Improvement of nuclear decommissioning and dismantling planning via experience exchange and optimisation methods

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Introduction

The International Energy Agency (IEA) expects that until 2040 about 200 nuclear reactors in various nuclear facilities worldwide have to be decommissioned and dismantled [IEA14]. In its Nuclear Illustrative Program the European Commission estimates that more than 50 nuclear reactors will be decommissioned until 2025 in the EU [COM16]. Altogether, the "Decommissioning will become an increasingly important part of the nuclear sector activity in the coming decades […]." [IEA15]

Concerning the IEA only 10 reactors have been completely decommissioned and dismantled worldwide so that the site is released from regulatory control [IEA14]. In Europe, only 3 reactors have so far been completely decommissioned (all in Germany) [COM16]. These nuclear decommissioning and dismantling (D&D) projects as well as current D&D projects show that D&D of nuclear power plants is technically possible and safe [TS15].

Apart from the technical aspects of D&D, the economic view is important. According to the European Commission, 123 billion Euros for D&D and 130 billion Euros for final disposal are needed until 2050. But, so far member states only have assets backing these expected costs, which amount to approximately 133 billion Euros. [COM16]. Consequently, a financial gap of 120 billion Euros still exists.

Altogether, project management and especially the project planning are important to minimize the costs of D&D. Project management is very challenging since D&D of nuclear facilities is a large-scale project with high requirements for safety and security, an expected makespan of about 15 to 20 years and a budget with about 0.5 to 1 billion Euros per facility. Furthermore, there is very little experience in D&D project planning and execution worldwide [COM16]. These challenges have high impact on project costs and poor planning often causes cost increase.

To meet these challenges, on the one hand experience exchange is needed to get best practices, which is essential to plan and perform D&D safely and cost-minimally. On the other hand, efficient planning tools are needed to generate a robust project plan. Therefore, we developed a decision making model that provides a calculation of a robust dismantling plan with minimal total project costs, which is presented in the following.

Decision making model

The aim of our research is to provide a robust dismantling plan with minimal total project costs in consideration of uncertainties. Therefore, two elements are important (see figure 1): documentation of experience data to get best practices and a method that calculates a feasible and cost-minimal project plan under uncertainty.

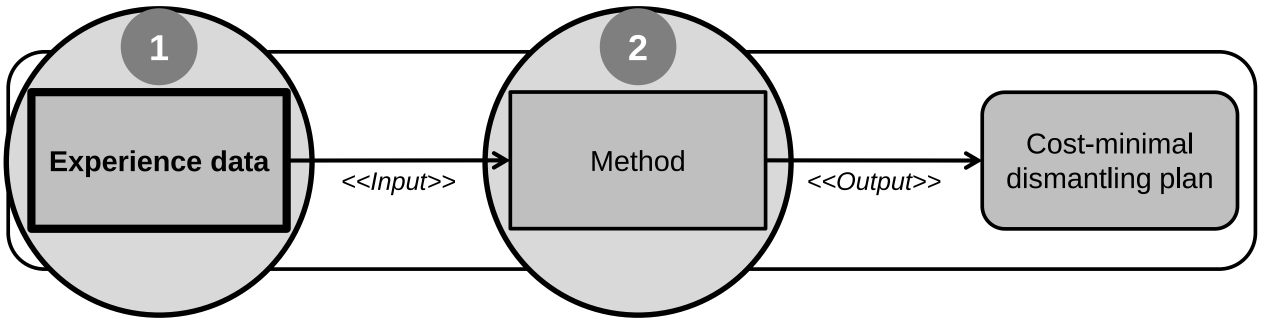

Figure 1: Elements to determine a cost-minimal dismantling plan under uncertainty

The less uncertainties exist, the less deviations from the plan appear. Uncertainties can be reduced by experience data such as expected activity durations, possible alternative execution sequences and resources needed for several D&D activities. The more experience data is available for the planning, the less uncertainties exist. Therefore, an experience exchange between companies and countries is essential to reduce uncertainties. For example, France and Germany both have decided to reduce their nuclear capacity so that D&D has to be done in both countries in the next decades [REP15], [ATG15]. Both countries already have little experience in D&D, but will gain further experience in the future. In France, the enactment of the law concerning the energy transition for green growth ("La loi de transition énergétique pour la croissance verte") has the aim to reduce the nuclear share of the electricity production to only 50% in 2025 [REP15]. As a result of this law, nuclear power plants with a capacity of at least 1,650 MWe will have to be shut down [WNA16]. In Germany, the nuclear phase-out until 2022 is legally defined [ATG15] so that all 18 nuclear power plants will be shut down by then. An international approach of cooperation in the optimization process of D&D would be beneficial and all parties involved would have the opportunity to become global leaders in D&D [COM16].

Despite the collection of experience data, uncertainties in such large scale projects will still remain. Therefore, we developed a decision making model that provides a calculation of a robust dismantling plan with minimal total project costs under uncertainty. The model includes three steps:

1. Simulation of different scenarios,
2. Calculation of a cost-minimal schedule for every simulated scenario,
3. Identification of robust solutions.

In a **first step**, we determine distributions of every single activity-duration. These distributions specify the probability of several activity durations. Thus, we depict the most probable activity duration but also improbable activity durations (see figure 2). In addition, we draw a stochastic network to illustrate possible sequences of activities (see figure 2). Not every sequence of activities has to be executed in reality, but is executed only with a specific probability. For example, if a wall near the pressure vessel has to be removed, different activities can be executed. Either contamination is not found and the wall can be teared down without any decontamination activity or contamination is found and several decontamination activities have to be performed. Maybe, also activities for static stabilisation have to be done when too many decontamination activities are necessary.

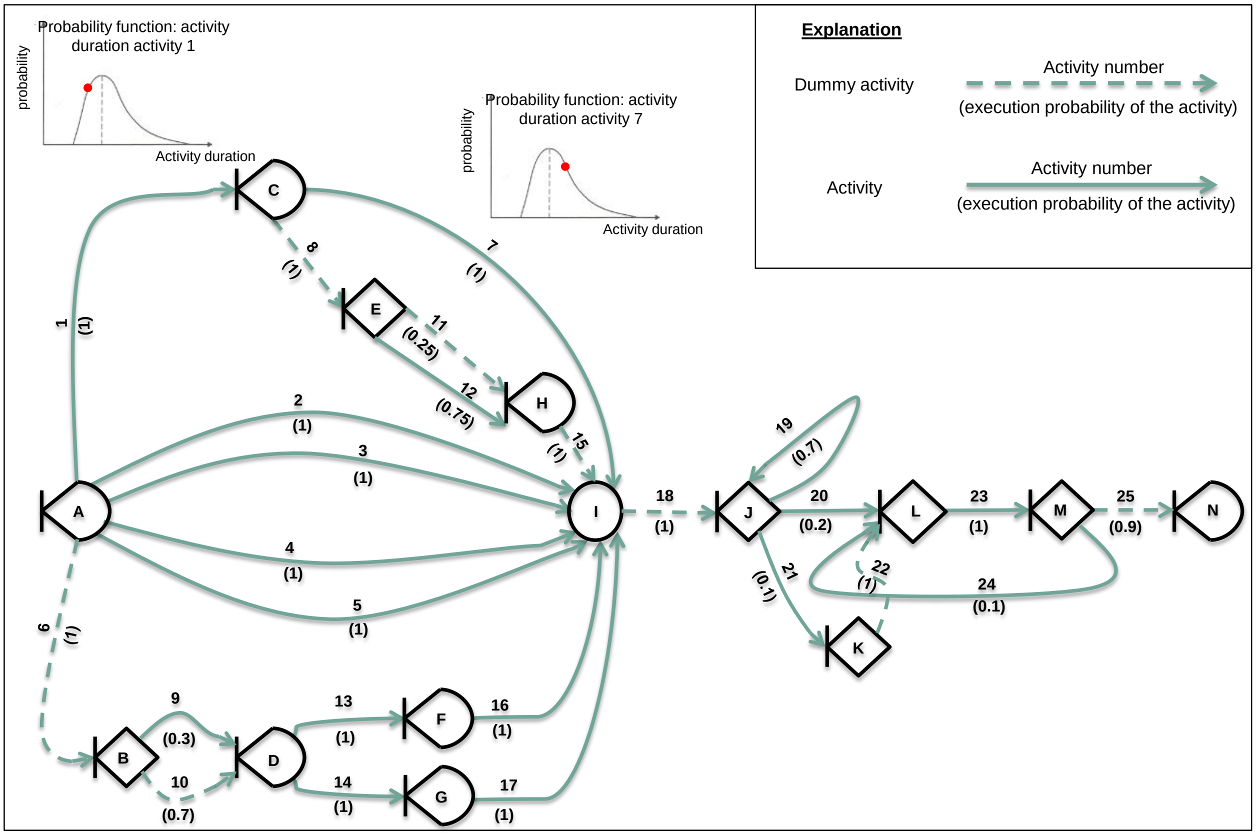

Figure 2: Stochastic network with exemplary execution probabilities for activities 1 and 7

Altogether, a lot multiple variations in activity durations and sequences of activities could appear. By considering the activity distributions and the stochastic network, we simulate different scenarios (e.g. 1000 scenarios). Via the scenario construction we simulate several foreseeable situations and thus consider uncertainties within the execution of a D&D project.

Since every scenario represents a possible realistic situation, in a **second step** we calculate a cost-minimal dismantling plan (so called schedule) for each scenario. This model contains a method which is based on the so called multi-mode resource-constrained project scheduling problem (MRCPSP) [SCH98]. This method is an optimization problem considering activity precedence and resource capacities during project execution. For the calculation of a cost-minimal schedule the method uses an algorithm that follows a relaxation-based enumeration approach [NEU03]. This means that we first solve the problem without any restrictions and gradually add the given restrictions to the problem, while keeping the schedule feasible. This procedure is described in detail in the following and is illustrated in figure 3.

First, we determine and solve the optimization problem without resource restrictions. In this case we only consider the given precedence constraints. Thus, every activity that could be executed in parallel with other activities according to the precedence constraints will be planned as parallel activity. Furthermore, we determine which resources are needed for every activity (so called activity mode). Then, we examine the resulting schedule with respect to renewable or cumulative resources conflicts. A renewable resource is for example the staff or machinery needed for the execution of an activity. The characteristic of a renewable resource is that it has a specific capacity per time-period. While it is needed for an activity it is not available for another activity at the same time. But, after finishing an activity the renewable resource is available again for other activities. Cumulative resources are for example temporary stores. These cumulative resources change their availability over time. For example, a temporary store can be filled up to its maximum capacity or things can be removed from it except for its minimal capacity.

If such a conflict exists, we solve these conflicts by introducing further appropriate precedence relations to find new feasible schedules. Furthermore, we evaluate every possible resource allocation (every possible mode) for each activity. Altogether, we create a complete enumeration tree that represents every feasible schedule.

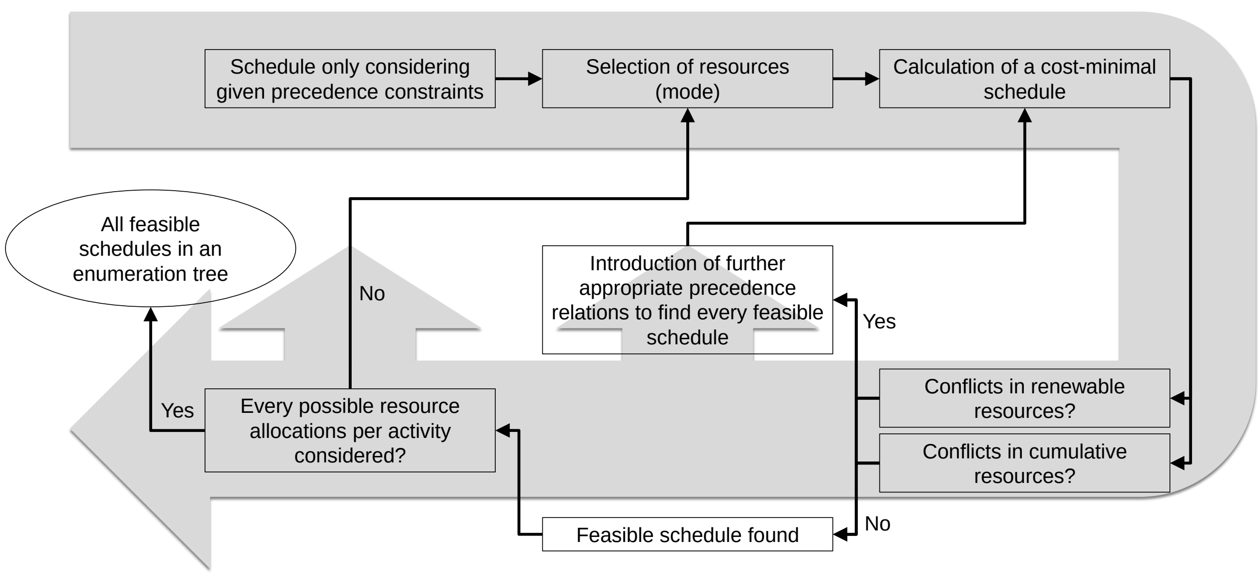

Figure 3: Approach to calculate a cost-minimal dismantling plan

In the enumeration tree every node represents a schedule S (see figure 4). By solving conflicts often several new feasible schedules can be found so that several paths to new feasible schedules will be add to the enumeration tree. When every conflict is solved all feasible schedules can be found at the leafs of the enumeration tree. Since every feasible schedule is listed in the enumeration tree, we still have to find the cost-minimal one. To find the cost-minimal schedule we use a branch-and-bound algorithm which eliminates certain parts of the enumeration tree by using upper and lower bounds (total costs). As a result of step 2, we determine the cost-minimal schedule of every simulated scenario.

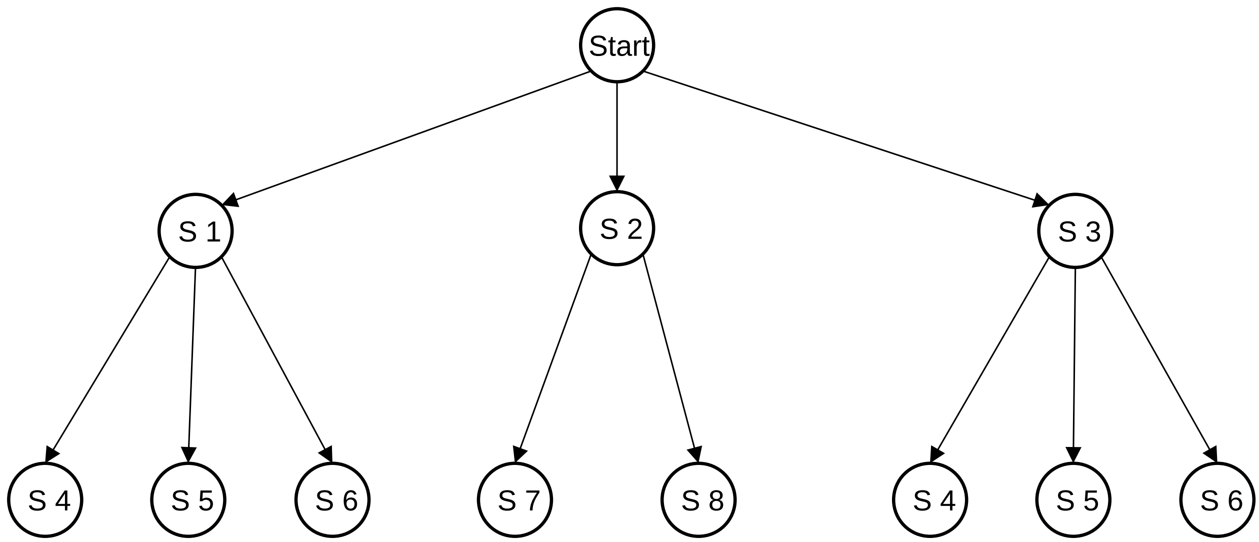

Figure 4: Enumeration tree with exemplary Schedules S for one scenario

In a **third step**, a robust dismantling plan with minimal total project costs under uncertainty has to be found. The meaning of a robust dismantling plan is that it can be executed even if there other scenarios than originally planned are realized. This has not to be the overall cost-minimal dismantling plan compared of every scenario. For example, it’s possible to create a scenario which represents a best case scenario. This best case scenario has very low total project costs but it is very improbable. Uncertainties in other scenarios are more probable and should be taken into account. Therefore, other scenarios than the best case scenario should be considered because the execution probability but also the total project costs are higher.

To find a cost-minimal (robust) dismantling plan with minimal total project costs under uncertainty, we have to evaluate the generated schedules of every single scenario. Since every activity has to be approved by a legal authority with its start time and the resources used for D&D in a nuclear power plant, the (approved) activities with their start times and their used resources should be kept constant even in different scenarios. If a schedule is not stable enough under different external conditions (scenarios) or due to forecast errors (high planning nervousness), temporary schedules have to be adapted to the new conditions [SCH01]. So, in D&D projects a stable dismantling plan is required that has not to be rescheduled when other scenarios than the originally planned one materialize and that just require minimal changes for different scenarios which do not have to be approved by a legal authority. This characteristic is defined as solution or planning robustness [SCH01].Therefore, we evaluate every calculated cost-minimal schedule of every scenario via solution robustness criteria to find a solution robust D&D schedule. To evaluate solution robustness there are several robustness criteria, e.g. the weighted sum of the deviations of planned and realized activity start times. Altogether, the identified solution-robust cost-minimal schedule is practical in several situations that could appear so that no re-planning and further approvals are needed.

Conclusions

The decommissioning and dismantling (D&D) of nuclear power plants and facilities is a worldwide growing market and part of nuclear plants' lifecycle. Apart from the technical aspects of D&D, the economic view is important. Therefore, cost-minimal project management and the planning of D&D are in the centre of attention. For the determination of a robust project plan two things are important: experience data and a method that calculates a feasible cost-minimal plan under uncertainty. The exchange of experience data among the parties concerned with nuclear D&D can contribute to the reduction of uncertainties in D&D projects. Nevertheless, uncertainties always exist in the project planning, especially of such large scale projects like the decommissioning and dismantling of nuclear facilities. Therefore, we developed a decision making model that provides a calculation of a robust dismantling plan with minimal total project costs. The calculation is done in three steps. First we simulate different scenarios by varying activity durations and possible sequences of activities. Second, we calculate the cost-minimal project plan for each scenario. Third, we determine a robust plan among all calculated schedules with the help of adequate robustness criteria.

For future research and to get more robust plans, more experience data on D&D of nuclear facilities is needed. For this reason we plead for more experience data documentation and exchange. Furthermore, in future work unforeseen uncertainties should be integrated in the operative project planning. Instead of the currently applied right-shifting of start times in the case of the occurrence of unforeseen uncertainties and interruptive events which mostly cause time delays, further methods could be used and implemented to integrate unforeseen uncertainties.

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