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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT
Remote handling operations during a shutdown of a fusion plant like JET or ITER are executed according to formally described and validated procedures. Unexpected events during the execution of the procedure may require rescheduling, suspending the execution of the current procedure to pick it up later. In this paper, we investigate whether the introduction of a certain amount of slack influences the robustness of the overall shutdown schedule. First we introduce a classification for different types of anomalies that may occur during execution of operations. We introduce a set of metrics to measure the robustness of a remote maintenance schedule against various types of disruption. We then simulate the occurrence of disruptions in a set of procedures, and evaluate the effect on the overall schedule. Finally, it is shown how the robustness of a shutdown schedule is affected by introducing different amounts of slack.

1. INTRODUCTION
The Maintenance procedures in fusion plants like JET or ITER can when suspended either continue to block access to reserved tooling, or temporarily release the reserved tools for use in another task. Depending on the way this is done, the rescheduling may in turn influence subsequent procedures, and hence affect the effectiveness of the maintenance schedule for the entire shutdown period.

1.1. A TYPICAL SHUTDOWN
In the typical overall ITER shutdown Remote Handling (RH) maintenance planning, maintenance activities take place in several parallel “operating theatres”, such as various work stations in the ITER Hot Cell Facility, the Neutral Beam Hot Cell, in port cells and inside the Tokamak. Transportation inside the Hot Cell facility typically takes place with the large overhead transport crane and smaller trolleys, which may become scarce resources. Transport between the Tokamak building and the Hot Cell facility take place with the Cask and Plug Remote Handling System (CPRHS). The CPRHS does not provide serious (lead wall type) radiation protection around its contents, hence Transfers between Tokamak and hot cell will only take place at night. This outs a severe boundary condition on the availability of the CPRHS, and relatively benign delays may already induce a more massive delays when an allocated transport slot is missed.

Other scarce resources are task specific tools like hoisting frames and tools related to weld preparation, welding and post weld inspection. Furthermore, the availability of skilled, trained and certified staff and personnel related resources have to be taken into account, fitting it all in a schedule containing typically around 500 task sequences, divided into up to eight different workflows.

For the remainder of this paper, we will try and focus on the RH maintenance activities that take place in RH workstation inside the ITER Hot Cell Facility during a typical ITER shutdown period. As the planning documents available at the moment on a task execution level have the overhead crane as the primary scarce resource, only this resource has been taken into consideration.

1.2. UNCERTAINTY IN PLANNING EXECUTION

Uncertainty in maintenance in ITER is found by looking at task execution in JET, such as the installation of the ITER-like beryllium sliced wall, with its encountered challenges described in [1, 2]. In [7], four categories are presented for classifying uncertainty. These are:

A: a changing environment, such as an increase radiation levels,
B: actuator imprecision, for example imprecise master/slave communication or operator imprecisions,
C: output uncertainties, which could be failing to measure or predict system output correctly, and
D: feasibility uncertainties

Mapping the common anomalies with the type classification summarizes sources of delays to:

- Reading, absorbing & understanding the operational procedures (type B, actuator imprecision), where also a large variance within but also between operators becomes apparent
- Orientation of camera view (type B, actuator imprecision)
- Operational process failures (type B, actuator imprecision), such as a wrongly prepared tool carrier, using the wrong key to fasten bolts
- A changed environment (type A, a changing environment), for example a nut which was unexpectedly loose
- Constrained RH feasibility (type D, feasibility)

1.3. DIFFERENCES BETWEEN JET RH TASK PLANNING AND EXECUTION

For the Iter-Like Wall (ILW), JET prepared a standard task sequence for installing one tile of the ILW. Part of the action is performed by the large boom transporter, other tasks are performed by means of the dexterous Mascot manipulator. In [2], actual execution times for Mascot moves were measured, which are presented in table 1. Comparing execution times with planned duration yields similar results as in [1], an underestimation of task durations.

2. DIFFERENCES BETWEEN JET AND ITER MAINTENANCE

For JET, the low mean time to repair was achievable since the RH system could be extracted in a short period of time to a location that it could be worked on manually [1]. In ITER, the equipment itself becomes considerably more contaminated and as such, manual work is not feasible unless it is decontaminated first.

In JET, little parallel work is foreseen. With the increasing RH work demand in ITER, planning gets more complex and as such more prone to uncertainty. A more complex planning also exhibits larger interdependency. Because of these two factors, robustness becomes increasingly important.

3. HOT CELL OPERATIONS DURING A TYPICAL ITER SHUTDOWN

In ITER, an 8 month shutdown is planned in every 24 month period. Over the entire ITER lifetime, four shutdown periods are planned for maintenance on TBM, diagnostic port plugs and heating port plugs (4). This paper focuses on the diagnostic and heating port plugs only.

In one shutdown period, on average, 5 equatorial and 5 diagnostic port plugs of RH class 3 are to be maintained. The shutdown period also includes 2 equatorial heating plugs, 1 equatorial ECRH and 4 upper port ECRH plugs, plus another 2 class 1 equatorial diagnostic plugs. This means that on average 10 equatorial and 9 upper port plugs are to be maintained in one shutdown. With an average of month per plug (5], the 4 months available for plug maintenance calls for the availability of two parallel remote handling work cells. Based on this, a representative sample scenario was drafted, as shown in table 2.

3.1. TOOL USAGE

Tool usage and maintenance duration was extracted from the respective Task Definition Forms (TDF). A sample time slice out of this planning can be seen at figure 1.

4. MEASURING ROBUSTNESS

When rating a schedule for robustness, the following task properties are taken into account for this paper: end time (denoted as t_{end}) and duration (denoted as $t_{duration}$). Based on this the following two metrics for measuring robustness were used: *fluidity* and *disruptibility.*

4.1. FLUIDITY

The temporal flexibility between tasks indicates the fluidity of the tasks: the ability for them to absorb temporal deviations with respect to tasks in its own work cell. See algorithm 1.

Algorithm 1 fluidity

$$fluidity = \frac{\sum t_{duration}}{\max t_{end}} \tag{1}$$

This metric divides the sum of used time by the end time of the last task. The difference between these can be used to absorb disruptions. It results in a number between 0 and 1, with 1 meaning no fluidity and 0 meaning maximum fluidity.

4.2. DISRUPTIBILITY

On delay, as few tasks as possible should be affected. See algorithm 2.

Algorithm 2 disruptibility

$$disruptibility = \frac{delayedTasks}{totalTasks} \tag{2}$$

This gives a fraction of disrupted tasks in comparison with the total amount of tasks, a number between 0 and 1, with 0 meaning no disrupted tasks and 1 meaning all tasks disrupted.

4.3. EVALUATING ITER PLANNING ROBUSTNESS

For evaluating robustness, a Monte Carlo method was selected to simulate ITER schedule. The average robustness figures of 500 executions of the sample planning was taken. These sample plannings were disrupted a total of 5 times, in a way comparable to delays that were encountered in JET. The delays were capped at the first and third quartile in table 1. The results of this evaluation can be found in table 3.

The first row marked with *initial* contains the schedule with no slack. All other rows are the same schedule, but with for each task a certain percentage of the task duration taken as slack. The duration and delayed duration columns state the total time for schedule execution and the total time taken when the schedule was delayed. Fluidity and disruptibility contain the metrics as described in section 4.

4.4. EFFECTS OF DISRUPTION

A small change in slack has a large effect on disruptibility of a schedule. The delayed tasks in total disrupt on average 693 of the planned tasks when no slack is used. Just 66 minutes of total delay is encountered, however, indicating that the effect on the overall shutdown schedule is minimal. If merely 13 slack is inserted, the predictability of a schedule rises considerably, disrupting just under 173 of tasks when a series of delays of the order described in section 1.3 is encountered.

4.5. RELIABILITY OF PLANNING

If reliability of the schedule is considered important, this should be a strong indication that inserting slack to become more robust against delays is to be executed. This would be the case in maintenance planning, as more personnel and scarce resources are included in executing this planning.

5. DISCUSSION

A more complete picture of the planning could be sketched if this paper is extrapolated to ITER shutdown level, including:

- Multiple operating theatres
- More serial operations: Cool down, port cell preparations before plug can be removed, cleaning and inspection before HCF operations take place, testing transport and installation afterwards
- Taking into account the limited amount of properly trained, qualified and certified staff
- More limiting resources: CPRHS, port cell access constraints, number of RH master stations, generic tooling to be used in parallel in several theatres. The scarce resources in ITER are larger than merely the overhead crane, which was the primary blocking resource in our investigation.

6. CONCLUSIONS

6.1. FRAMEWORK FOR EVALUATING ROBUSTNESS

A framework for evaluating the robustness of ITER remote maintenance schedules has been proposed. Two metrics, namely fluidity and disruptibility, summarize the main factors for robustness. However, as more is learned regarding the nature of delays, other parameters could be integrated in this method.

6.2. PLANNING ESTIMATIONS

If planning is underestimated structurally (e.g. by basing duration expectations on the performance of the best operator), adding slack is of little use. Instead, schedules should be designed for an operator with average performance, and some additional slack should be added afterwards to increase robustness.

6.3. SCHEDULE PREDICTABILITY

Using the framework, it was shown that at the level of RH workstations in the ITER Hot Cell Facility the introduction of slack can help to improve the schedules' robustness. Adding just a small amount of slack affects preditability of the schedule under disruptions considerably. However, this effect is marginal on the overall shutdown schedule, especially as only few scarce resources have been accounted for. The finding of robustness requirements can be used as an incentive to include slack in actual RH schedules. The amount of slack should be in the order of magnitude of expected delays in the schedule, which in ITER can be based on JET data.

6.4. UNCERTAINTY SOURCES

It was found that the most common sources of anomalies are caused by actuator imprecision, both from operator imprecisions and equipment inaccuracies. This cause could partly be mitigated by having more operators have the same level of skill. Training of operators would have a large effect on robustness of execution. Using other measures such *as* helping operators with artificial views or shared control could also have a positive effect on schedule execution predictability.

7. RECOMMENDATIONS

7.1. ENABLE BETTER LEARNING

Comparing schedules with planning execution in JET is challenging since not all operations were time logged with sufficient accuracy and resolution for our benchmarking and simulation purpose. To create a better picture and to better enable learning from past experiences, analyzing video-data of JET maintenance would help. To improve learning from future maintenance, a better system for logging should be implemented, possibly automated scene analysis and automatic action level progress logging.

7.2. EXTRAPOLATING PLANNING RESEARCH

An interesting point of research would then also be how the quality of schedules quality and robustness improves when adding additional resources. For this, investigating which resources or tasks cause the schedules to require much slack to be workable can point to how improvement of schedules' performance can take place.

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REFERENCES

[1]. S. Collins, et al., Factors affecting remote handling productivity during installation of the ITER-like wall at JET, Fusion Eng. Des. (2013), http://dx.doi.org/10.1016/j.fusengdes.2013.02.117

[2]. H. Boessenkool, J. Thomas, C. J. M. Heemskerk, M. R. de Baar, M. Steinbuch, and D. a. Abbink, "Task analysis of human-in-the-loop tele-operated maintenance: What can be learned from JET?," Fusion Engineering and Design, Vol. **89**, No. 9–10, pp. 2283–2288, Oct. 2014.

[3]. Stephen F. Smith [2004], Generating Robust Schedules through Temporal Flexibility, AAAI.

[4]. Didier van Houtte [2009], Impact of the Hot Cell Facility on ITER machine availability, IDM 2MNKN4

[5]. A.Tesini [2008], ITER Maintenance Operations Time Estimate, IDM 2F6XE5

(6]. TO40 ITER RH Supervisory Control System – Design Support [2013]

[7]. Hans-Georg Beyer, Bernhard Sendhoff (2007), Robust optimization – A comprehensive survey, Computer Methods in Applied Mechanics and Engineering, Volume **196**, Issues 33–34, Pages 3190–3218.

Planned duration (min)	Mean duration	Stddev	1st quartile	Median	3rd quartile
18	25.52	13.80068	16	21	29.5

Table 1: execution evaluation.

# per shutdown	procedure
1	Lower steering mirror replacement
1	Upper steering mirror replacement
1	Upper port mirror exchange
1	Waveguide steering mirror replacement
2	Generic Upper Port Plug (GUPP) M2 replacement
3	GUPP Diagnostic Shield Module (DSM) M3 replacement
3	Injection mirror
2	Focus mirror
1	Equatorial Launcher Blanket Shield Module
7	Generic Equatorial Port Plug DSM

Table 2: Sample scenario.

	Duration (min)	Delayed duration (min)	Fluidity	Disruptibility
Initial	19007	19073,61	0,835762	0,685844
Slack 1%	19194	19219,54	0,829283	0,165195
Slack 2%	19381	19397,35	0,82163	0,086182
Slack 5%	19942	19943,46	0,799039	0,029948
Slack 8%	20503	20503,46	0,777261	0,012961

Table 3: robustness evaluation.

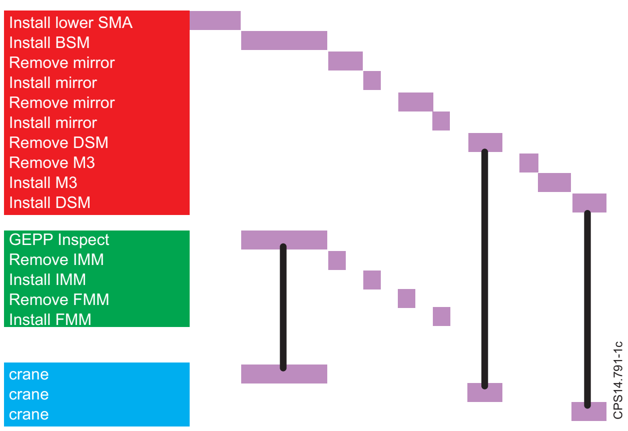

Figure 1: sample time slice of planned schedule, showing tasks two workcells (orange and green; top two) and their usage of the most scarce resource (blue; bottom).