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Loading optimization algorithm for solving assembly assignment problem in the final disposal of spent nuclear fuel in Finland

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ABSTRACT

In Finland, the final disposal of spent nuclear fuel assemblies includes inserting them into disposal canisters being disposed of in bedrock. This final disposal will be a century long process. The choice of which fuel assemblies are assigned to which canisters determines the decay heat powers of canisters. A loading optimization algorithm to make these choices is developed. The assembly assignment problem is formulated as a multiobjective mixed-integer nonlinear programming problem, but the loading optimization algorithm will solve the problem heuristically. The developed algorithm can be seen as a new version of the algorithm to solve the minimax canister formation problem, where canisters disposed of in the near future are considered more carefully than the rest of the canisters being more exposed to uncertainties related to schedule and predicted decay heat powers of future fuel assemblies. Furthermore, new constraints and objectives have been taken into account. The developed loading optimization algorithm facilitates the safe and cost-efficient assignments of fuel assemblies to canisters in Finland.

1. Introduction

There are five nuclear reactors in Finland. Olkiluoto 1 (OL1), Olkiluoto 2 (OL2) and Olkiluoto 3 (OL3) are located in Eurajoki and operated by Teollisuuden Voima Oyj (TVO). Loviisa 1 (LO1) and Loviisa 2 (LO2) are located in Loviisa and operated by Fortum Power and Heat Oy (Fortum). By Finnish legislation the companies operating nuclear power plants are responsible for the final disposal of their nuclear waste. Nuclear waste management is an important part of the sustainability and acceptability of low-emission nuclear power. We consider the final disposal of high level nuclear waste, that is, spent nuclear fuel assemblies (FAs). In 1995, TVO and Fortum founded Posiva Oy to do this task. In 2021, Posiva submitted to the Finnish Government an operating license application for spent nuclear fuel encapsulation plant and disposal facility first in the world. Posiva aims to start final disposal in approximately 2025. The final disposal of FAs is based on the KBS-3 concept, where the FAs are inserted into disposal canisters (DC) which are disposed of deep underground. In this paper, we consider the problem of choosing which FAs should be inserted into which DCs. Because the final disposal will last a long time in Finland, there are naturally large uncertainties related to schedule and predicted decay heat powers of future FAs. Our approach is to define the assignments for the DCs disposed of in the near future more carefully than the assignments for the rest of the DCs being more exposed to uncertainties related to schedule and predicted decay heat powers of future FAs. During the final disposal process, this assembly assignment problem is repeatedly solved using updated schedule and predictions for future FAs.

There are three different types of reactors implying three different fuel types to consider. Reactors OL1 and OL2 are boiling water reactors and we call the FAs of these reactors OL1-2 fuel. OL3 is European pressurized water reactor and we call its fuel OL3 fuel. LO1 and LO2 are Russian type pressurized water reactors and their fuel is called LO1-2 fuel. The FAs from different reactors differ by mass, dimension and shape among other things implying that each fuel type requires its own type of DC. In total, there will be approximately 5500 tonnes of uranium (tU) or 2750 DCs to dispose of. The final disposal is planned to commence in mid 2020s and to end in 2100–2120 being almost a century long process.

In Ranta and Cameron (2012), Ranta (2012) the minimax canister formation problem is formulated and an optimization algorithm to solve it is developed. In Kuopanportti and Lahtinen (2019), an applied study on the minimax canister formation problem is shown for Loviisa FAs which utilizes the optimization algorithm developed in Ranta and Cameron (2012), Ranta (2012). The minimax canister formation problem is a part of the optimization of the final disposal studied in Ranta (2012). The final disposal should be done safely and economically.

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Within the constraints imposed by safety requirements a cost efficient disposal schedule was determined in Ranta (2012) by solving a mixed-integer linear programming model. These schedules are used when solving the minimax canister formation problem in Ranta (2012). The model for the scheduling problem has been developed further into multiobjective mixed-integer nonlinear programming model in Montonen et al. (2019, 2020).

Determination of the DC decay heat powers is included in the scheduling model, where all spent nuclear fuel in Finland and the interim storage, the encapsulation plant (EP), and the disposal facility (DF) are considered simultaneously. The objective of the scheduling model is to minimize the total cost of the disposal. The most important economical constraints are the capacities and operating times of different facilities. The main physical constraints limiting the disposal pace are the decay heat generation of spent nuclear fuel and the temperature on the bentonite buffer at the outer surface of a DC in the DF. Due to the complexity of the problem, the FAs are not individually present in the scheduling model and they are modeled as a continuous variables with each removal having its own decay heat power. A removal corresponds to FAs that are removed from the core in one year. The solution of the scheduling problem includes one DC decay heat power for each fuel type and the average DC decay heat power in each period is forced to be less than this value. By having this DC decay heat power as low as possible makes the DF cost-efficient as the required disposal and central tunnel lengths are also as low as possible (Ikonen et al., 2018). Consequently, the average DC decay heat power in each period will usually be the same. Thus, the schedule obtained from the scheduling model is a good candidate for a schedule where even decay heat powers among the DCs of a certain fuel type can be obtained. The scheduling model is not considered in this study, but we will utilize the obtained schedule and DC powers.

When the disposal schedule of a certain fuel type has been given, the minimax canister formation problem is solved in Ranta and Cameron (2012), Ranta (2012), Kuopanportti and Lahtinen (2019) by minimizing the highest DC decay heat power. In the minimax canister formation problem, we use the decay heat power of each individual FA making the DC decay heat powers more accurate. Furthermore, the solution gives the information what FAs to insert into what DCs. It turns out that the highest DC decay heat power is close to the theoretical lower bound obtained by relaxing binary variables to continuous ones (Ranta and Cameron, 2012; Ranta, 2012; Kuopanportti and Lahtinen, 2019). Furthermore, the decay heat powers among the DCs were found to be even. In addition, the average DC decay heat power is close to the one obtained from the scheduling problem (Ranta, 2012).

Many aspects of the final disposal are studied in terms of optimization. The loading optimization of DCs is studied also in Jeoung et al. (2022), Rochman et al. (2020), Solans et al. (2020, 2021), Vlassopoulos et al. (2017), Žerovnik et al. (2009). The scheduling of final disposal is considered also in Rautman et al. (1993) where the disposal facility area is minimized with a linear transportation model. Other studies utilizing optimization include (Johnson et al., 2017), where the multiobjective MILP problem is given to determine where to place waste in a repository and Kim et al. (2019), where the optimal design conditions of repository were investigated with multiobjective optimization. In Taji et al. (2005) multiple criteria decision analysis is used to decide where to place a disposal repository. Optimization is used to route the transfer of the nuclear waste in Alumur and Kara (2007) and hazardous waste in general in ReVelle et al. (1991). The optimal nuclear power plant shutdown date is studied in Lappi and Lintunen (2020), Petersen (2016). Safety-related studies include the optimization of nuclear safeguards in Johnson et al. (2019), Shugart et al. (2018) and the safety assessment of nuclear waste repositories in Tosoni et al. (2019).

This study continues the work of Ranta and Cameron (2012), Ranta (2012), where the minimax canister formation problem is formulated and an optimization algorithm to solve it is developed. Here, this work has been extended by formulating the closely related assembly assignment problem and developing further the optimization algorithm to solve the assembly assignment problem. Compared to the minimax canister formation problem we take new requirements into account in the assembly assignment problem.

The production of the EP proceeds in batches in which the FAs for the DCs of the current batch are loaded. The DCs of the current batch are disposed of in the near future and the defined assignments to them are the final ones. The DC powers of the DCs disposed of in the near future has been defined beforehand through planning. Hence, the DCs in the current batch are called *DCs with goal heat powers* and the goal heat power for each of these DCs must be given. The DC powers of the DCs with goal heat powers should be under the goal heat powers but within a given $accuracy$ from the goal heat powers. For example, if the goal heat power of a DC is 1700 W and accuracy is 0.1 W, then the DC power is tried to get within range [1699.9 W, 1700 W].

In addition to having goal heat powers for the DCs disposed of in the near future, there are new requirements on the assembly assignment problem. There can be FAs that are not allowed to be disposed of in the DCs with goal heat powers. To prohibit FAs to be disposed of in the DCs with goal heat powers, these FAs can be set as $banned$. There are few fuel rods with leakage and they are disposed of in the distant future. The procedures to dispose of these leakaged fuel rods will be determined later. It is assumed that these leakaged fuel rods are bundled together to form FAs. There will be only few individual FAs containing these leakaged fuel rods and these will be banned at the beginning of the disposal. Furthermore, FAs that has not yet been transferred to interim storage will be banned. In addition, there can be FAs that must be disposed of in the DCs with goal heat powers. To achieve this, the FAs can be $preassigned$. For each preassigned FA the DC to which the FA is assigned must be provided. The time to dispose of the FAs containing leakaged fuel rods can be planned beforehand and, thus, they are forced to be disposed in the DCs with goal heat power at some point. This can be done with preassignments. For OL1-2 fuel there are some $dechannelled$ FAs without channel nose piece having different dimensions than ones with channels. It is preferred to have a constant number of dechannelled FAs in a transfer cask as explained later. In the Olkiluoto interim storage there are lids over water pools that need to be lifted if FAs are taken from the corresponding water pool. Unnecessary lifting of the lids should be avoided.

The paper is organized as follows. In Section 2, we describe roughly how FAs are transferred from a reactor to the underground repository. In Section 3, the problem definition for the assembly assignment problem with a mathematical formulation is given. In Section 4, the loading optimization algorithm to solve the problem is derived. The loading optimization algorithm is used to define the assignments in a few example cases in Section 5. Discussion on the loading optimization algorithm is given in Section 6.

2. Spent nuclear fuel disposal process in Finland

The final disposal of FAs is based on KBS-3 concept developed originally by the Swedish Nuclear Fuel and Waste Management Company (SKB). In this concept the FAs are inserted into DCs. The DC consists of cast iron insert, which is encapsulated by copper overpack. The DC is put into a vertical disposal hole on the floor of a disposal tunnel located in the DF more than 400 m below ground level. In the disposal hole, the DC is surrounded by bentonite buffer and tunnels leading to disposal holes will be filled. More information on safety functions of these barriers can be found, for example, in Posiva Oy (2012). A schematic visualization of these barriers are given in Fig. 1.

When an FA is taken out of the reactor it is first held at pools at the reactor halls. After cooling few years it is transferred with a transfer cask to an interim storage near the power plant for additional cooling. In the interim storage, the FA is held in a water pool for decades in order to guarantee safe disposal. When time has come to dispose of an

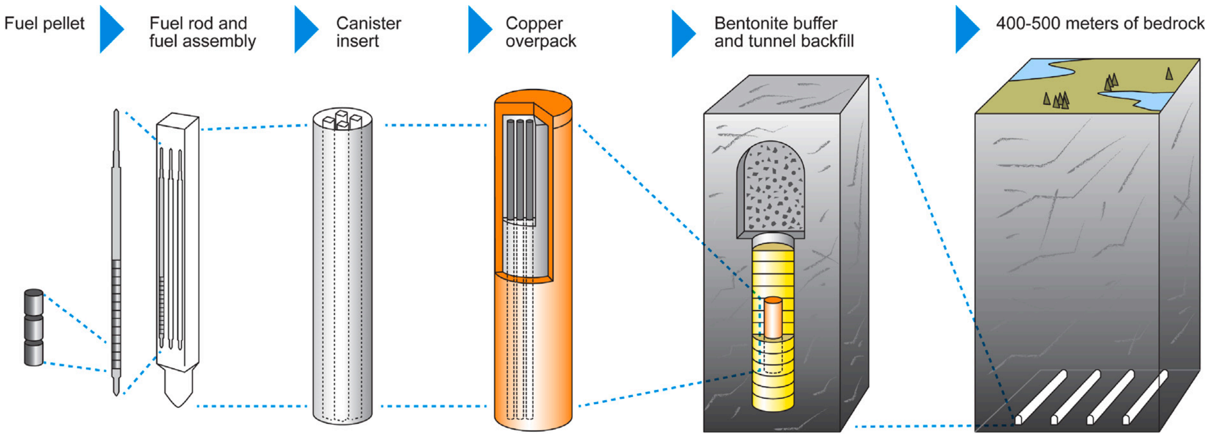

Fig. 1. An illustration on disposal of spent nuclear fuel. Posiva Oy.

FA it is transported in a transfer cask to the EP where it is inserted into a DC. Depending on the fuel type the DCs have capacity for 4 (OL3) or 12 (OL1-2, LO1-2) FAs. A transfer cask can hold a number of FAs to fill few DCs. The final disposal progresses in campaigns one disposal tunnel at the time. Several DCs are filled and stored in the EP or in the DF. A certain number of DCs are transferred into a disposal tunnel to fill every disposal hole in that tunnel. The disposal tunnel will be filled with bentonite clay and sealed afterwards. The disposal tunnels are located on both side of the central tunnel. The bentonite buffer at the surface of a DC should be kept under 100 °C in order to guarantee its protective properties (Posiva Oy, 2012). To keep the temperature low enough the DC spacing, disposal tunnel spacing and DC power needs to be planned appropriately.

3. Problem definition

In this study, the work in Ranta and Cameron (2012), Ranta (2012) on the minimax canister formation problem is extended by formulating the closely related assembly assignment problem and developing further the optimization algorithm to solve it. In the assembly assignment problem, goal heat powers are given to DCs disposed of in the near future. The found assignments to DCs with goal heat powers are supposed to be the final ones. The found assignments to other DCs gives a forecast on what DC powers these DCs can be disposed of. For these other DCs we minimize the greatest DC power. The lower the DC power of the other DCs the better.

The DC powers for the DCs with goal heat power are tried to get lower than their goal heat powers but still within the accuracy. This makes it possible to load DCs with given DC power according to plan if the schedule and FA decay heat powers allow it. The fact that the goal heat powers can be defined individually for the DCs with goal heat powers allows, for example, adjusting DC decay heat powers at the both ends of the disposal tunnels. In Ikonen et al. (2018) it was shown that the temperature at the end of the disposal tunnels are lower than at the center. Thus, it is possible that the DCs inserted at the end of the disposal tunnels will have higher DC power than the DCs at the center of the disposal tunnel.

In the Olkiluoto interim storage there are lids over water pools that need to be lifted if FAs are taken from the corresponding water pool. In this study, we model, for simplicity, that there is one lid over each water pool. It is desirable that as few lids are lifted as possible when filling a transfer cask. It is expected that at some point a rearrangement of OL1-2 FAs is done to make them use as few water pools as possible, and thus, freeing up a water pool to store OL3 fuel. Hence, it is impossible to forecast on which pool each FA is when they are disposed of. Therefore, we minimize lifting of the lids only for the DCs with the goal heat powers.

Getting the heat powers of the DCs with goal heat powers to their goal heat powers, minimizing the greatest DC power of the DCs without goal heat power and minimizing lifting of the lids are objectives for our optimization problem. The first and third objectives are new compared to the minimax canister formation problem. The assembly assignment problem includes the same constraints as the minimax canister formation problem in Ranta and Cameron (2012), Ranta (2012). Each FA needs to be assigned to exactly one DC and for each DC the number of FAs assigned to it must be equal to DC capacity. Furthermore, all FAs need to be cooled down at least the minimum cooling time. There are new constraints related to banned, preassigned and dechannelled FAs in our optimization problem.

The banned FAs are not allowed to be assigned to DCs with goal heat power. FAs that potentially could be banned includes FAs containing leakaged fuel rods and FAs that have been cooled down enough time but still are in reactor pools and not in the interim storage. Another reason to ban FAs is, if the lid of a certain pool is not wanted to be opened. Banning all the FAs in the corresponding pool achieves this goal. The DCs for the preassigned FAs have been given before optimization and, thus, there is nothing to optimize for these FAs. Allowing preassigned FAs is useful. For example, if it is decided that FAs containing leakaged fuel rods are to be disposed of in the DCs with goal heat power, this can be forced with preassigning those FAs. For OL1-2 FAs it is required that there are constant number of dechannelled FAs in a transfer cask. Since there are FAs for 3 DCs in a transfer cask we may as well give the number of dechannelled FAs in each DC. Having predefined number of dechannelled FAs in a DC facilitates the production of the EP. When FAs are transferred from the interim storage to the EP they need to be inserted in a transfer cask. There needs to be an additional piece of material for the positions where dechannelled FAs are inserted. Furthermore, there needs to be an additional piece of material in position of the DC where dechannelled FA is inserted.

There are criteria related to radiation dose rate and criticality safety, but this is beyond our consideration. The decay heat power of a DC can be altered through optimization but the given schedule defines the limits for the average decay heat power. In our case, we require that the minimum cooling time for each FA is 20 years, provided by the radiation safety. Moreover, safety aspects are considered also when it is decided to what exact place in the DC the FAs are inserted. This configuration optimization is also beyond our scope.

3.1. Mathematical model

In this section a mathematical formulation of the assembly assignment problem for a single fuel type is given. Define the following sets

$\mathcal{I}$ Set of DC indices

$\mathcal{J}$	Set of FA indices
$\mathcal{R}$	Set of DCs that have goal heat power
$\mathcal{B}$	Set of banned FAs that cannot be assigned to DCs with the goal heat power
$\mathcal{P}$	Set of pairs (i, j), that indicates that preassigned FA j should be assigned to DC i
$\mathcal{W}$	Set of water pools where FAs are held in interim storage
$\mathcal{T}$	Set of transfers with transfer cask used for DCs with goal heat powers
$\mathcal{I}_t$	Set of DCs in transfer $t, t \in \mathcal{T}$.

The mathematical model has the following parameters

G_i	Goal heat power of DC i
C	Capacity of a DC
A_{ij}	Heat power of FA j at the time when DC i is disposed of
D_j	Indicator whether FA j is dechannelled or not
E_i	How many dechannelled FAs are wanted to dispose of in DC i
W_{rj}	Indicator whether FA j is under water pool lid r,

continuous variables

h_i	Heat power of DC i
h_{max}	Highest heat power among DCs without goal heat powers

and binary variables

w_{tr}	$1,$ if pool lid r is needed to lift when filling transfer cask for transfer t
x_{ij}	$1,$ if FA j is assigned to DC i.

The considered assembly assignment problem can be formulated as a multiobjective mixed-integer nonlinear programming problem

$$\min \max_{i \in \mathcal{R}} (G_i - h_i) \tag{1}$$

$$\min \max_{i \in \mathcal{I} \setminus \mathcal{R}} h_i \tag{2}$$

$$\min \sum_{r \in \mathcal{W}} \sum_{t \in \mathcal{T}} w_{tr} \tag{3}$$

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

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

$$\sum_{j \in \mathcal{J}} A_{ij} x_{ij} = h_i, \quad \forall i \in \mathcal{I} \tag{6}$$

$$h_i \leq G_i, \quad \forall i \in \mathcal{R} \tag{7}$$

$$x_{ij} = 0, \quad \forall i \in \mathcal{R}, j \in \mathcal{B} \tag{8}$$

$$x_{ij} = 1, \quad \forall (i, j) \in \mathcal{P} \tag{9}$$

$$\sum_{j \in \mathcal{J}} D_j x_{ij} = E_i, \quad \forall i \in \mathcal{I} \tag{10}$$

$$\sum_{j \in \mathcal{J}} \sum_{i \in \mathcal{I}_t} W_{rj} x_{ij} \leq w_{tr}, \quad \forall t \in \mathcal{T}, r \in \mathcal{W}. \tag{11}$$

The first objective minimizes the greatest difference from the goal heat powers for the DCs with goal heat power. The second objective minimizes the highest heat power among DCs without goal heat powers. The third objective minimizes the lifting of the lids. Constraint (4) requires that there will be exactly C FAs assigned to each DC. Constraint (5) requires that each FA is assigned to a single DC. Constraint (6) defines the heat power of each DC. Constraint (7) requires that the DC powers are below the goal heat powers for the DCs with goal heat powers. Constraint (8) guarantees that no banned FAs are assigned to the DCs with goal heat powers. Constraint (9) guarantees that the preassigned FAs are assigned accordingly. Constraint (10) guarantees that there will be correct number of dechannelled FAs in DCs. Finally, constraint (11) checks which lids are needed to lift for each transfer.

The nonlinear max-functions in the objectives could be transformed into linear objective and several linear constraints resulting in a multiobjective mixed-integer linear programming problem, but this is unnecessary as the problem is solved heuristically.

4. Loading optimization algorithm

Due to the large number of binary variables, the problem is solved heuristically as was done in Ranta and Cameron (2012), Ranta (2012). There are three objectives in the problem implying that there are several mathematically equally good solutions called Pareto optimal solutions (Miettinen, 1999). However, there is some hierarchy between different objectives and thus we can use a lexicographic approach (Miettinen, 1999) in the solution process. The first objective of getting DC powers to their goal heat powers is the most important. The third objective of minimizing lifting of the lids is the second most important. The purpose of the second objective is to get reasonable assignments for the DCs without goal heat powers. Thus, it gives an example on how low DC powers can be obtained in the future.

The loading optimization algorithm to solve the assembly assignment problem is divided in steps in Fig. 2. First, an initial solution is determined. After that, the different conditions and constraints are taken into account. The highest decay heat power of all DCs is minimized first and then the goal heat powers are taken into consideration. After that, the highest decay heat power of the DCs without goal heat powers is minimized. Lastly, the lifting of lids is minimized. In the following, each step is considered in more detail. The pseudocodes of the related procedures are given in Appendix.

To visualize the effect of the steps to the solution, we show the heat power of each DC after each step when applied to an example. The schedule of this example is OL1-2 fuel disposal schedule given in Section 5. In the example, there are 14242 FAs and 1187 DCs implying there are total 4 empty slots in DCs. These empty slots are modeled by adding FAs that have 0 decay heat power at all times to the model. There are approximately 850 dechannelled FAs being 6% of all OL1-2 FAs. In the example, the dechannelled FAs are chosen to be disposed of with rate 1 dechannelled FA per DC until they are all disposed of. Since the dechannelled FAs have rather low decay heat power, there is a limit how many we can insert into one DC and still reach goal heat power or even decay heat power among the DCs without goal heat power. However, finding this number is beyond the scope of this study.

4.1. Initial solution

The initial solution is generated by greedily minimizing the highest DC power. The FAs are ordered in decreasing decay heat power calculated from the time when the last DC is planned to be disposed of. Then the FAs are inserted one by one into DCs such that the decay heat power of the DCs, where the current FA is added, is as low as possible after the assignment. By this procedure, the first assignment is to put the FA with the highest heat power to the DC that is disposed of last. The second assignment is to put yet unassigned FA with the highest decay heat power to the DC that is disposed of as late as possible but is still empty. The heat power of each DC is given in Fig. 3 after this step. There are two FAs that does not satisfy the minimum cooling time in this solution leading to corresponding DCs to have decay heat powers over 2000 W. This is due to the fact that the heat power of such FAs is set to be over 2000 W.

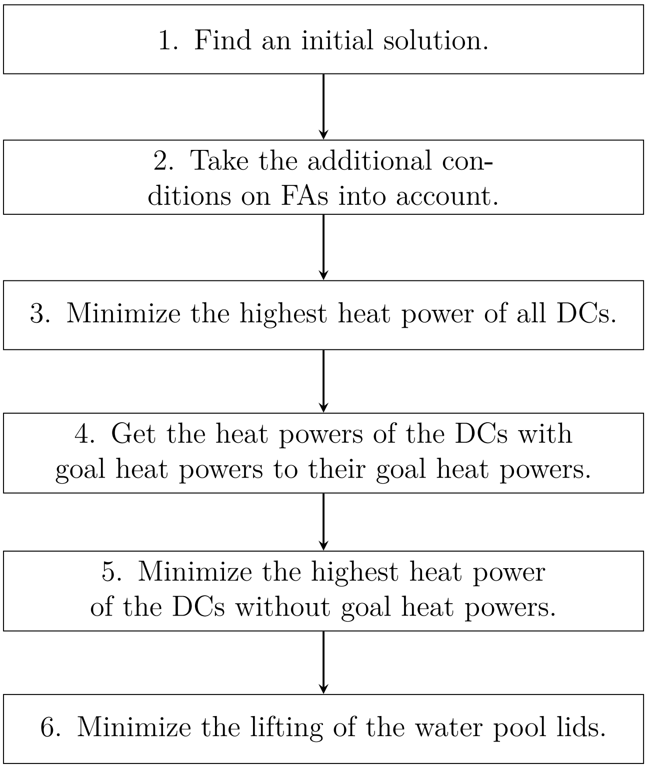

Fig. 2. Major steps in the loading optimization algorithm.

4.2. Taking the additional conditions on FAs into account

The additional conditions on FAs are related to dechannelled, banned, or preassigned FAs and the minimum cooling time. The conditions are considered in this order in the algorithm.

The first condition to take into account is related to the dechannelled FAs. These FAs are old and hence have below average decay heat power. There is no optimization related to decay heat powers involved in this step and the goal is to have correct number of dechannelled FAs in a transfer cask. Hence, we pick dechannelled FAs in the order determined by the index of FA. It is possible that dechannelled FAs are changed later in the algorithm, but it is required that the number of dechannelled FAs in each DC is constant after a change.

The dechannelled FAs in the DCs with goal heat powers are determined first according to a user given parameter (e.g. 3/cask = 1/DC). The algorithm gives a warning if the condition on the number of dechannelled in a DC with goal heat power cannot be satisfied. This will most probably happen at some point of the disposal when there are not enough dechannelled FAs, and thus, it does not stop the algorithm. If possible, and there are no preassigned dechannelled FAs in the DCs without goal heat powers, the same disposal rate of dechannelled FAs is applied also for these DCs, until there are no dechannelled FAs remaining. Otherwise, they are distributed evenly in the DCs without goal heat powers. Since the dechannelled FAs are taken into account before preassigned and banned FAs, the dechannelled FAs that are preassigned or banned must be considered appropriately in this procedure. All the dechannelled FAs satisfy the minimum cooling time criterion and, thus, we do not need to check this condition when taking into account dechannelled FAs.

The second condition to consider is related to the preassigned FAs. For the preassigned FAs the user gives a table that contains information which FAs are assigned to which DCs. Every item in the table is gone through. If an FA in the table is not in the corresponding DC, it is changed with the FA with the highest heat power in that DC. The reasoning behind this choice is that preassigned FAs are most probably to be used for the DCs with goal heat powers and it is considered a good thing to avoid disposing hot FAs as they can be cooled down. Alternatively, we could take any other FA that is not preassigned nor dechannelled from that DC. If there are more preassigned FAs for a single DC than DC capacity, the algorithm stops.

The third condition to take into account is related to the banned FAs. Some FAs might be banned. This means that they are prohibited from the DCs with goal heat powers. Banned list is taken into account by going through every FA assigned to a DC with goal heat power. In the case there is a banned FA i in a DC j with goal heat power, it is changed to a non-banned FA from the DC without a goal heat power. Furthermore, the non-banned FA cannot be dechannelled nor preassigned. From the FAs satisfying these criteria the one with the closest decay heat power to the FA i at the time DC j is disposed of is chosen to be changed. If there are banned FAs in a DC with goal heat power after this procedure the algorithm will stop. This may occur, for example, if a banned FA has been mistakenly preassigned to a DC with goal heat power.

The fourth condition to take into account is related to the minimum cooling time. If an FA does not satisfy the minimum cooling time criterion at a certain time, we give its decay heat power a large value that is greater or equal to 2000 W. For comparison, the DC power for any of the disposed fuel types is planned to be below 2000 W. If an FA does not satisfy the minimum cooling time criterion at time t_0 we know that it is not satisfied at time $t \leq t_0$ either. The heuristic to make FAs to satisfy the minimum cooling time criterion goes through DCs in the order of disposal time and makes sure the criterion is satisfied for each FA in the DCs. If at some point a non-preassigned FA i assigned to the current DC j is found that does not satisfy the minimum cooling time criterion, then it is changed with an FA k that is disposed of later and it satisfies the minimum cooling time criterion in the current DC j. In addition, it is required that the FA k is not dechannelled nor preassigned and, in the case the current DC j has a goal heat power, the changed FA k cannot be a banned FA.

Note that the FA decay heat power is greater than or equal to 2000 W if the FA does not satisfy minimum cooling time criterion, and thus, the heat power of DC with such FA is greater than 2000 W. Hence, when the highest DC power is minimized we should be able to get rid of such assignments. The main point of the procedure taking the minimum cooling time into account, is to check that there exists a solution such that the minimum cooling time criterion is satisfied for each FA. If there exists no such solution the algorithm will be stopped and the given schedule and/or preassigned FAs must be revisited.

After this step the additional conditions are met and they must be respected in the subsequent procedures. The heat power of each DC is given in Fig. 3 after this step. Almost all the changes from the initial solution are due to satisfying the condition related to dechannelled FAs.

4.3. Minimizing the highest DC power

Before we try to get the DC powers of the DCs with goal heat powers to their goal heat powers, the highest heat power among all the DCs is minimized. This will usually lead to rather even DC power. Since all the DCs are considered in this minimization also the decay heat power of each FA at the disposal time of each DC is considered. This takes implicitly into account how each FA cools down. Those FAs that cool down fast will be disposed of later. The procedure to minimize the highest DC power is quite similar to that studied in Ranta and Cameron (2012), Ranta (2012). There are some adjustments added to take into account the additional conditions. The procedure to find an improving change with 1-1 changes is given in Algorithm 1. In a 1-1 change, two FAs from different DCs are exchanged.

This procedure is repeated and the change returned is done as long as a new change is found. Since the maximum DC power or the number of DCs with the maximum DC power is reduced in each

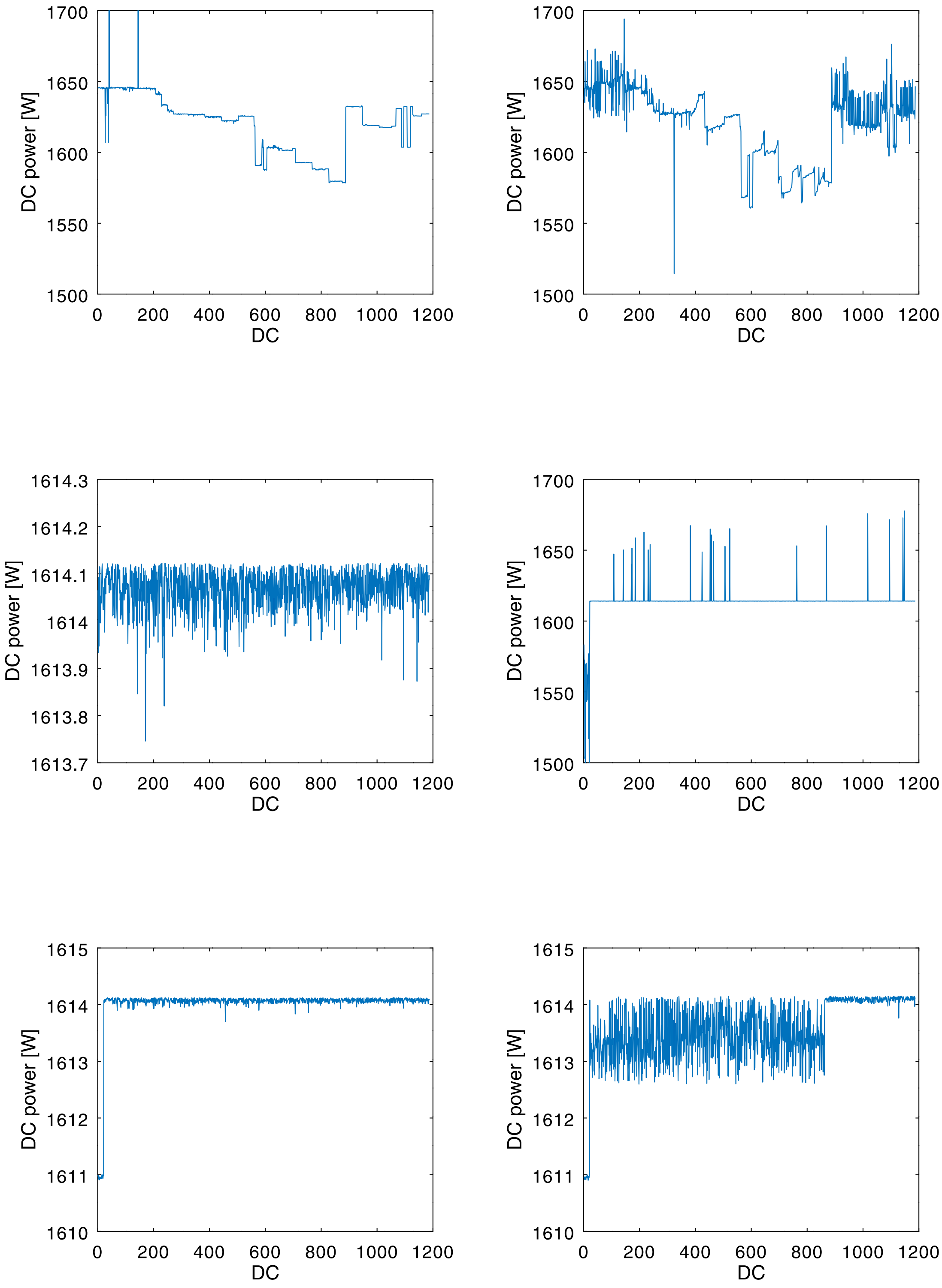

Fig. 3. DC powers of OL1-2 fuel in given example after finding deterministic initial solution (top left), after the additional conditions on FAs are taken into account (top right), after the highest DC power has been minimized (center left), after getting the DCs with goal heat powers under their goal heat powers (center right), after getting DCs with goal heat powers to their goal heat powers and minimizing the maximum DC power of the rest (bottom left) and after minimizing lifting of the lids (bottom right).

iteration, the procedure will end after a finite number of iterations. Note that this procedure relying on 1-1 changes is heuristic and there is no guarantee for a global optimal solution. As in Ranta and Cameron (2012), Ranta (2012) we will use also 2-2 changes. These are used after the procedure with 1-1 changes cannot find improving changes anymore. In 2-2 changes we change a pair of FAs instead of a single FA. Thus, for a single DC with capacity C there are totally $\binom{C}{2}$ pairs to change.

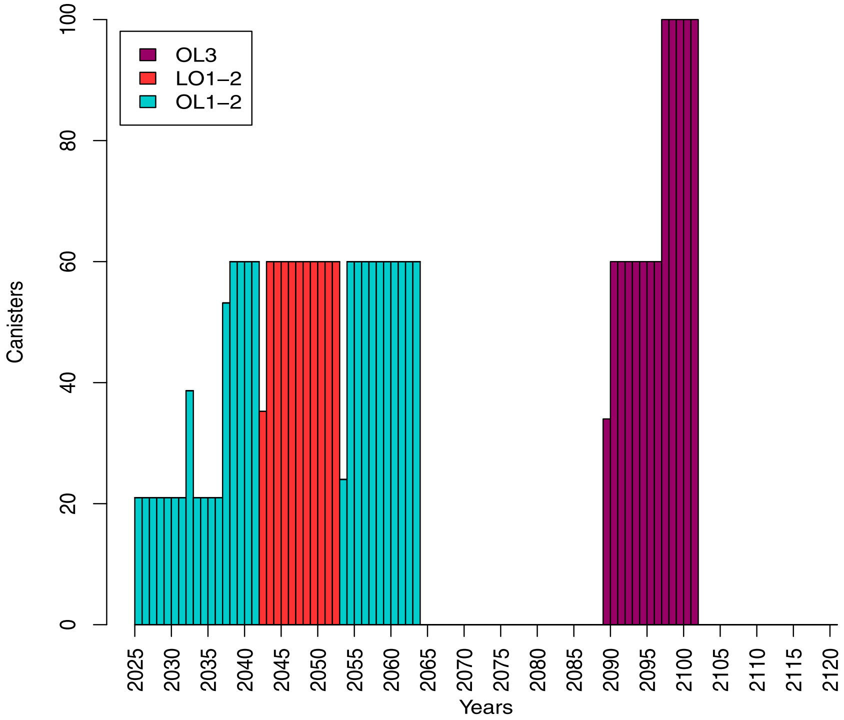

Fig. 4. The disposal schedule for each fuel type used in all of the examples.

Algorithm 1 Find a change to minimize the highest DC power

```
for $i$ going through the DCs with the highest heat power do
    Make a list $A$ consisting of non-preassigned FAs of DC $i$.
    for $j$ going through the DCs do
        Make a list $B$ consisting of non-preassigned FAs of DC $j$.
        Find a change between FAs in the lists $A$ and $B$ such that the maximum heat power of the DCs $i$ and $j$ is minimized. The number of dechannelled FAs must be preserved and no banned FAs are allowed to be assigned to DCs with goal heat powers.
        if The heat powers of DCs $i$ and $j$ are at least 0.001 % lower than the current maximum then
            return the FAs that needs to be changed.
        end if
    end for
end for
```

After this step the DC powers are usually rather even, although, this is not guaranteed. The given FA heat powers, disposal schedule, capacity of a DC, and additional conditions on FAs all affect whether evenly distributed DC powers can be obtained. The heat power of each DC is given in Fig. 3 after this step.

4.4. Optimizing DCs with goal heat powers

To get the decay heat powers of the DCs with goal heat powers to their goal heat powers, a choice have to be made to which DC we will make changes first. Since it is required that the DC decay heat powers must be under their goal heat powers, it is reasonable to make changes to those DCs which decay heat surpasses the goal heat power. This process is done in a separate procedure that gets the decay heat powers of the DCs under their goal heat powers.

The procedure will go through all the DCs with goal heat powers. If the DC power is above the goal heat power, the FA with the highest decay heat power is changed. The other FA for the change is searched from the DCs without goal heat powers one DC at a time starting from the one with the lowest decay heat power. The FAs in the DC are ordered in increasing order of decay heat power. If such a change is found that the additional conditions are satisfied after the change and the decay heat power of the DC with a goal heat power is decreased after the change, that change is performed. This process is repeated until the DC power is below the goal heat power. To see the effect of this procedure on the solution, one can compare the center left and right images in Fig. 3. The first 21 DCs are the ones with the goal heat power. On the center left image these DCs are above their goal heat power of 1611 W. On the center right image they are under their goal heat power. To achieve this, one FA was changed for each of these DCs. The spikes in the center right image correspond to the DCs where the changed FAs ended up.

At this point, the DC powers of the DCs with goal heat powers should be below their goal heat powers. If DC power of a DC is higher than the goal heat power of the corresponding DC, then no changes are done to that DC. The user given parameter accuracy defines how close to the goal heat power we need to get. For example, if the accuracy is 0.1 W the algorithm stops finding improvements if the DC power is within 0.1 W from the goal heat power. To get DC powers close enough to their goal heat power the greatest difference from the goal heat powers is iteratively minimized with 1-1 and 2-2 changes. Thus, changes are searched to the DC, which DC power deviates from the goal heat power the most. At first, the changes are done between the DCs with goal heat powers and DCs without goal heat powers. After this step, the changes are made between the DCs with goal heat powers. While this last step may not do any changes if there are not many DCs with goal heat powers, it allows to use the algorithm if every DC is given a goal heat power. This can be convenient in the last years of the disposal.

The basic structure to find a change is similar to the Algorithm 1. The criterion to choose the best change is different though. When

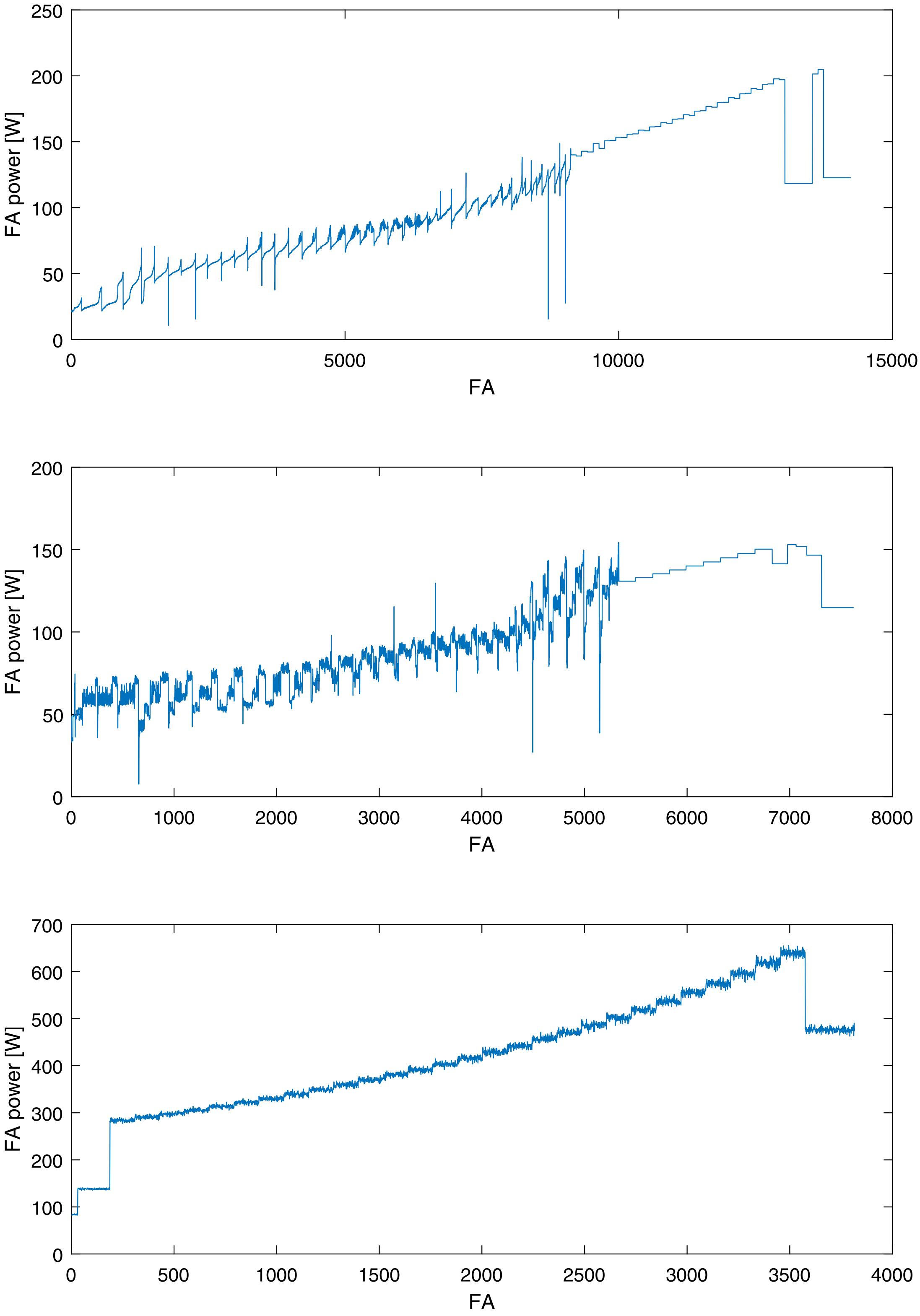

Fig. 5. FA powers of OL1-2 (top), LO1-2 (center) and OL3 (bottom) fuel at the beginning of the year 2063, 2052 and 2101, respectively.

changes are made between DCs with goal heat powers and DCs without goal heat powers, we want to get as close to the goal heat power as possible, but still below it. When changes are made between DCs with goal heat powers, the greatest difference from the goal heat powers should be as small as possible while both heat powers remain under their goal heat powers.

At first, the greatest difference between goal heat powers and DC powers is minimized. After that, we minimize the next greatest difference and so on. This makes sure that we try to get DC powers of all DCs close to their goal heat powers. Minimizing only the greatest difference could result in that all DC powers of DCs with goal heat powers are far from their goal heat powers because there was one DC for which the goal heat power could not be reached accurately enough.

4.5. Minimizing the highest decay heat power of the DCs without goal heat powers

After DCs with goal heat powers have been optimized we minimize the highest heat power of the DCs without goal heat powers. The heat powers of these DCs give an estimate at what heat power these can be disposed of in the future. The procedure is the same as in Algorithm 1, but the DCs with goal heat powers and FAs assigned to them are not considered at all. The DC powers of the example case after this step are given in Fig. 3.

4.6. Minimizing the lifting of the pool lids

In the Olkiluoto interim storage there are lids over water pools. Each pool is modeled to have one lid over it. The FAs are taken from the pools to a transfer cask and 3 DCs of OL1-2 fuel are filled with these FAs. If we do not optimize lifting of the lids we need to open lids unnecessary many times. It is still an open question how many casks will be filled after opening certain lids. In this study we assume that only one cask is filled. To explain this further, suppose that the first cask is filled with FAs from pools 1 and 2. Then if we need to open 2 lids to fill the second cask it does not matter from which pools we will take the FAs. We will always need in total 4 lifting of lids to fill these two transfer casks since the lids are closed after filling one cask.

When minimizing the lifting of the lids we do the following for each transfer cask. We first check what lids we need to currently lift. Then we try to iteratively reduce this number by doing part of the optimization again with all the FAs that are not in certain pools banned. In this optimization we use the current solution as an initial solution. The minimization of the highest heat power before getting DCs to their goal heat powers is omitted. Otherwise, the optimization is done as previously. Furthermore, in this optimization the DCs with goal heat powers other than the ones to be filled with the FAs in the current transfer cask are removed from the problem together with the FAs assigned to them. This makes sure that we do not change these FAs. If we can get the decay heat powers within *the accuracy for minimizing the lifting of the lids* from the goal heat powers with reduced lifting of lids, this solution is accepted and lifting of the lids is tried to minimize further starting from this solution. The DC powers of the example case after minimizing the lifting of the lids are given in Fig. 3.

To illustrate the iterative procedure to minimize lifting of the lids, suppose that the lids over pools 1,2,3 and 4 are needed to be lifted to fill the next 3 DCs. These pools are ordered in certain way, say (4,2,3,1), and then we try to solve the problem by banning all FAs but the ones that are in three pools. Hence, we obtain four problems with non-banned FAs taken from pools (2,3,1), (4,3,1), (4,2,1) and (4,2,3), respectively. If we find an acceptable solution when non-banned FAs are from pools 2,3 and 1, we take it as the current solution and next ban all FAs but the ones in two pools leading to alternatives (3,1), (2,1) and (2,3). The process to minimize the number of lifting of the lids continues as long as we get the DCs with goal heat powers to their goal heat powers within accuracy for minimizing the lifting of the lids.

5. Computational results

In this section the loading optimization algorithm is used to do different investigations. There are two kinds of considerations. First, we apply the algorithm to the case where the DCs of the first year of disposal of corresponding fuel is set as the DCs with goal heat powers. In the second set the whole production of the EP is determined by iteratively setting one year of production as the DCs with goal heat powers.

Some parameters used in the investigations are given in Table 1. There are no banned nor preassigned FAs. The decay heat powers of FAs are given by the power companies and they cannot be published accurately. However, these are given in the last year of disposal of corresponding fuel type in Fig. 5. For OL3 fuel a random noise from normal distribution with 1% standard deviation has been added to the FA heat powers. This facilitates finding even DC powers. It is also realistic that FAs from the same removal have different heat powers. The schedules used for the results are given in Fig. 4. These are derived from the scheduling problem of which one multiobjective version is given in Montonen et al. (2020). The goal heat power of the first year in the first test set is derived from the scheduling problem as well.

Table 1
Parameter values for the example problems.

Parameter	OL1–2	LO1–2	OL3
Number of DCs	1187	636	954
Capacity of a DC	12	12	4
Number of DCs in the first year of disposal	21	36	34
Goal heat power of the first year of disposal [W]	1611	1280	1794
Accuracy [W]	0.1	0.1	0.1
Accuracy for minimizing lids [W]	1	–	–
Number of dechannelled per cask	3	–	–

5.1. Assembly assignment problem, one year

The DC powers for each fuel type after applying the loading optimization algorithm are given in Fig. 6. On the images on the left the DCs with goal heat powers are the ones disposed in the first year of disposal year of the corresponding fuel. The DC powers of the DCs with goal heat powers are within accuracy 0.1 W from their goal heat powers for all fuel types.

The OL1-2 fuel is the only fuel type for which lifting of the lids is applied. There are 7 transfers needed for the first 21 DCs. Before the lifting of the lids was minimized we needed to lift 24 lids to take the FAs to the first 7 transfers. After the lifting of the lids was minimized this was reduced to 12 lifts. This has an effect on how well the DCs without goal heat powers can be disposed of. From Fig. 3 we see that before the lifting of the lids was minimized the DC powers of the DCs without goal heat powers is approximately 1614 W and DC powers are quite even. After the lifting of the lids was minimized the DCs, that are disposed before LO1-2 fuel, have greater variance in DC powers than the DCs that are disposed after LO1-2 fuel is disposed of. However, the variance is still rather small.

For LO1-2 fuel all the DCs without goal heat powers but one have rather even heat power. The DC power of this one DC is 1230 W. As this deviation happens in the DCs without goal heat powers and only the FAs in the DCs with goal heat powers correspond to final assignments, this deviation can be neglected for now.

For OL3 fuel the DC powers of the DCs without goal heat powers are rather even, but there is more variance than in LO1-2 DC powers or OL1-2 DC powers that are disposed after LO1-2. This effect has been seen consistently and it is most probably due to the capacity of DC being 4 instead of 12. The smaller the capacity of DC the less possibilities there are to even out the DC powers.

5.2. Assembly assignment problem, whole production

In this section the loading optimization algorithm is iteratively applied to define assignments of the whole production of the EP. In the previous section assignments for the one year were defined. The next step is to drop out these DCs and FAs assigned to them and define assignments for the next year by similar procedure. By iteratively doing so we end up with the assignments for all DCs. Only one goal heat power is used for each fuel type.

For OL1-2 the lifting of the lids is minimized for the first ten years. This cannot be done for all the DCs since it is unknown at which pool a certain FA is put if it is not yet in a pool. Furthermore, it is probable that some sort of rearrangement of FAs takes place when enough FAs

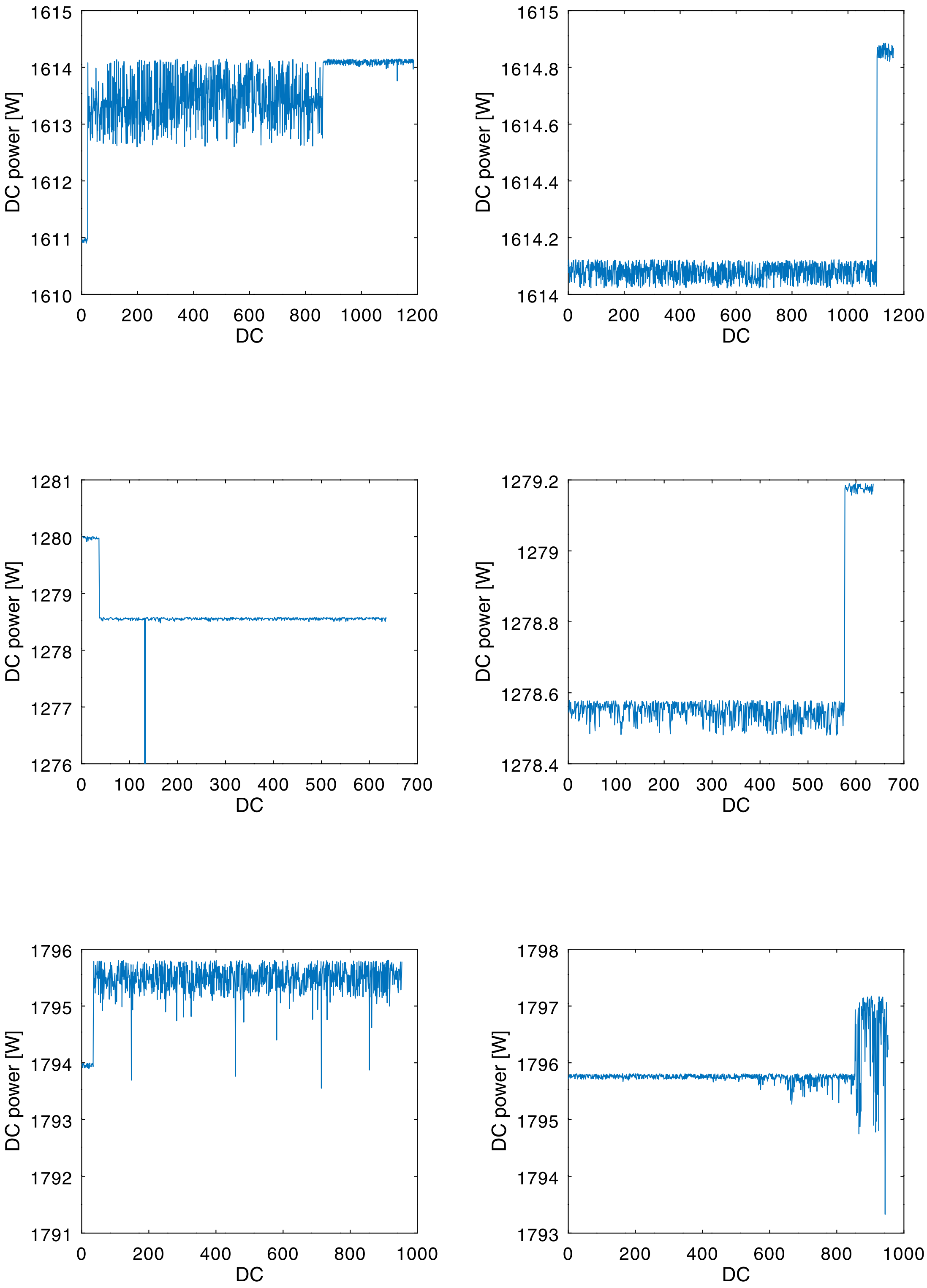

Fig. 6. DC powers of OL1-2 (top left), LO1-2 (center left) and OL3 (bottom left) fuel when optimization is done for one year. DC powers of OL1-2 (top right), LO1-2 (center right) and OL3 (bottom right) fuel when optimization is done for all DCs one year at a time.

are disposed of which further makes defining pools for each FA difficult. For the first ten years we need to lift lids 150 times being slightly under 2 per transfer cask. If we do not minimize the lifting of the lids the number of times lids need to be lifted for the first ten years would be 273.

The DC powers for fuels OL1-2, LO1-2 and OL3 are given in Fig. 6. The goal heat powers are 1614.1 W, 1278.6 W, and 1795.8 W, respectively. For each fuel type, the last year is problematic in the sense that goal heat powers are not attained. As this happens in the distant future, this can be neglected for now. The disposal schedule should be revised, when new data is available. This problem occurs, most probably, because the procedure to get heat powers to their goal heat powers is greedy as when finding changes only the criterion for getting DC power to goal heat power is considered. For OL1-2 and LO1-2 DCs powers are within accuracy 0.1 W, from their goal heat power in other than the last year of disposal. For OL3 there are several DCs whose DC power deviates from the goal heat power more than accuracy from around 580th DC on. One reason for the fact that OL3 is more difficult case than OL1-2 or LO1-2 is that OL3 has lower DC capacity.

6. Discussions

The assembly assignment problem where fuel assemblies (FAs) need to be assigned to disposal canisters (DCs) taking into account several constraints and three objectives were studied. The problem is related to final disposal of FAs from nuclear reactors in Finland into crystalline rock during several decades. The loading optimization algorithm is given and it is used to define the assignments in a few example cases with given decay heat data, goal heat powers and disposal schedule. By simulating the whole production of the EP with the algorithm, it was found out that the production of the EP succeeds well also in the long run. There are some variations but it is within 1 W for OL1-2 and LO1-2 fuel and mostly within 2 W for OL3 fuel. The loading optimization algorithm is implemented in Posiva's fuel database.

The given data did not include any uncertainties in decay heat powers of FAs and taking these into account will be studied in the future. Even if the lids were not minimized for OL1-2 it may happen that the pools are emptied quite evenly. This would mean a lot of rearrangement of OL1-2 FAs in the Olkiluoto interim storage if one pool is required to be empty at the given time for OL3 fuel to be stored in. Making it possible to empty a pool at a given time is a property that will be added to the loading optimization algorithm in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix. Pseudocodes

In this appendix we give the pseudocodes for each procedure other than the one given previously in the text.

```
procedure INITIAL SOLUTION
    Order the FAs in the decreasing order of decay heat power at the time when the last DC is disposed of.
    for $i$ going through the FAs do
        Find such a DC with free position whose power will be lowest after the addition of the FA $i$.
        Assign the FA $i$ to the DC found.
    end for
end procedure
```

```
procedure TAKE THE DECHANNELLED FAs INTO ACCOUNT
    Initiate the table $A$ to which we collect assignments for dechannelled FAs:
    $A(i,j)$ tells for each $j$ that FA $A(2,j)$ is allocated to DC $A(1,j)$.
    Allocate the dechannelled FAs that are preassigned in the DCs with goal heat powers correspondingly in the table A.
    Make a list $B$ of dechannelled FAs that are not preassigned nor banned.
    Calculate how many dechannelled we need in each DC with a goal heat power to satisfy the given rule.
    for $i$ going through the DCs with goal heat powers do
        Allocate the dechannelled FAs from the list B to the DC $i$ in table A.
        Update list $B$ by dropping the allocated FAs.
    end for
    Allocate the dechannelled FAs that are preassigned in the DCs without goal heat powers correspondingly in the table A.
    Make a list $C$ of the dechannelled FAs that are not yet allocated to DCs in this procedure.
    Calculate how many dechannelled we need in each DC without a goal heat power to satisfy the given rule. If the given rule cannot be satisfied or there are preassigned dechannelled FAs in the DCs without goal heat powers, distribute dechannelled evenly.
    for $i$ going through the DCs without goal heat powers do
        Allocate the dechannelled FAs from the list C to the DC $i$ in table A.
        Update list $C$ by dropping the allocated FAs.
    end for
    for $j$ going through the columns of table $A$ do
        if FA $A(2,j)$ is not in DC $A(1,j)$ then
            Find the least hot FA in DC $A(1,j)$ and change it with the FA $A(2,j)$.
        end if
    end for
end procedure
```

```
procedure TAKE THE PREASSIGNED FAs INTO ACCOUNT
    for $i$ going through the preassigned FAs do
        if FA $i$ is not in the correct DC then
            Find an FA from the DC that is not preassigned to it.
            Change this FA with FA $i$.
        end if
    end for
end procedure
```

```
procedure TAKE THE BANNED FAs INTO ACCOUNT
    for $i$ going through FAs in the DCs with goal heat powers do
        if FA $i$ is banned then
            Order the FAs by increasing order of absolute difference of decay heat power from FA $i$ at the time of disposal of DC where FA $i$ currently is.
            $j \leftarrow 1$
            while $j \leq$ number of FAs do
                if FA $j$ is not in the DCs with goal heat powers and is not banned and is not preassigned and is not dechannelled then
                    Change the assignments of FA $i$ and $j$.
                    $j \leftarrow$ number of FAs.
                end if
                $j \leftarrow j + 1$.
            end while
        end if
    end for
end procedure
```

```
procedure TAKE THE MINIMUM COOLING TIME INTO ACCOUNT
    Order the DCs according to the increasing disposal time.
    for $i$ going through the DCs do
        for $j$ going through the FAs of DC $i$ do
            if the minimum cooling time is not satisfied for FA $j$ then
                Find a DC $k$ such that the minimum cooling time is satisfied if FA $j$ is inserted into it and the DC $k$ contains FA $l$ which satisfies the minimum cooling time at the time when DC $i$ is disposed of. The additional conditions related to dechannelled, preassigned and banned FAs need to be satisfied if the FAs $j$ and $l$ are exchanged.
                if the DC $k$ is found then
                    Change the assignments of FAs $j$ and $l$.
                else
                    Find a DC $k$ which contains FA $l$ which satisfies the minimum cooling time at the time when DC $i$ is disposed of. The additional conditions related to dechannelled, preassigned and banned FAs need to be satisfied if the FAs $j$ and $l$ are exchanged.
                    Change the assignments of FAs $j$ and $l$.
                end if
            end if
        end for
    end for
end procedure
```

```
procedure GET THE DCs WITH GOAL HEAT POWERS BELOW THEIR GOAL HEAT POWERS
    for $i$ going through the DCs with goal heat powers do
        if The DC power of DC $i$ is greater than its goal heat power then
            for $j$ going through the DCs without goal heat powers in order of increasing heat power do
                Find the FA $k$ in DC $i$ that has the highest decay heat power, is not preassigned, and is not dechannelled.
                Find the FA $l$ in DC $j$ that has the lowest decay heat power at the time DC $i$ is disposed of, is not preassigned, banned nor dechannelled.
                Change the assignments of the FAs $k$ and $l$.
                if the heat power of DC $i$ is lower than its goal heat power then
                    Stop the inner for loop.
                end if
            end for
            if the heat power of DC $i$ is greater than its goal heat power then
                for $j$ going through the DCs with goal heat powers do
                    Find and do a change between the FAs of DC $i$ and DC $j$ such that the heat power of DC $i$ is lowered and the heat power of DC $j$ remains under its goal heat power.
                end for
            end if
        end if
    end for
end procedure
```

```
procedure MINIMIZE THE MAXIMUM DIFFERENCE FROM THE GOAL HEAT POWERS
    Set temporary goal heat powers to match the goal heat powers.
    while the differences between DC powers and temporary goal heat powers are greater than accuracy do
        change ← true
        while change == true do
            Try to find an improving change between DCs without goal heat powers and the DC with the greatest difference between DC power and the temporary goal heat power.
            if a change was found then
                Execute the change.
            else
                change ← false.
            end if
        end while
        Set the temporary goal heat power to the DC power for the DC with the greatest difference between DC power and its temporary goal heat power.
    end while
end procedure
```

```
procedure FIND A CHANGE TO MINIMIZE THE DIFFERENCE FROM THE GOAL HEAT POWERS
    Calculate the differences between DC powers of the DCs and their goal heat powers.
    if the greatest difference is greater than accuracy then
        for i going through DCs with the greatest difference do
            Make a list $A$ of FAs in DC $i$ that are not preassigned.
            for $j$ going through the DCs without goal heat powers do
                Make a list $B$ of FAs in DC $j$ that are not preassigned nor banned.
                Find a change between the FAs in lists $A$ and $B$ such that the DC power of the DC $i$ is as close to its goal heat power as possible, but still under it. The change must keep the number of dechannelled FAs in the DCs constant.
                if a change improving the DC power of DC $i$ is found then
                        return the change found.
                end if
            end for
        end for
    end if
end procedure
```

```
procedure MINIMIZE LIFTING LIDS
    for $i$ going through each transfer cask containing FAs for DCs with goal heat powers do
        Omit other DCs with goal heat powers than the ones filled with FAs from cask $i$ and omit FAs allocated to them from the data.
        improvement ← true
        success ← false
        while improvement == true do
            improvement ← false
            Make a list $A$ of lids that need to be lifted when taking FAs to the transfer cask $i$.
            $j \leftarrow 1$
            while improvement == false and $j \leq$ number of elements in list $A$ do
                Ban every FA under the lid $A(j)$.
                Solve the optimization problem with updated data and bans.
                if The DC powers of the DCs in the cask $i$ deviate from the goal heat powers less than the accuracy for minimizing the lifting of the lids then
                    Save the solution found.
                    improvement ← true
                    success ← true
                end if
                $j \leftarrow j + 1$
            end while
        end while
        if success == true then
            Set the solution found as the current solution.
        end if
    end for
end procedure
```

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