International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:10, No:10, 2016

Logistical Optimization of Nuclear Waste Flows during Decommissioning

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Abstract**—**An important number of technological equipment and high-skilled workers over long periods of time have to be mobilized during nuclear decommissioning processes. The related operations generate complex flows of waste and high inventory levels, associated to information flows of heterogeneous types. Taking into account that more than 10 decommissioning operations are on-going in France and about 50 are expected toward 2025: A big challenge is addressed today. The management of decommissioning and dismantling of nuclear installations represents an important part of the nuclear-based energy lifecycle, since it has an environmental impact as well as an important influence on the electricity cost and therefore the price for end-users. Bringing new technologies and new solutions into decommissioning methodologies is thus mandatory to improve the quality, cost and delay efficiency of these operations. The purpose of our project is to improve decommissioning management efficiency by developing a decision-support framework dedicated to plan nuclear facility decommissioning operations and to optimize waste evacuation by means of a logistic approach. The target is to create an easy-to-handle tool capable of i) predicting waste flows and proposing the best decommissioning logistics scenario and ii) managing information during all the steps of the process and following the progress: planning, resources, delays, authorizations, saturation zones, waste volume, etc. In this article we present our results from waste nuclear flows simulation during decommissioning process, including discrete-event simulation supported by FLEXSIM 3-D software. This approach was successfully tested and our works confirms its ability to improve this type of industrial process by identifying the critical points of the chain and optimizing it by identifying improvement actions. This type of simulation, executed before the start of the process operations on the basis of a first conception, allow 'what-if' process evaluation and help to ensure quality of the process in an uncertain context. The simulation of nuclear waste flows before evacuation from the site will help reducing the cost and duration of the decommissioning process by optimizing the planning and the use of resources, transitional storage and expensive radioactive waste containers. Additional benefits are expected for the governance system of the waste evacuation since it will enable a shared responsibility of the waste flows.

Keywords**—**Nuclear decommissioning, logistical optimization, decision-support framework, waste management.

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The authors would like to thank all colleagues who have collaborated with the authors and contributed to the success of this work, and in particular the Altran Research MADEN project team.

I. Introduction

A worldwide challenge is addressed here. 300 nuclear facilities will be stopped around the world in the next 20 years [1] and more than 10 decommissioning operations are on-going in France. 50 to 60 are expected toward 2025. Bringing new technologies and new solutions into decommissioning methodologies is mandatory to complete our mastery of nuclear-based energy all along its lifecycle and to improve the quality, cost and delay efficiency of these operations, reducing the impact of the decommissioning cost on the electricity price.

Decommissioning a nuclear facility requires the mobilization of an important number of technological equipment and high-skilled workers over long periods of time; the process generates complex flows of information and waste and high inventory levels. The decommissioning of a nuclear facility is a complex process in which a number of different criteria must be simultaneously met: it is compulsory to comply with the safety rules and to protect the operators by designing process which minimize the exposure doses and protect the environment, but it is also necessary to make an effort to minimize the waste volume, cost and delays and maximize the resources use.

If it is currently recognized that early planning is the key to a smooth preparation for decommissioning before the final shutdown and during the transition period [1], the heterogeneity of these criteria and the big volumes of information related to this process make it impossible today to obtain the ideal performance from a nuclear decommissioning process: decommissioning today is not an optimized process. For example, the efficiency of the waste evacuation from a site being dismantled is limited by many factors, such as unexpected waste amounts or ineffective forecasts. It is difficult to achieve a continuous waste flow evacuation, and no forecast tool is used to support planning and decisions. Another limiting factor is the fact that the regulatory framework is circuitous: A delay to obtain one authorization or signature can suddenly stop or delay the dismantling operations by an unknown period of time. The main consequence of these constraints is the fact that the waste flow slows down, the project takes longer and the costs increase. Furthermore, once the facility is fully dismantled, it is not simple to capitalize the lessons learned for optimization future dismantling, all the more so as each nuclear facility is unique.

To better prepare the future decommissioning processes a new method is needed, being capable to treat the huge and heterogeneous amount of data and knowledge associated to a single nuclear installation and exploit this information to model, design, simulate, test and display waste evacuation flows in a nuclear facility in order to clearly identify bottlenecks and capitalize on every operator field experience. This need has been mentioned by many authors, for example [2] who proposes an Integrated Decommissioning Information Management System. However, a good arrangement of the information is not enough to optimize the performance of the waste treatment chains by itself. In our opinion, the best way to achieve this objective is by means of a logistic approach. In fact, nuclear decommissioning could be seen and managed as an industrial process in which the final products are the nuclear waste elements. Thus applying logistic-models and production optimization methods currently used in manufacturing fields should be possible. To date, there is no simulation or optimization tool based of logistic models for decommissioning installations. We can mention the work of [3], who proposed computer systems for planning reactor decommissioning, but did not include logistic-based optimization models.

In this work, we perform a logistic simulation of the nuclear waste flows associated to specific decommissioning process. Preliminary advancements have been presented in [4]. The purpose here was to evaluate the performance of proposed scenario for these operations and to determine where and how improve process performance in term of cost, time and performance indicators. A discrete-event simulation was carried on, which is currently used to support decisions in manufacturing logistics [5]). In these types of simulations, the system is represented only by the points in time in which a change occurs. The simulation jumps in time from one event to the next and the inactive periods (no events) are not accounted, contrary to continuous simulation that requires the collection of information at every point in time [6], [7]. As the system is observed only at selected discrete points, DES presents the flexibility and efficiency necessary to be used over a very wide range of problems. Applied to manufacturing logistic process, DES can help to analyze the production lines, lot sizing, planning, and to support supply-chain decisions [5]. In the case of decommissioning, no scientific work based on DES evaluation has been identified.

The simulations were performed with a model built in FlexSim [8]. This discrete-event simulation (DES) software is capable of making a 3-dimensional simulation environment that helps to make decisions in the design and operation of a system and can model a large variety of systems treating basically three kinds of problems: service, manufacturing and logistic problems, which adapts perfectly to our case. FlexSim is suited to production manufacturing, storage and delivery, transport system and other fields.

By simulating a system with FlexSim, the behavior of an industrial process can be evaluated before its implementation, studied in a shorter time frame and for less cost than with the actual system. Beyond that, this "what-if" tool, is suited to analyze and test different configurations proposed by nuclear main actors, as well as manage storage, delivery, transport system and has been successfully used in varied industrial processes, for example logistics distribution centers [9] or outpatient pharmacy optimization [10]. FlexSim allows testing a process configuration and the interaction between different units concerned. It can help to understand resource requirements, timelines for complex large-scale missions, and the effects of arbitrary events on mission plans.

In this article, we present our early results on the application of DES method to nuclear decommissioning supported by FlexSim. As decommissioning is a very complex process, a single part of the whole process was selected to the simulation: the core dismantling. Simplifications of the problem had to be realized to build the model and be able to represent our process as a manufacturing process adaptable to the FlexSim possibilities.

Based on a core dismantling typical scenario, the performance of this process in terms of capacity of waste storage, treatment, and evacuation has been tested. The critical points and bottlenecks has been identified and used to propose modifications of the scenario proposed in order to obtain an optimal configuration.

II. Simulation Process and Input Data

A. Model

The simulation and modeling was executed with an academic version of FlexSim V.16.0.2, and it followed the typical simulation steps showed in Fig. 1

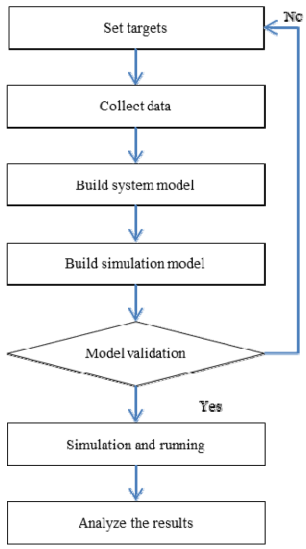

Fig. 1 FLEXSIM modeling and simulation steps [9]

The core dismantling flowchart process simulated is shown in Fig. 2. It concerns the pathway of nuclear waste produced during the core dismantling, from the precutting until evacuation of the site. This flowchart is the basis to the simulation model in FLEXSIM, each nuclear waste unit will be called item, and it is necessary to classify each elements of the process as a source, queue, processor, transport, sink as a function of the actions concerning the item:

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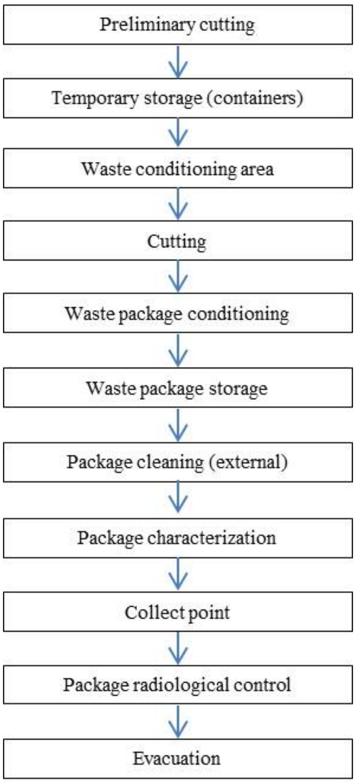

Fig. 2 Flowchart of core dismantling process

Source: Every FLEXSIM model needs at least one source, the source is the provider of items. The source may create the items in different modes, such as according to a schedule or to a statistical law. In our example we chose to use a simple schedule sending around seven items per week.

Sink: Its function consists of destroying the items that are finished in the model. For us, it concerns the evacuation of the site.

Queue: The queues are used to stock the items when the downstream object cannot receive it. The queues will receive the items until it reaches its maximum content. This is an adapted object to represent waiting queues, storages, waiting lists, etc.

Processor: The processors are used to simulate any kind of treatment of an item in the model. Each item that arrives in the processor will spend a certain amount of time in this object, which can be chosen according to a schedule, statistic laws, etc. Finished the process time, the item is sent forward if the downstream object is available. Here we chose constant process times that will be shown hereafter.

Combiners and Separators: are like Processors, except that they may change the quantity of items on the exit: combiners send out one item that was originally two or many, and Separators may split items or separate items that were combined.

Transporter: The transporters are mainly used to transport the items from an object to another. It can also transport many items at a time if needed. We can adjust its speed, capacity, loading and unloading time, for example.

In Fig. 3, the model built in FlexSim from the core dismantling process is represented.

TABLE I
INPUT DATA OF THE MODELS

Parameters	Value
Waste unit mass	50 kg
Number of units per waste package	20
Number of packages available for conditioning	20
Number of pieces produced by cutting	Pieces after cutting = 2*pieces before cutting
Number of pieces produced after pre-cutting	7 pieces produced per week (1 on Mon, 2 on Tue, 1 on Wed, 2 on Thu and 1 on Fri)
Number of transporters	2 (one for waste unit, one for waste package)
Maximal capacity of storage areas:	
Containers	20 items
Conditioning	20 items
Package storage	10 packages
Collect point	10 packages
Process time per operation (hours/item):	
Cutting	4
Package conditioning	48
External cleaning	120
Characterization	240
Radiologic control	100

B. Input Data and Assumptions

The data considered for the simulations are illustrative values that respect typical order of magnitudes of nuclear decommissioning. However, the complexity of nuclear industry means that each nuclear site presents its dimensions and specificities, and so its own values. The input data applied to the model is shown in Table I.

Assumptions:

- For each process, pieces are treated one by one.
- Flows are considered as push-flow: as soon as next step is available, the piece is sent.
- Administrative constraints are not considered
- All pieces are identical
- Operatives' and teams' fluctuations are not considered.
- The source produces items only during the working days, However, the rest of the operations turns 7/7 and 24/24.
- The chain is linear at most part of the process: one process can only receive items from the previous on and it can only send items to the following one.

C. Results and Discussion

Once the model is built, simulation can be performed and one progress of the system as a function of time can be observed. In Fig. 4, we can see an instantaneous capture of simulation, in which nuclear waste pieces ("items" -yellow box) are created, treated, transported and then evacuated.

When the simulation begins, the pre-cutting unit, the "source", starts to generate the items (waste units) at a rate of 7 items par week (determined by us). Items stay at the precutting object while waiting for the availability of the next step (containers), this is due to the push flow hypothesis, valid for all the objects and queues of the chain.

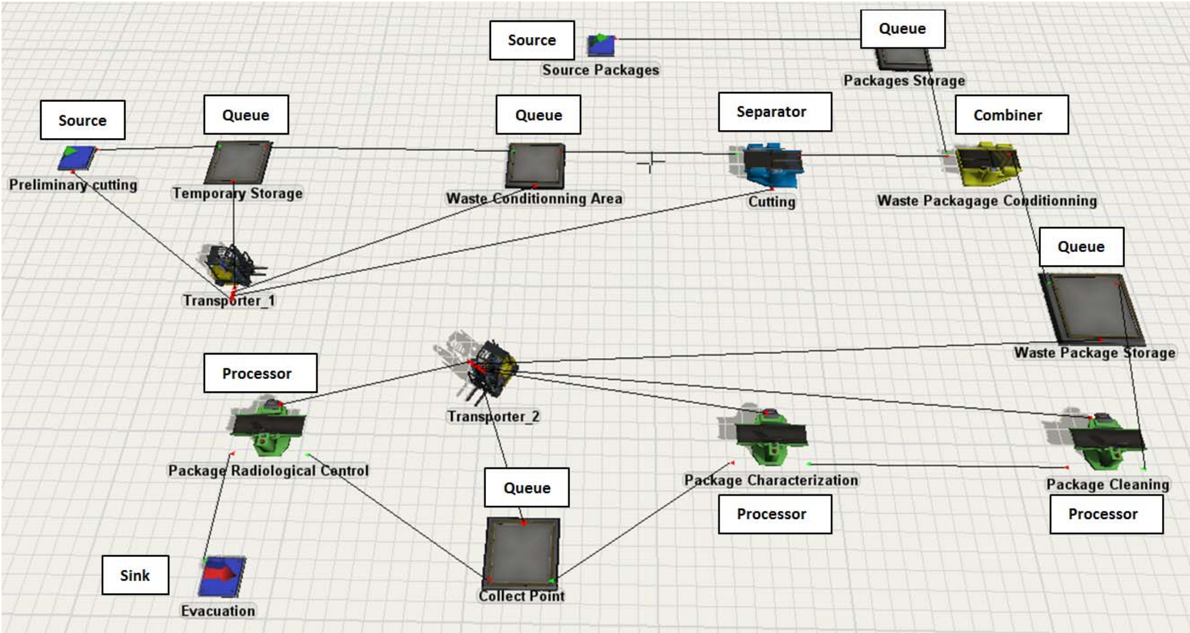

Fig. 3 View of the model in FLEXSIM's interface

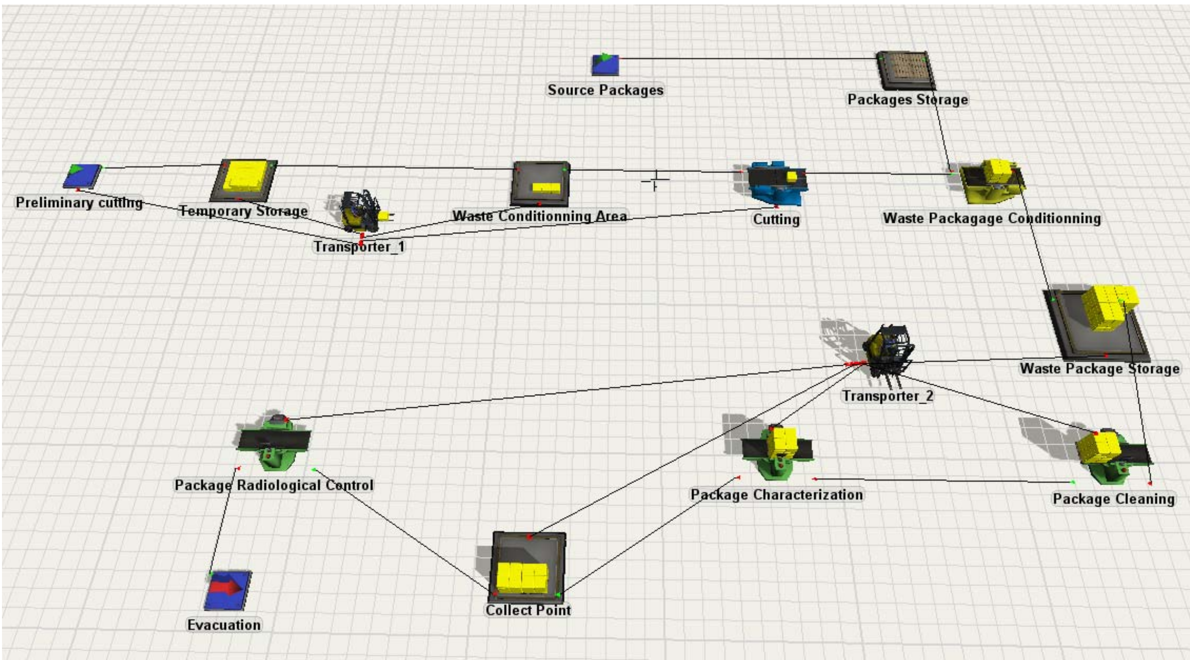

Fig. 4 View of the model in progress

The simulation results allow estimating the total necessary time for the whole dismantling of the core: 7000 hours (almost 10 months). This is the time needed to evacuate all the waste packages from the site. The simulations also give performance indicators that are showed hereafter. These indicators are precious since they give the key points to reorganize the scenario configuration and obtain a more performant process.

First of all, the average content of the queues (all the intermediate storage zones) as displayed on Fig. 5. As the image shows, the waste conditioning area is quite close to its maximum, which may represent a risk as a bottleneck to the process. These first results indicate that the storage capacity of this zone have to be increased in order to deal with unexpected events. Additionally, in Fig. 6 the evolution of the queues is displayed as a function of time. The two first queues, temporary storages and waste conditioning area, after a while are frequently saturated: either with 20 or 19 contents. When temporary storage is saturated it refuses to receive the items already created by the source, blocking the flows. In a real situation, it would mean that the logistic chain is not capable to treat in time the waste stemming from the pre-cutting. On the other hand, the last two queues have never exceeded half of its maximum contents (10 each one), which means they are far from being a bottleneck. These data give a second recommendation to optimize scenario: These storage zones must be compulsory be expanded before complete 1000 hours of operations. It is also possible to track the activity of the two transporters and see how much of the time there were busy (transporting, loading, unloading, etc.) and how much as it idle as figured in Fig. 7.

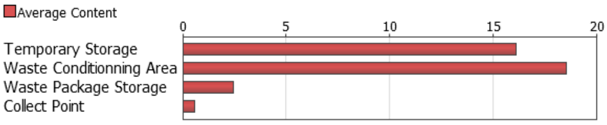

Fig. 5 Average content of the queues during process

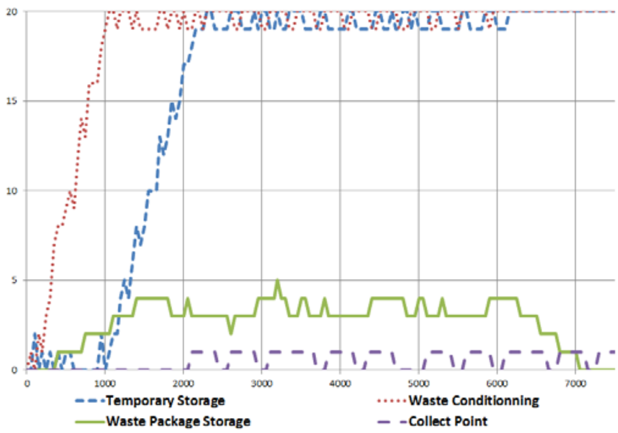

Fig. 6 Content of the queue through time (items per hour)

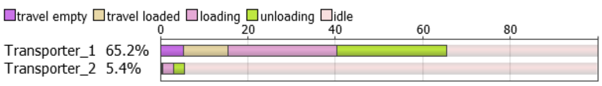

Fig. 7 Proportional distribution of the transporter's states (hours)

We see that at over 90% of the time, the Transporter_2 was idle, while Transporter_1 was in activity nearly 85% of its time. Furthermore, if one considers exclusively the time in activity of each transporter, loading and unloading represent roughly 80% of their activities. As a conclusion, it might be conceivable to optimize the load/unloading task or to provide a second transporter to the first steps. For example, transporter 2 could be considered for operations carried on by 1 (if technical characteristics of 2 are suitable).

It can be concluded from the graphs obtained that concrete and easy-to-apply logistics recommendations can be made from our results in order to optimize the process. However, it is important to mention that considering nuclear industry as a traditional manufacturing industry is valid as a logistical simplification, but it is not strictly accurate since many of the constraints related specifically to nuclear sector must be simplified. One of these factors is the radiological aspects: radiological dosimetry for each operative, monitoring of radioactive contamination of waste item or packages or risks considerations. We can also mention the regulatory framework associated to nuclear industries, which is highly complex and can stop the nuclear flow evacuation. Another factor, among others, is the spatial and geometric restrictions related to risks of nuclear criticism that should be taken into accounted. Nevertheless, FlexSim is versatile software and the model construction possibilities may enable including some of the constraints mentioned before. For example, the limits for intervention time for the employees with respect to radiological doses can be included. We can also consider administrative delays as "black box" processors of specific residence time. It may also be possible to block the flows evacuation if nuclear authorities refuse to receive a nuclear waste and packages cannot be evacuated. On the opposite way, some of the process data required to simulate the environment on FlexSim are not actually collected or measured on decommissioning process. For example, there are not mathematical models to describe the source production rate, statistical data describing the processors operation time, or exact information about transport time between the different units. Consequently, the number of assumptions becomes considerable, which decreases reliability of the results obtained. For future works, all this information could be collected from a decommissioning site and more accurate simulations by means of collaboration research on decommissioning optimization with nuclear major groups.

III. Conclusions

The DES of a typical decommissioning operation has proved the interest of applying this method to nuclear industry, from waste production to waste evacuation. The results showed the interest of making this kind of analysis to identify bottlenecks and saturation zones, and to obtain key parameters performance indicators. The initial decommissioning scenario was tested and the results allowed us to propose improvements. DES tool confirmed to be a useful tool to help to decrease cost and delays associated to decommissioning industry. To achieve a more optimized simulation in future works, new data are necessary from decommissioning process, especially concerning kinematic parameters related to operations, sources and queues.

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