UK Atomic Energy Authority

UKAEA-RACE-PR(20)01

Nikola Petkov, Huapeng Wu, Roger Powell

Cost-benefit analysis of Condition Monitoring on DEMO Remote Maintenance System

Cost-benefit analysis of Condition Monitoring on DEMO Remote Maintenance System

Nikola Petkov, Huapeng Wu, Roger Powell

This is a preprint of a paper submitted for publication in
Fusion Engineering and Design

Fusion Engineering and Design 160 (2020) 112022

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Cost-benefit analysis of condition monitoring on DEMO remote maintenance system☆

Nikola Petkov [a,b,*], Huapeng Wu [b], Roger Powell [a]

[a] RACE, UKAEA, Culham Science Centre, Oxfordshire, United Kingdom
[b] LUT University, Lappeenranta, Lahti, Finland

ARTICLE INFO

Keywords:
Condition monitoring
Cost-benefit
DEMO RMS
Fusion

ABSTRACT

The DEMO remote maintenance system (RMS) will have a significant role in keeping the power plant operational, and therefore, would have a large impact on its economic feasibility. The identification of impending mechanical failures of the RMS equipment during active maintenance operations is crucial if unscheduled and or unplanned recovery and rescue operations are to be avoided. The purpose of this research is to provide cost-benefit analysis and assessment of the effectiveness of the condition monitoring system (CMS) at reducing costs as well as improving the reliability of DEMO RMS. The research is also steering the CMS design requirements from a performance perspective. It is focused on the blanket transporter (BT), which is a critical component for conducting maintenance operations on DEMO. The results show that the CMS repayment could happen after 1 maintenance mission period and describe the other major benefits that are not easily quantifiable into common metric. The main assumption for this research is that by increasing the detection of a failure mode, the likelihood of the failure mode happening will decrease, and hence it will result in savings in availability and downtime.

1. Introduction

The remote maintenance system (RMS) of a future fusion power plant will have a significant role in keeping the power plant operational, and therefore, would have a large impact on its economic feasibility. A remote maintenance system will comprise a wide range of different types of robotic system, which will be tasked to carry out maintenance operations in hazardous environments around and inside the fusion reactor. The extreme environment is expected to cause the condition of the maintenance equipment to gradually deteriorate over time. As a result of the worsening condition of the equipment, the likelihood of failure will increase and if preventative action is not taken fusion plant down-time will be prolonged, leading to lower availability and reduced economic performance of the actual fusion power plant. The equipment's end of life (EOL) is defined as the moment a particular piece of equipment is no longer safe to use. Remaining useful life (RUL) is the length of time a machine is likely to operate before it requires repair or replacement. Having the ability to monitor the equipment's condition over time can provide valuable information about the deterioration state of the equipment and aid in the estimation of its expected EOL. By knowing the equipment's RUL in real time, it becomes possible to mitigate the occurrence of the failure modes before they happen, especially during active maintenance mission operations, and reduce unexpected downtime caused by unplanned equipment recovery operations. A dedicated CMS should make the health of the RMS transparent and visible, allowing predictive maintenance tasks of its equipment to be scheduled according to the actual needs, while at the same time mitigating unplanned equipment failures.

2. Condition monitoring on DEMO RMS

The demonstration power station (DEMO) is an ambitious project for the design and build of the world's first fusion power plant capable of generating 300 to 500 Megawatt net electricity to the grid, with Q ≥10 (ITER). [1].

The remote maintenance system of DEMO (DEMO RMS) will be

☆ This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom Research and Training Programme 2014–2018 and 2019–2020 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

* Corresponding author at: RACE, UKAEA, Culham Science Centre, Oxfordshire, United Kingdom.
E-mail address: nikola.petkov@ukaea.uk (N. Petkov).

https://doi.org/10.1016/j.fusengdes.2020.112022
Received 12 June 2020; Received in revised form 29 August 2020; Accepted 16 September 2020
Available online 17 October 2020

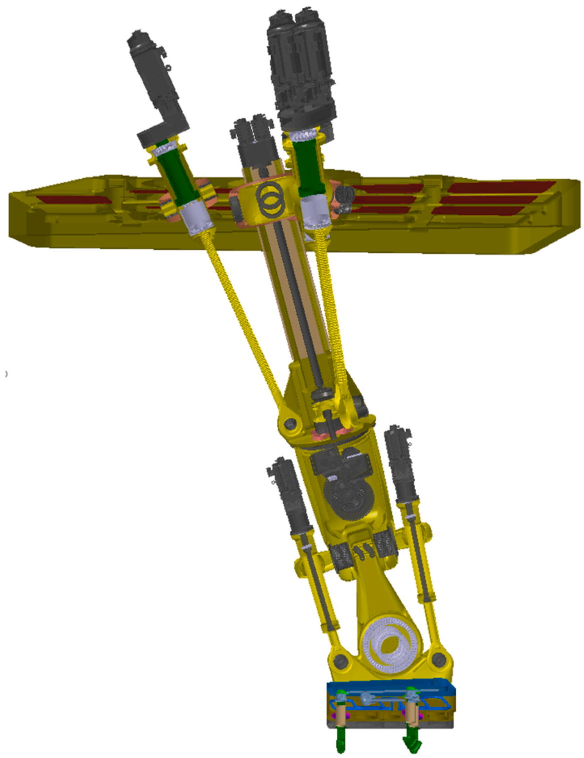

Fig. 1. DEMO RMS blanket transporter concept (approx 10 m high).

responsible for all of the maintenance operations of the DEMO fusion reactor.

In order for the availability goals of the DEMO power plant to be achieved, the DEMO RMS will need to have at least 4 identical systems running operations in parallel during a maintenance mission [2]. The estimated cost of the downtime for DEMO is close to 3M €/day. It means that a maintenance mission being finished a day sooner or later could have a highly positive or negative impact on the overall economic performance of the power plant [2].

The identification of impending mechanical failures of the RMS equipment during active maintenance operations is crucial if unscheduled and or unplanned recovery and rescue operations are to be avoided. The unscheduled recovery and rescue operations could happen both as a result of the failed RMS equipment compounded by any additional cascading failures caused by the initial recovery or rescue [3]. Having the ability for correct and reliable assessment of the condition of the RMS equipment, could help prevent unscheduled maintenance operations and increase the overall system reliability and availability. By monitoring the underlying deterioration processes of the equipment, the periodic maintenance interval of the RMS equipment could be also optimized, so that the expected maintenance is carried out only when it is actually needed.

CMS represents a system whose primary objective is to give an early warning of any impending equipment failure by monitoring the underlying condition of the equipment. The main principles of the CMS are to ensure early detection, identification and prognostics of equipment failures in order to leave enough time for mitigation actions to be taken. The main goal of this research is to assess the theoretical effectiveness of the CMS at reducing costs as well as improving the reliability of DEMO RMS. The research is also steering the CMS design requirements from a performance perspective. It is focused on the blanket transporter (BT), which is a critical component for conducting maintenance operations Fig. 1, [4,5]. A reliability model has been created according to the maintenance concept of DEMO RMS with 4 BTs working in parallel. The data used in the reliability model is taken from the Design Failure Mode Effect and Criticality Analysis (DFMECA) [6] of the BT concept design.

The cost benefit analysis (CBA) in this research is based on the availability estimated by the Discrete Event Simulation (DES) of the created reliability model. In order to simulate how the condition monitoring (CM) performance could effect the availability and the downtime of the system overall, a sensitivity analysis is performed on the reliability model to the Occurrence Ratings of the failure modes

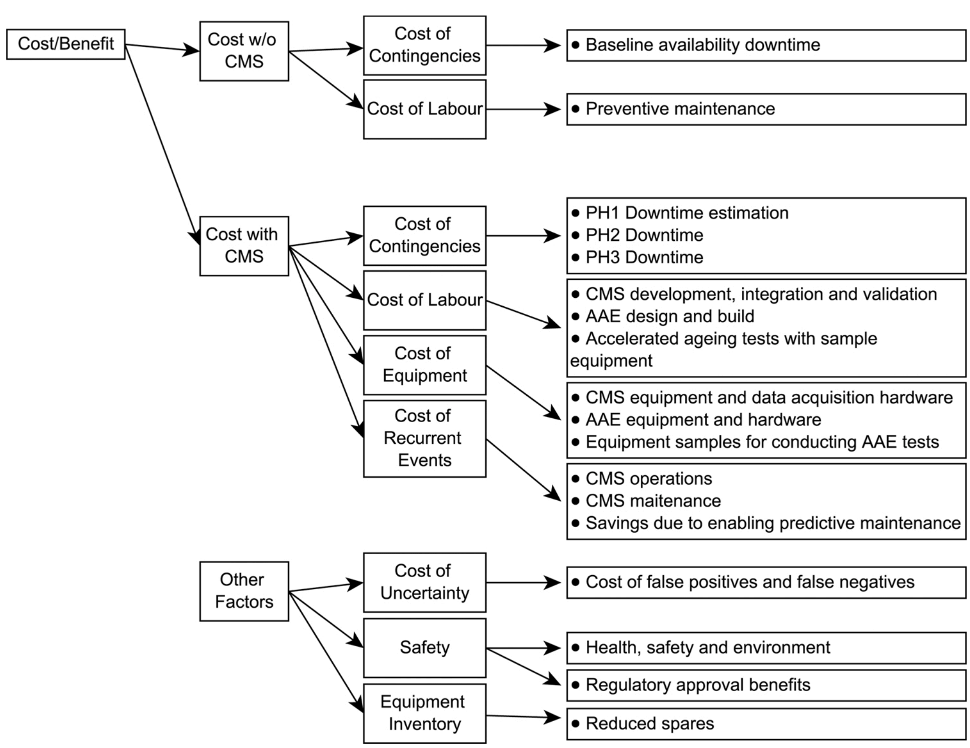

Fig. 2. CBA model and factors considered.

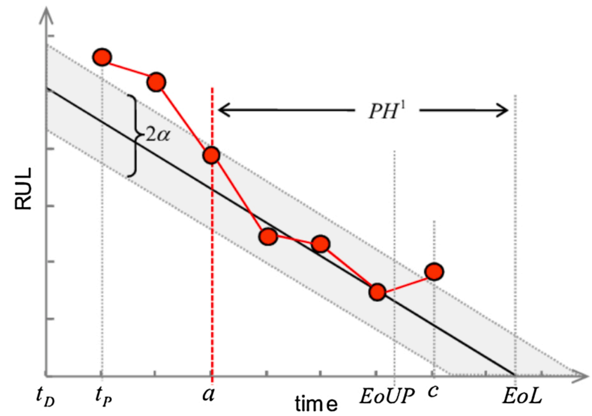

Fig. 3. Prognostic horizon illustration [9].

where CM could be reasonably applied.

The methodology used for estimating the possible economic benefit compared to the cost, and assessment of safety and reliability benefits is described in Sections 3 and 4. The result of the research and the discussion is given in Section 5. Fig. 2 represents the cost-benefit model considered in this research.

3. Cost-benefit analysis methodology

Cost benefit analysis (CBA) is a systematic technique used to compare the costs and benefits of a project using a single common metric. In the industries with a critical downtime cost (oil and gas, nuclear, fusion, etc.), CBA is mainly used for comparing a cost of investment against the benefits of reduced equipment downtime [7].

$$Cb_{net} = \begin{array}{l}(Cost_{CMS} - Cost_{noCMS}) \\ -(\text{Benefit}_{\text{CMS}} - \text{Benefit}_{\text{no CMS}})\end{array} \quad (1)$$

The cost benefit analysis carried out in this research estimates the economic impact of applying condition monitoring on DEMO RMS [8].

It covers the case where 4 separate RMS are used in parallel for maintenance missions operations. Throughout the planned life-cycle of DEMO RMS, it is expected that it is going to be used on 2 to 3 planned maintenance missions [2]. This does not cover the case for any unplanned maintenance operations or if the DEMO power plant gets to be used beyond its planned life-cycle. Therefore, the CBA in this research covers a period of 10 maintenance mission durations.

Factors used as inputs in the CBA:

- Cost of contingencies of DEMO RMS maintenance operations.
- Cost of hardware and equipment needed for the CMS.
- Cost of labour to design, build operate and maintain the CMS.
- Recurring mission costs.

Factors that were not used in the CBA:

- Benefits due to system safety increase.
- Benefits towards receiving regulatory approval.
- Savings due to reduced RMS equipment inventory.
- Initial wear downtime reduction.
- Cost of uncertainty of the CMS estimates.

3.1. Assumptions

The impact that the CMS will have on the overall costs of running the DEMO RMS is not easily quantifiable. For the purpose of this research, the contingency benefits are modelled as downtime reduction caused by the increase of availability on DEMO RMS. The term "detection" of a failure mode is defined as the numerical estimate of the effectiveness of the controls to prevent, detect or numerically quantify the cause of a failure mode before the failure occurred. For the purpose of our research we consider the length of the PH to be equivalent to the effectiveness of the detection of a failure mode.

The CMS could provide transparent knowledge of the equipment's health and estimate its RUL in near real time, therefore increasing the detection level of the applicable failure modes and reducing the likelihood of equipment failure during maintenance operations. The Prognostic Horizon (PH) is a performance measure for condition monitoring defined as the difference between the time index t_a when the EOL estimation starts converging inside boundaries of 2α and the time index t_E for the event E when EOL occurs (Fig. 3).

$$\text{PH} = t_E - t_a \quad (2)$$

PH in general, means how much time in advance can the CMS inform about equipment's EOL with known uncertainty.

If we achieve long PH lengths that are, in theory, larger or equal to a single maintenance mission duration, means that we will be able to estimate the EOL of the equipment with known and constrained uncertainty right from the mission start.

It also means that a large PH, combined with an ability to (we assume always) take a corrective actions or do a predictive maintenance before any failures occur theoretically eliminates the possibility of failure of the applicable equipment during maintenance operations.

Increasing the level of the PH may only be possible with greater investment in the CMS. Finding the highest value for the PH that will maximize the benefits compared to the costs of so doing is one of the goals of this research.

For the purpose of calculating the sensitivity of the availability to the prognostic horizon, PH0, PH1, PH2 and PH3 represent the theoretical detection increase of 0, 1, 2 and 3 levels accordingly, modelled as 0, 1, 2, and 3 levels of Occurrence rate decrease in the reliability model and DES.

This research only covers the Failure Modes of the BT that are included in the existing DFMECA made for the current concept design [6,4].

The occurrence and severity of the failure events considered in the DFMECA are defined for a mature DEMO, where failures due to the novelty of the systems are much reduced. It only considers failure modes affecting normal RM operation, whereas a recovery and rescue are not considered.

The maintenance missions of the DEMO RMS will cover large time frame which could be equal or greater to the estimated lifetime of DEMO. Therefore, it needs to be mentioned that all the costs in this research are measured in euros (€) at current prices. No account has been taken of net present value (NPV) or predicted fluctuations in material costs, energy costs or currency value.

This research assumes that the maintenance duration is unaffected by any repair or exchange of monitored equipment. Monte Carlo studies of maintenance durations would be required in order to assess the impact of the length of time a repair might take but representative mean values are not available at this time. Furthermore, the costs of any corrective action that is recommended by the condition monitoring system is considered to be negligible compared to the benefits of avoiding the failures and unscheduled rescue operations. The reason behind this assumption is that both the avoided failure and the corrective action will have a similar likelihood of happening, but the cost of the downtime will be much greater when unscheduled maintenance needs to take place compared to a scheduled extraction of equipment for repairs.

The methodology used herein simply assumes that by increasing the detection of the equipment failures, the likelihood of failure will decrease and lead to a reduction in overall maintenance time with a concomitant increase in profitability of the plant.

Table 1
DFMECA occurrence rating.

Value	Description	MTBF
1	Very low	>2000 years
2	Low	>200 years <2000 years
3	Moderate	>20 years <200 years
4	High	>2 years <20 years
5	Very high	>10 weeks <2 years
6	Frequent	<10 weeks

Table 2
DFMECA severity rating.

Value	Description	Unavailability
1	Weak <1 h	<1 h
2	Moderate <1 day	>1 h <1 day
3	Serious <1 week	>1 day <1 week
4	Severe	>1 week <2 months
5	Critical <1 year	>2 months <1 year
6	Catastrophic >1 year	>1 year

3.2. Cost of contingencies

The costs of contingencies is related to the equipment's availability and reliability. Therefore, the unavailability of the RMS translates linearly to both downtime and costs.

Reliability analysis of the BT for various failure modes was performed for the purpose of estimating the contingency costs. A reliability model of the BT was created using the blanket transporter DFMECA which describes the failure modes and the criticality indexes of the BT [6].

The possible impact of the CM application on the BT was modelled as a mitigation of the occurrence levels of all failure modes where rotating machinery is involved (electric actuators, bearings, gearboxes and lead screws).

A sensitivity analysis was performed for estimating the impact of the reduction in occurrence frequency of the failure modes related to rotating machinery to the overall RMS availability.

The reliability and sensitivity analyses were performed using DES with the ReliaSoft^{TM} BlockSim software for a duration of 10 maintenance missions.

The occurrence and severity ratings of the failure modes and the reliability model of the blanket transporter are described in Tables 1 and 2 . The duty cycles of the failure modes used in the reliability models were estimated using the Maintenance Duration Estimator tool [2].

Due to the particularities of the simulation software used, the mean time between failures (MTBF) and the mean time to recovery (MTTR) were modelled as exponential distribution functions instead of using bath-tub type curves, therefore, the initial wear failures are not accounted for in this research.

The parameters for the simulations are the RMS operational time and the occurrence index mitigation levels for the failure modes where CM can be applied. The occurrence index mitigation level parameter ranges from 0 to 3 levels and are labelled PH0, PH1 PH2 and PH3 respectively (Fig. 4).

The simulation model PH0, where there are 0 levels mitigation of the occurrence index, represents the baseline availability for the BT without CMS, and hence is a control variable for this research.

3.3. Cost of CMS equipment

The CMS for DEMO should help mitigate the failure modes where at least some of the parameters indicating the equipment condition could be reliably quantified by measurements from sensors. The failure modes where CM is applicable are generally related to rotating machinery e.g. poor performance of bearings, gearing, lead screws and electrical motors. Sensors used for monitoring wear on bearings, gearboxes and lead screws include: vibration sensors, acoustic emissions sensors and temperature sensors. Other sensors used for monitoring the state of electrical motors include electrical power sensors and speed sensors. The estimates of the total cost of the equipment includes the quantity of sensors needed over and above those already planned. The costs per unit

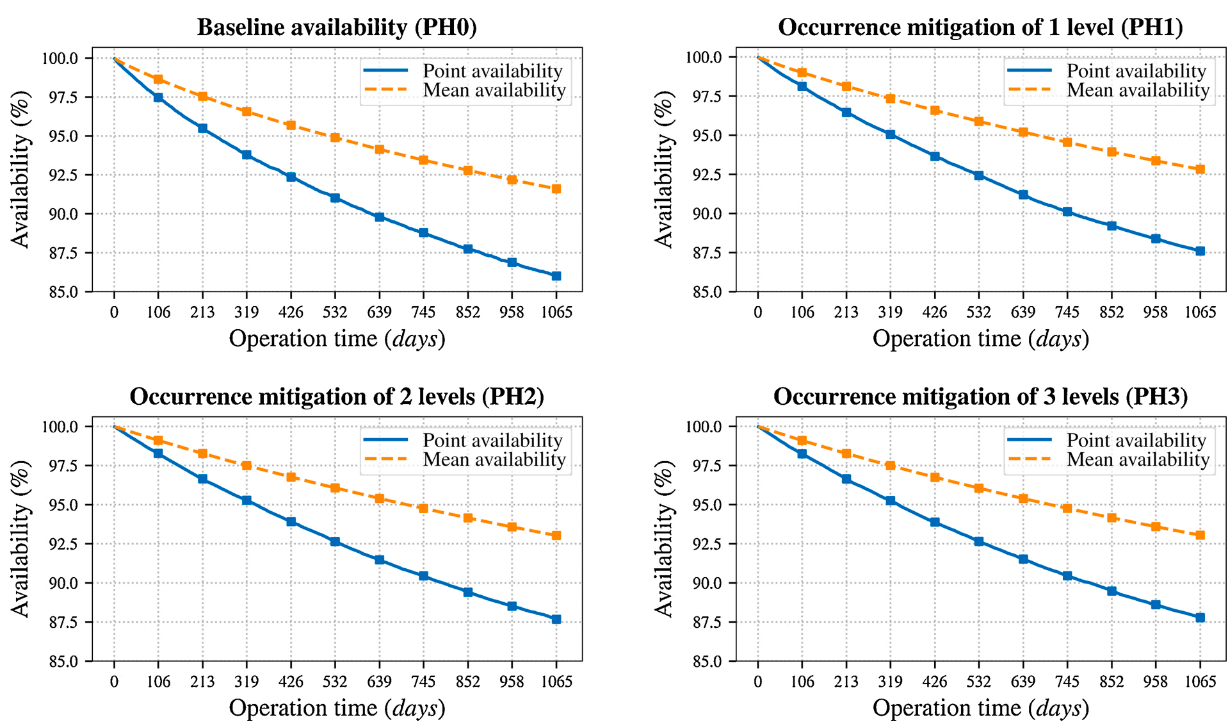

Fig. 4. Results from the reliability simulations of the developed reliability models: PH0, PH1, PH2, PH3.

Table 3
Estimated equipment and hardware costs.

Equipment	Quantity	Unit cost [€]	Cost [€]
Vibration sensor	176	313	55,088
Acoustic emissions sensor	168	469	78,792
Temperature sensor	168	124	20,832
Electrical power sensor	48	100	4800
Displacement sensor	12	140	1680
Speed sensor	8	425	3400
Data acquisition hardware	4	30,000	120,000
AAE hardware	1	50,000	50,000
Equipment samples for AAE	1	50,000	50,000
		Total [€]:	384,592

Table 4
Estimated labour costs.

Labour	Quantity [work hours]	Unit cost [€]	Cost [€]
Design	4176	60	250,560
Development	2088	60	125,280
Integration	2088	60	125,280
Validation	1044	60	62,640
AAE design and build	4176	60	250,560
Accelerated ageing tests	4176	60	250,560
		Total [€]:	1,064,880

for a particular sensor is calculated as an average of three of the off the shelf sensor costs. Data acquisition hardware is also included in the equipment costs.

For the purpose of learning the degradation properties of the monitored equipment, accelerated ageing environment (AAE) will be used. The AAE should be designed as an offline test environment that simulates equipment degradation in accelerated manner. It should have the ability to quantify and record the trends of the degradation parameters during accelerated ageing tests. Using the recorded data a damage propagation models will be made for the purpose of estimating the condition and RUL of the equipment.

The estimated costs for the AAE to be designed, developed and built are included in the total equipment cost estimate. The AAE hardware cost is an approximation based on prior experience of the author in similar scale projects.

3.4. Labour costs

The cost of labour is divided into six categories. They comprise design, development, integration and validation work for the actual CMS, and the construction of the AAE system and the labour cost of running it on sample equipment. The costs are calculated according to the estimated work hours needed for an engineer for each of the categories.

3.5. Recurring costs

The recurring costs considered in the CBA are the estimated labour costs for the operation and maintenance of the CMS, and the possible labour cost reductions that can happen as a result of using predictive maintenance on the BT. The maintenance cost also take account of the cost of replacement of 5% of all the CM sensors on the four BTs per maintenance mission.

4. Case study

The outputs from the reliability analysis of the PH0, PH1, PH2 and PH3 models of the BT described in Section 3, represent important factors for the CBA.

Fig. 4 shows the point and mean availability results from the reliability simulation of the 4 different models respectively.

Table 5
Estimated recurring costs/benefits.

Recurring event	Quantity [work hours/ mission]	Unit cost [€]	Cost [€/mission]
CMS operation	1056	60	51,360
CMS maintenance	1044	60	62,640
RMS predictive maintenance	− 4176	60	− 250,560
		Total [€]:	− 136,560

Tables 3–5, describe the equipment, labour and recurrent events cost for 4 BTs.

The point availability results from the reliability simulations were used in Eq. (3) for calculating the cumulative downtime cost of each of the simulation models respectively, where $C_d(d_i)$ represents the cumulative downtime cost on day d_i, $A_d(d_k)$ represents the point availability of the simulation model at day d_k (Fig. 5).

$$C_d(d_i) = \left\{ \sum_{k=0}^{i} [1 - A_d(d_k)] \right\} \cdot 3 \cdot 10^6 \tag{3}$$

5. Results and discussion

The estimated total savings for each of the reliability models are shown in Fig. 6. From the results shown we can conclude that the PH3 model results with the highest savings.

If we compare the results from the different models, we can conclude that the highest increase in savings occurs when PH1 is reached from the initial PH0 baseline. We can also conclude that the PH3 model and any further mitigation in occurrence will not result in any significant increase in savings.

Fig. 7 shows the repayment period for PH1, PH2 and PH3. The results show that for all the reliability models the repayment period is estimated to be around 1 mission time. The total net savings for PH3 and 10 missions duration is estimated around 45M € (Eq. (4)).

$$\begin{aligned} & \mathrm{Cb}_{\mathrm{net}}(m = 10, \mathrm{PH} = 3) = \\ & = C_t(m = 10, \mathrm{PH} = 3) - B_t(m = 10, \mathrm{PH} = 3) \\ & = -44.90 \cdot 10^6 \end{aligned} \tag{4}$$

Another major concern regarding a fusion power plant is the risk it poses to the health, safety and environment. Fusion reactor is a source of radiation, and it means that the DEMO RMS equipment will be active at some level. A critical failure in a critical time could pose a serious threat to safety and poses a serious health risk to the people in a close proximity of the fusion power plant.

The health, safety and environment concerns lead to strict regulatory screening process for gaining an approval for operation of DEMO. The CMS could help reduce the risks of the safety concerns by delivering transparent readings of the condition of the critical equipment in near real time, allowing corrective actions to be taken before a critical failure happens.

The RUL predictions made by the CMS are uncertain in nature [8]. It means that the ability to have a good estimation of the uncertainty in the predictions is crucial for the prognostics performance of the CMS. Not having a good estimation of the uncertainty could lead to false positives and false negatives. False positives means throwing away equipment which could still be fit for purpose. False negatives mean that the component has failed before reaching the estimated EOL threshold. For DEMO RMS the cost of false negatives will be significantly higher than the cost of false positives because of the operating environment of the equipment and the risk of cascading failures during recovery operations. Having more of a conservative estimations of the EOL should be the preferred from having optimistic EOL estimations. The cost of the prognostics uncertainty is not easily quantifiable and therefore it was

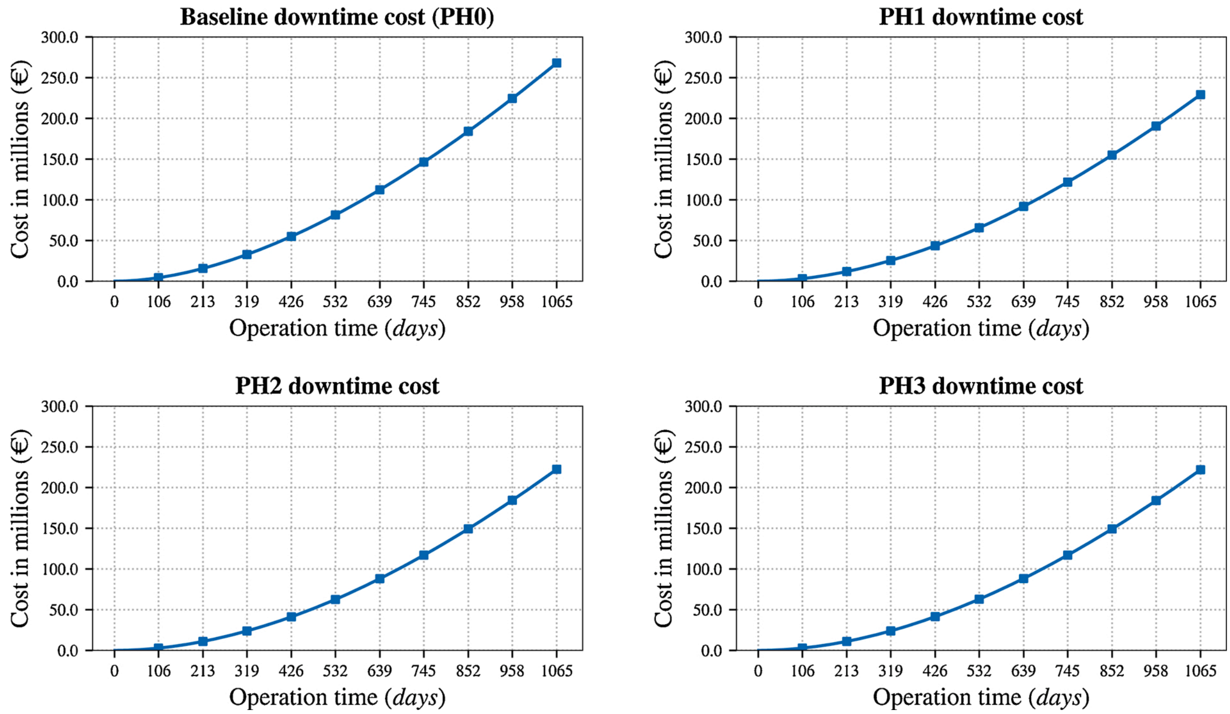

Fig. 5. System downtime costs estimation using reliability simulations of PH0, PH1, PH2, PH3.

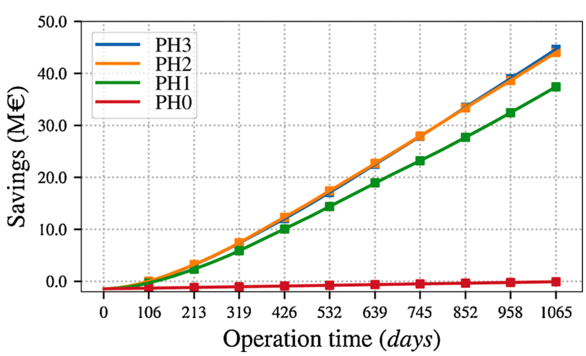

Fig. 6. Estimated total savings for PH0, PH1, PH2 and PH3.

not included in the CBA calculation.

6. Conclusion

This research introduces a CBA method and provides economic feasibility study for application of CM of DEMO RMS. The method for the CBA used in this research has been described in Section 3 and shown with the current concept design for the BT of the DEMO RMS in Section 4.

As shown in Fig. 7, the repayment period of the CMS will happen after 1 maintenance mission for all the reliability models (PH1, PH2 and PH3).

The ceiling of the benefits is hard to be determined because the length of operation time of the RMS is uncertain. For a period of 10 maintenance missions, the estimated economic benefit could come close to 45M € if 3 levels of failure modes occurrence mitigation is achieved.

This research is intended to be used as a guidance for the further design of the DEMO RMS. The results show that using CMS on the DEMO RMS could introduce significant economic benefits by increasing the overall availability of DEMO RMS. Some of the other factors not used in the CBA (increased fault detection and isolation, predictive maintenance scheduling and operations optimization) could provide even further economic benefit. Other major benefit of using CM could be the impact the CM could have on reducing the risk that DEMO poses to health, safety and environment.

Further work could be done in making an overall CBA for application of CM to the whole of the DEMO RMS in similar manner to the method presented for the BT in this research. Monte Carlo Simulation could be used for estimating the uncertainty propagation and the CBA could be modelled with stochastic variables of all cost/benefit factors.

The CBA method of estimating of CM benefits could also be used in other work packages of DEMO e.g. breeding blanket segments health monitoring.

Authors' contributions

Nikola Petkov: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – Original Draft, Visualization.
Huapeng Wu: Methodology, Validation, Resources, Writing – Review & Editing preparation, Supervision, Project administration.
Roger Powell: Methodology, Validation, Resources, Writing – Review & Editing preparation, Supervision, Project administration.

Conflict of interest

The authors declare no conflict of interest.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fusengdes.2020.112022.

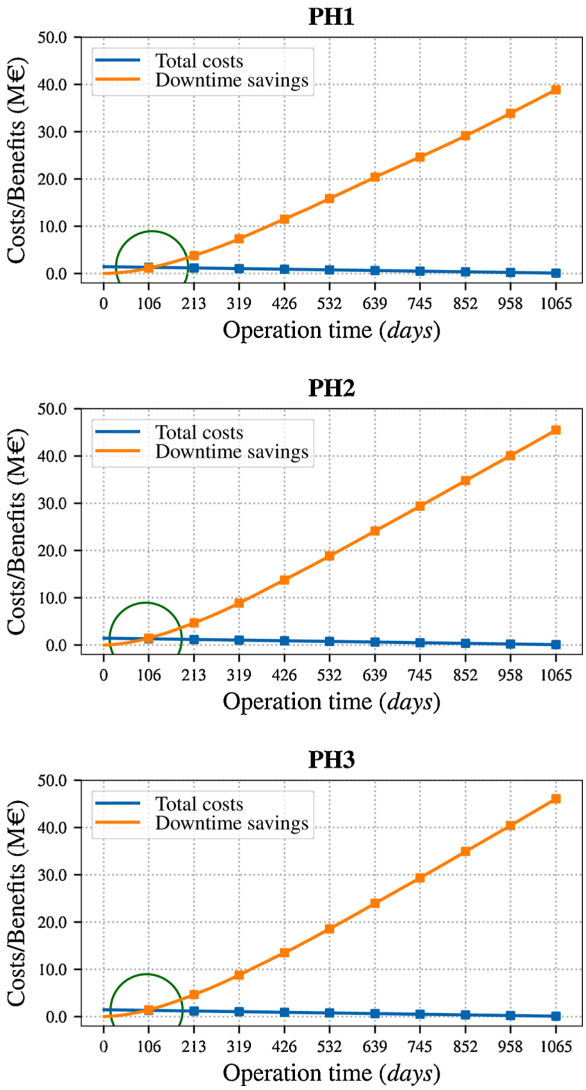

Fig. 7. Repayment period for simulated PH1, PH2, PH3 models.

References

[1] T. Donné, W. Morris, X. Litaudon, C. Hidalgo, D. McDonald, H. Zohm, E. Diegele, A. Möslang, K. Nordlund, G. Federici, P. Sonato, C. Waldon, D. Borba, P. Helander, European Research Roadmap to the Realisation of Fusion Energy – Long Version, 2018.

[2] I. Farquhar, Maintenance Duration Estimator, EUROfusion, 2018. IDM reference: 2NBXBQ.

[3] S. Budden, V. Agudo, A. Barturen, L. Hannoun, J. Keep, A. Loving, P. Shaughnessy, G. Keech, Rescue and recovery studies for the DEMO blanket transporter, Fusion Eng. Des. 146 (September) (2019) 2494–2497.

[4] S. Budden, Concept Design Description For Blanket Transporter, EUROfusion, 2018. IDM reference: 2MRZLG.

[5] G. Keech, C. Bachmann, C. Vorpahl, C. Gliss, T. Franke, F. Cismondi, S. Ciattaglia, F. Maviglia, R. Kembleton, A. Loving, J. Keep, Issues of the vertical blanket segment architecture in DEMO: current progress and resolution strategies, Fusion Eng. Des. 146 (September) (2019) 1408–1412.

[6] L. Hannoun, Blanket Transporter DFMECA, EUROfusion, 2018. IDM reference: 2NEG4B.

[7] B. Mehrafrooz, P. Edalat, M. Dyanati, Cost consequence-based reliability analysis of bursting and buckling failure modes in subsea pipelines, J. Ocean Eng. Sci. 4 (March) (2019) 64–76.

[8] K. Goebel, M. Daigle, A. Saxena, I. Roychoudhury, S. Sankararaman, Prognostics: The Science of Making Predictions, 1st ed., Createspace Independent Publishing Platform, 2017.

[9] A. Saxena, J. Celaya, B. Saha, S. Saha, K. Goebel, On Applying the Prognostic Performance Metrics, 2009. January.