions

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Data Availability

The data that has been used is confidential.

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