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A logistical simulation tool to quantitatively evaluate the effect of different maintenance solutions on the total maintenance downtime for fusion reactors

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The goal of the DEMO project is to demonstrate that a profitable nuclear fusion power plant is viable. The high level of neutron activation, however, implies time-consuming maintenance processes occurring during the reactor shutdown, which lower the reactor availability and economic viability. As part of the design process, different concepts are continuously proposed and quantitatively evaluated to optimise the plant performance, a key component of which is maintenance duration. One accurate way to quantitatively evaluate and compare different concepts is to simulate the occurrence of the maintenance activities across the time with a logistical simulation tool. This work aims to present the logistical simulation tool, which has been developed within the DEMO project, along with the methodology used to quantitatively evaluate and compare maintenance concepts. We use the self-developed methodology to assess two example concepts. The first one, called Cask Concept, is based on the utilization of vertical maintenance system casks to replace the In-Vessel components. The casks are remote handling containers that are docked on the upper ports of the machine and provide the interface to extract and insert the pieces of hardware without contamination of the area above the upper ports. The second one, called Hot Cell Concept, is based on an overhead crane system situated above the upper ports of the tokamak using the complete area as a Hot Cell. The results show clear and interesting differences between the two concepts and demonstrate the relevance of the developed methodologies to assessing maintenance durations for new or modified plant concepts.

Keywords: DEMO, Logistics, Maintenance, Cask Concept, Hot Cell Concept, Logistical simulation

1. Motivation

The goal of the DEMO project is to build a fusion power plant that is not only able to produce a positive net energy from a technical point of view but also which is economical from a cost point of view. As a result, at this early design stage, it is important to support the system and maintenance design (i.e. maintenance tools, strategies, resources and plant layouts) with a quantitative tool that enables the evaluation and comparison of different maintenance solutions from the logistical point of view. Each maintenance solution includes different aspects, e.g., the plant layout, the maintenance resources, the maintenance processes and the maintenance strategy.

2. Logistical simulation tool

The application of discrete-event simulation is a well-known approach to investigate this class of problems [1], whose goal is to simulate the occurrence of a number of activities over time and to provide an estimate of the total duration.

2.1 Methodology

The simulation methodology is to present the activities in flowcharts, which has the advantage of a simple and intuitive representation of the logical dependencies and process sequencing.

For example, Figure 1 represents how a simple flowchart for the maintenance of a fusion reactor could look like. Between the "Start maintenance" and the "End Maintenance" block there are some blocks representing maintenance activities, also called missions. Possible maintenance missions are:

- Transport hardware and equipment
- Collect/Store equipment
- Dock/Undock equipment
- Extract/Store/Collect/Install hardware
- Operations (e.g. unbolting, connecting pipes and cables, unplug electrical connections, etc.)
- Inspect the hardware
- Etc.

Each mission is characterized by a description (e.g. Open Bioshield), a duration (e.g. 1.40 hours), a list of required resources (e.g. Overhead crane and Bioshield Lifting Tool) and the place where it takes place.

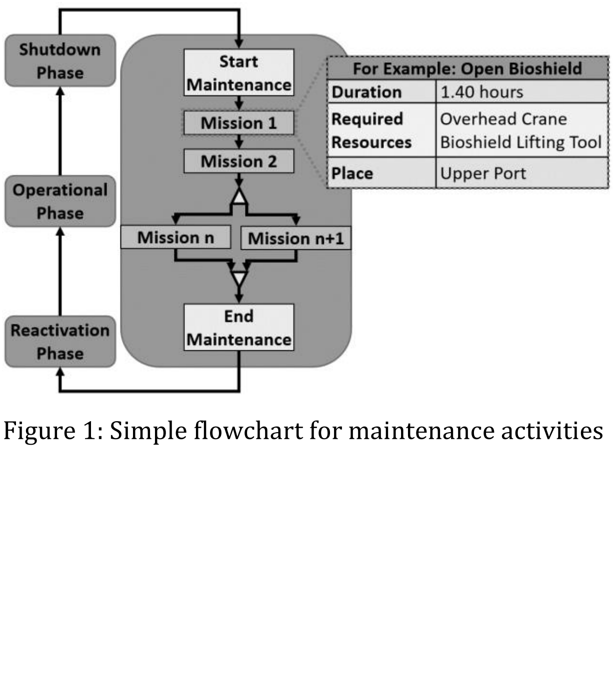

Figure 1: Simple flowchart for maintenance activities

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Different types of resources can be considered in the simulation:

- Transporters and manipulators, responsible for the material handling
- Paths and transfer points, which enable the possibility to model traffic situations
- Remote operators
- Tools
- Etc.

The parallel missions, for example missions carried out for the maintenance of different reactor ports, concur for the resources, which are available in a limited amount, namely that it can happen that a mission cannot start due to the temporary lack of a particular resource. For example, if it requires an overhead crane, which is temporally used by another mission.

Moreover, since there are many high-risk activities to be performed in the current designed of the DEMO power plant, the simulation model allows to include failure scenarios in each mission. A failure scenario is characterized by an occurrence probability which defines how often it is triggered once the mission is started.

Any change in the plant design (e.g. a different number of cranes, use of a different transportation system, different layout, etc.) implies some changes in the corresponding activity flowchart. As a result, it is possible to simulate both the old design and the changed one and to find out which one implies the lowest overall maintenance time.

2.2 Input information

To perform a simulation, a big amount of input information regarding the maintenance solution is required. The main pieces of input information are represented in Figure 2 and are:

- Plant layout
- Duration of missions
- Available equipment
- Maintenance strategy
- Failure Scenarios

This missing information must be then be replaced by assumptions, and the corresponding flowchart must be created. Afterwards, the simulation is ready to be performed with the logistical tool.

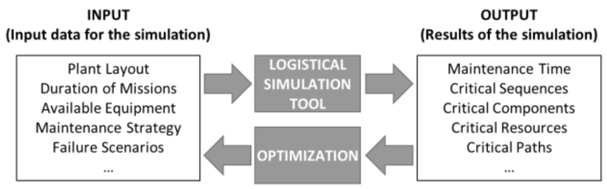

Figure 2: Input/output structure and optimization loop

2.3 Output structure and optimization

The logistical simulation tool returns the total maintenance time along with other useful results. The most important ones are represented in Figure 2 and are:

- Critical sequences
- Critical components
- Critical resources
- Critical paths

All those indicators define where the maintenance solution could be further improved. On the basis of this new information, the maintenance solution can be modified, and new simulations can be iteratively started with new maintenance solutions.

3. Concepts presentation

The DEMO tokamak includes three different levels where maintenance port allow access to the inside of the vacuum vessel. The upper port, lower port (divertor port) and the equatorial port. Each port allows different aspects of the plant to be maintained.

Maintenance operations must be considered for every port separately but also the impact of the maintenance process of one port on the other port has to be considered.

The aim is to use the logistical simulation tools (developed in [2]) to model and investigate the remote operations occurring during the reactor maintenance to replace a set of pieces of hardware of the reactor in DEMO.

In this paper, we use the developed logistical simulation tool to assess two example concepts for the maintenance process of the upper ports. The first one, called Cask Concept, is based on the utilization of vertical maintenance system casks to replace the In-Vessel components. The casks are remote handling containers that are docked on the upper ports of the machine and provide the interface to extract and insert the pieces of hardware. The second one, called Hot Cell Concept, is based on an overhead crane system build inside a Hot Cell above the upper ports of the machine. In the following sections, the two concepts are explained more in detail.

In this chapter the two concepts to be compared, Cask Concept and Hot Cell Concept for the upper port, are introduced. Finally, the results of the simulation runs are presented and commented

3.1 Cask Concept

For what concerns the reactor hardware handling in the cask concept, three main devices are involved in the hardware extraction or insertion through the upper port (see Figure 3):

- The Vertical Maintenance System cask (VMS-cask), which is docked on the upper port and contains a sliding vertical system that can lift or lower the reactor hardware to be replaced and transfer the maintenance equipment down through the upper port to perform In-Vessel remote maintenance.

- The hardware cask, where the lifted and contaminated hardware is laid down during the extraction process or from where the new hardware is taken during the insertion process.
- The equipment cask, from where the required maintenance equipment and tools are handed over to the VMS cask and where, once the maintenance equipment is no more needed, it is given back and stored inside the equipment cask.

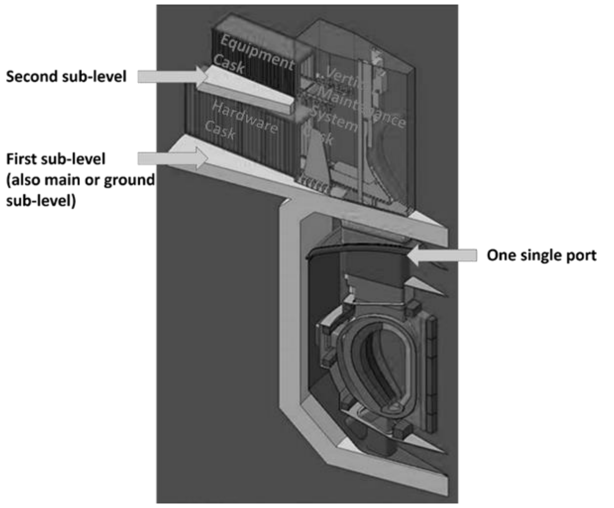

Figure 3: Representation of the cask concept during the lifting of one blanket [3]

While the VMS cask can just be moved by a crane in the reactor building, the equipment and hardware casks are considered to be casks with an integrated generic motive power undercarriage, namely that they can move (and navigate) autonomously in the DEMO facility, for instance, from their storage area (i.e. the Active Maintenance Facility (AMF)) to the reactor building and to the port where needed.

3.2 Hot Cell Concept

The Hot Cell Concept implies to have a hot cell above the tokamak that includes all the upper ports and some additional corridors that connects the reactor building to the DEMO facility. The lead option for the transportation of hardware and remote maintenance equipment into and around the hot cell is a single overhead rail system (see Figure 4) where several overhead cranes can operate at the same time.

This handling and transport systems in the upper port is as modular as possible. The maintenance process is carried out with overhead cranes on which different lifting attachments or the required maintenance equipment and tools can be attached. Once the maintenance equipment is no longer needed, it is released and stored in the correspondent warehouse and a different tool is collected and attached.

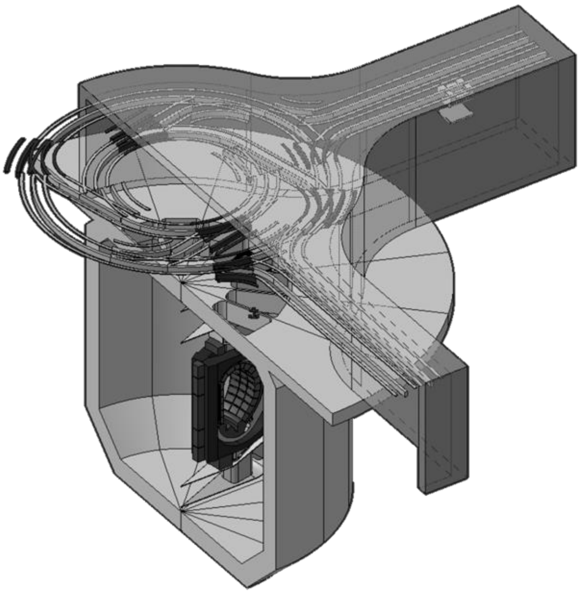

Figure 4: Top view and generic view of the Hot Cell Overhead Rail System [4]

Other transportation systems are still considered but only this lead option has been taken into account in the comparison presented in this paper.

3.3 Available data structure

This chapter presents some of the available maintenance information, which were used to feed the logistical simulation model.

- Facility characteristics (plant layout, number of reactor ports, number of access levels to the reactor, number of components to be replaced, etc.)
- Maintenance resources (number of available maintenance tools, number of automated guided vehicles, number of cranes, number of casks (VMS, hardware casks, equipment casks), etc.)
- Maintenance processes (list and sequence of the missions to be carried out, required resources and time for each mission, possible mission failure modes, etc.)
- Maintenance strategy (mission parallelization, etc.)
- Assumptions need to be made for unavailable data

The simulation model is able to take all the available information as an input to simulate the correspondent material flow and to return an estimation of the correspondent reactor downtime.

The simulation is performed in AnyLogic [6], which is a discrete-event simulation software based on Java Code and able to autonomously read and import the information contained in Excel spreadsheets.

3.4 Results and comparisons

In this chapter, the results of the performed simulation tests are described and compared. For more details about the performed simulation refer to the report “Perform simulation tests/ scenarios for the upper port” [5].

The aim of this simulation to get an answer which concept performs better. Four different mission sequences for each concept (Hot Cell and Cask Concept) are considered, which means 8 different mission sequence topologies.

The following four different mission sequences were considered:

- No Failures No Parallelization
- No Failures With Parallelization
- With Failures No Parallelization
- With Failures with Parallelization

The aim of this simulation was to find the absolute minimum and maximum value for the maintenance time. The “X” value represents the variable which is changed between one run and the next run. Starting with one resource (just one port can be maintained) and increasing by one up to eight (eight ports can be maintained simultaneously). All resources were always increased by one.

The results are depicted in the following table.

Table 1 Results of the performed simulation runs

X	1	2	3	4	5	6	7	8
Hot Cell - total maintenance time NoFailureNoParallelization [d]	431	215	161	108	108	81	81	54
Hot Cell - total maintenance time NoFailureWithParallelization [d]	431	215	159	108	105	78	78	54
Cask - total maintenance time NoFailureNoParallelization [d]	479	240	180	120	120	90	90	60
Cask - total maintenance time NoFailureWithParallelization [d]	440	220	162	110	107	80	79	55
Hot Cell - total maintenance time WithFailureNoParallelization [d]	536	272	191	143	127	103	97	79
Hot Cell - total maintenance time WithFailureWithParallelization [d]	532	269	184	141	117	98	86	77
Cask - total maintenance time WithFailureNoParallelization [d]	623	314	216	164	143	118	112	90
Cask - total maintenance time WithFailureWithParallelization [d]	522	270	186	141	126	104	96	80

The most important obtained results can be explained as follows:

- The maintenance time is decreasing with increasing number of resources.
- The parallelization of missions reduces the maintenance time for both concepts.
- Failure scenarios extend the maintenance time dramatically, for the Hot Cell Concept the maintenance time is increased up to 25 % and for the Cask concept even up to 30 %.
- The Hot Cell concept has overall slightly lower maintenance times than the Cask concept
- Resources are more interdependent than expected. Increasing one resource (which is currently the bottleneck) will turn another resource into a bottleneck.

However, it is important to notice that the considered modelling of the maintenance process is based on a set of assumptions, which may have an influence on the results and on the conclusions when they will be replaced by actual data.

Furthermore, it has to be kept in mind that the achieved results are just valid for the herein used input data and assumptions and may differ greatly from the results obtained here if other input data is used.

4. Conclusions and outlook

In this paper the maintenance process for the Hot Cell and the Cask Concept have been simulated via a discrete logistical simulation tool. The main focus was on the maintenance time of the two concepts. With the help of the simulation results it was possible to compare the two different concepts. The current results have shown, that the Hot Cell Concept performs better than the Cask Concept. But much more actual data and much more simulation runs are necessary to be performed to confirm or rebut this statement definitively.

Further extensions of the logistical simulation model are also planned for the future. On the other hand, it is planned to consider in detail the effect of activity planning strategies on the total maintenance time. On the other hand, to extend the type of decisions not only to the activities to be started but also to the tool choice and to the routing.

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