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Maintenance optimization: Application of remanufacturing and repair strategies

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Abstract

Power plant facilities located in remote and difficult to access regions often experience significant production losses due to failures, inaccurate remanufacturing, maintenance activities in addition to prolonged lead time delays while procuring critical spares. This is especially the case given unanticipated power plant failures which could portend significant power generation losses besides outages that could lead to significant societal disruptions, for instance, off grid hospital facilities. This study uses a discrete event simulation model to analyze the effect of remanufacturing and maintenance as part of circular economy strategies, on power plant availability and maintenance time. The proposed study is demonstrated through the use case of a thermal power plant located in a remote region, where findings suggest replacing components upon failure has the most significant impact and effect on system availability as well as maintenance time. Moreover, a reduction of mean time before Overhaul (MTBO) seems to lengthen the component's usage-life, hence reduces the maintenance time, and at the same time, increases the system availability. Reuse activity also yields a better mean time to recovery (MTTR), while repair has the highest amongst the evaluated recovery strategies. The study adds value by developing a framework, further applying a simulation modelling approach for evaluating the effects of remanufacturing and maintenance strategies on plant availability.

Keywords: Circular economy; maintenance; recovery actions; critical subsytem

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1. Introduction

1.1. Background

Circular economy (CE) is considered as an innovative approach used to increase the resource efficiency in companies by keeping equipment functioning for as long as possible. This is done while extracting maximum value from such equipment during use, recovery after failure by restoring components back to normal condition and renewing the components to as good as new state at the end of their serviceable life. Many authors concur that CE incorporates reuse, remanufacturing, recycling and maintenance [1–4]. Maintenance can be defined as activities aimed at restoring from fault and renewing a component to a condition whereby it can physically perform as required. It incorporates reactive repairs and replacement triggered by failures as well as planned and predictive tasks such as preventive replacement, inspection, scheduled repairs and others [5].

Nomenclature

CE	Circular Economy
EOU	End of Use
RUL	Remaining Useful Life
MTBO	Mean Time Before Overhaul
TNF	Time to Next Failure
AGAN	As Good as New
MTTR	Mean Time to Recovery

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ISO 14224 defines the CE recovery actions above, along with component replacement, repair, modification, adjustment, refit, inspection, testing, service, overhaul, or a combination of the aforementioned recovery actions among other, as maintenance activities [6]. Maintenance aims at enhancing the operability and functionality of the power plant. This may include aspects such as extending the plant operable lifetime, reducing maintenance-related costs and power generation losses of the power plant facility. Thus, these activities align with the definition of CE in industrial ecology, where the economic and environmental value of the component is safeguarded for as long as possible by keeping the component in the economic system, through lengthening its life using maintenance or reuse [7]. For this reason, maintenance activities are critical for extending the system operable lifetime, minimizing the operation and maintenance costs, optimizing electric power production for the power plants and facilitating the recovery at EOU.

1.2. Study aim and motivation of research

In the manufacturing sector, maintenance is becoming a crucial aspect towards realizing a tenable productivity especially when considering the entire life cycle of assets and equipment [5,8]. The life cycle time from production to disposal of a piece of equipment determines the productivity, operational costs and durability, which in turn has significant impact on the EOU treatment of assets and equipment. During the usage phase, life cycle time is impacted by the equipment reliability, maintenance and recovery strategies. To optimize the lifecycle of the equipment, while achieving lower operating costs during this phase, optimizing equipment maintenance and reliability is important. This can be attained by having an elaborate strategy, right manpower and structures, appropriate tactics, confined work activities through proper scheduling and planning, maintenance optimization and process re-formulation. The use of various maintenance activities, included in product recovery activities under the CE context also described as EOU operations, influences the component's life cycle and reliability aspects, such as availability [9]. Moreover, the maintenance time a component incurs, when translated to monetary value, often constitutes a significant cost component and impact on the total life cycle cost of the equipment.

This study seeks to analyse the effect and impact of the circular economy (CE) on the operations and maintenance activities of power plant facilities located in remote and difficult to access areas. For such facilities, components' downtime often impacts negatively on the subsystem availability and maintenance time. Hence, a simulation model is developed for evaluating the impact of remanufacturing and maintenance activities such as component replacement, reuse, repair, reconditioning and overhaul on the equipment availability. The activities further consider the end of life treatment within a time-based, condition based maintenance framework [10].

2. Relevant Literature

In this section, a brief review of maintenance activities incorporated within the CE framework are discussed, where activities under remanufacturing and maintenance strategies are evaluated.

2.1. Remanufacturing

Various authors have defined remanufacturing as the process involving restoring a component to as-good-as-new state, through activities such as component replacement, reuse and reconditioning [9,11–14]. Remanufacturing aims to return the re-manufacturable components that have reached their end of use phase back to their desired specifications by passing through several stringent industrial recovery processes [13].

Part of the activities under remanufacturing include replacement, which is the process of replacing a defective component with a new one or one in the as-good-as-new state. Replacement may be triggered by a failure, age or condition monitored. For example, a bearing that has failed may require to be replaced. Reconditioning involves restoring or replacing parts that have failed or are on the verge of failing, hence returning them to acceptable serviceable standards [9,13]. Reuse is the process of using the component again, whether for its original or different purpose and without carrying out any significant repair [9]. Reuse often slows down the flow of materials from production to recycling by avoiding production of new components through recycling [4]. Cannibalization refers to removing a component of an equipment necessary for repair from another similar equipment, rather than from inventory. Cannibalization of parts for reuse is common in the aircraft industry, and a good example of reuse strategy [15]. Several reasons that lead to increased component cannibalization include pressure to meet operational needs, shortcomings of spare part replenishment and untrained maintenance team in problem diagnosis. Lack of testing equipment, along with the others lead to cannibalization due to convenience especially if there is a source. In power plants, a subsystem under prolonged downtime, while awaiting receipt of critical spare parts may easily become a candidate of cannibalization, especially when a similar subsystem requiring an alternative component fails.

2.2. Maintenance strategies

Maintenance strategies include corrective maintenance, carried out after detection of defect with an aim to restore normal operating conditions, preventive maintenance which involves periodic inspection, preventive tasks and overhaul. Risk-based maintenance integrates analysis, measurements and periodic tests to the preventive maintenance, while condition-based maintenance incorporates performance monitoring and corrective actions taken as a result [5].

Most industrial setups adopt an integrated strategy where they utilize the activities of both the planned and unplanned actions. We briefly review repair and preventive maintenance in our case overhaul. Repair strategy entails the process of bringing a damaged or faulty component back to a functional condition following a planned or unplanned corrective repair activities [9]. In our context, repairs are random and unplanned where a component is repaired after wear, malfunction, break down or condition deterioration. Examples of repair actions include welding. ISO 14224 defines overhaul as the comprehensive inspection which involves extensive disassembly and replacement of items according to a specified schedule [6]. The overhaul process involves simultaneous activities combining most of the maintenance and remanufacturing activities affecting all subsystem components.

3. Methodology

The methodology consists of several steps. Step 1 involves data collection and pre-processing, Step 2 involves data exploration. Step 3 includes extraction of critical variables for incorporating as input to a simulation model for evaluating the impact of alternative remanufacturing and maintenance strategies on power plant availability. Step 4 entails developing the simulation model and performing simulation experiments, while Step 5 entails evaluating and interpreting the results of the simulation experiments.

3.1. Data collection

In this study, the analysis utilizes maintenance data documenting failures from thermal power plant engines. The power plant is located remotely in East Africa. The power plant has fuel oil driven engines for power generation which we define as equipment. Each engine consists of several inter-linked subsystems such as cylinder, turbocharger and others. A subsystem is made up of several components, for instance the turbocharger subsystem has a turbine rotor, bearings, bellow, lube oil (LO) pipe as components. The data was recorded in a free text format and collected over five years (2011-2015). The data includes component failure occurrences, detailed subsystem and components which failed, together with the date and time of occurrence. The data also includes repair actions performed on the failed components, the date and time the repair was finalized, and so on. Owing to data inconsistencies, it was pre-processed using a standardization step following the ISO 14224. Data was pre-processed linking the various components with their respective subsystem as well as expert consultations were done where clarity was needed.

3.2. Data Exploration

Due to the free text format, the data was explored using a text mining approach where labelling, association rules were extracted, and descriptive statistics performed to derive the maintenance actions performed on the failed components. The power plant engine was decomposed into subsystems, from which the turbocharger subsystem was selected as critical for further analysis based on the failure frequency. The turbocharger data was analysed in terms of its constituent components, where critical components of the turbocharger subsystem were prioritized using Pareto analysis. The latter analysis was based on performance measures such as power production loss and subsystem downtime owing to component failures.

3.3. Model parameter extraction

The turbocharger subsystem selected for analysis was initially decomposed to its components. Thereafter, failure analysis was performed against each component, where modelling parameters relevant to the simulation model were derived. The derived parameters included frequency of component failure, individual contribution of the component failure to subsystem unavailability and recovery activities performed on the failed component. Moreover, the mean time to recover (MTTR) for each of the recovery activities was also derived for input to the simulation modelling framework. Apart from the MTTR, the time to next failure (TNF) for each component was determined by computing the time between restoring the component to operable state up until its next failure. Overhaul information of the turbocharger were derived from the preventive maintenance planning manual of the sub-system, from which the parameters on the mean time between overhaul (MTBO) and the MTTR were retrieved.

3.4. Modelling

A discrete event simulation-Arena modelling framework which mimics aspects such as component failure generation, components undergoing the various remanufacturing and maintenance actions, then normal running until the next failure occurrence was built. An impact factor ε ranging from 0 to 1, is introduced for estimating the component hazard rate (impact of the recovery action on the RUL of the component) in each recovery action. The extreme values $\varepsilon = 0$ depict 'as bad as old' while $\varepsilon = 1$ construe 'as good as new'(AGAN). Probabilistic modelling was performed to model the deterioration process of the components based on the specific remanufacturing and maintenance actions utilized. Some of the assumptions considered in the model include:

- The condition of the plant equipment and subsystem is aging and most of the components have been involved in earlier regenerative activities hence seldom does their state become AGAN. In this case it deemed appropriate to have the impact factors $\varepsilon < 1$.
- The component EOU is not reached during the simulation time hence the impacts of component aging failures (EOU failures) are ignored. This is part of the future modelling issue.

3.5. Evaluation and interpretation

From a set design of experiment (DOE), a full 2^k factorial design (k=5, depicting the replace, reuse, recondition, repair and overhaul) was conducted and computations of the main effects and interactions generated. Main effect is the effect of one recovery action on the response variable, while ignoring the effects of all other recovery actions. An interaction is the effect of one recovery action on the response variable, whilst depending on the level of another recovery action.

4. Results

4.1. Data collection and pre-processing

The chart in Fig. 1 summarizes the maintenance actions frequency utilized in the entire power plant where the first three actions, replace (391), reuse (133) and repair (128) represent over 66% of all the actions.

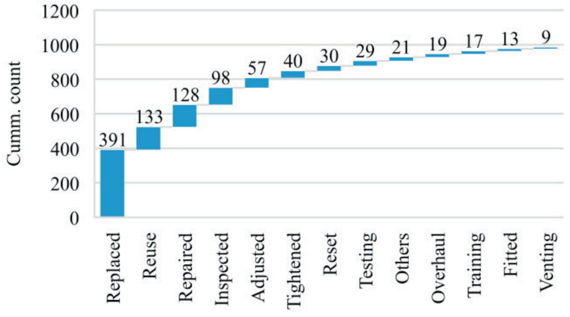

Fig. 1. Frequency of maintenance actions utilized.

The classification in Fig.1 was extracted from the failure data of the power plant using text mining. Text mining is a software used to extract patterns and knowledge from unstructured text documents. This was used because the maintenance data was in a free text format which included both handwritten and typed sections. Fig. 2 illustrates the failure frequency for each of the subsystems where the turbocharger had the most failures recorded followed by fuel subsystem, lubrication, cylinder and cooling respectively. The 'other' category in Fig. 2 represents summation of all the remaining subsystems which individually contributed less than 3% of total failures.

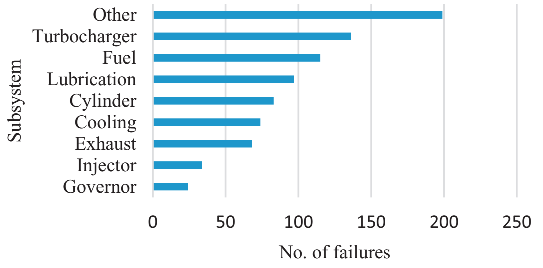

Fig. 2. Frequency of failure for engine subsystems.

4.2. Data exploration

The pareto chart in Fig. 3 illustrates the components of the turbocharger subsystem and their contribution to the downtime loss of the power plant system. The first five components, i.e., bellows, bearings, base plate, LO pipe and turbine rotor were seen to cumulatively contribute over 80% of the downtime loss. Consequently, they were selected as critical components for inclusion in the simulation model. The remaining components were classified together as 'others' and incorporated in the model as the sixth "component".

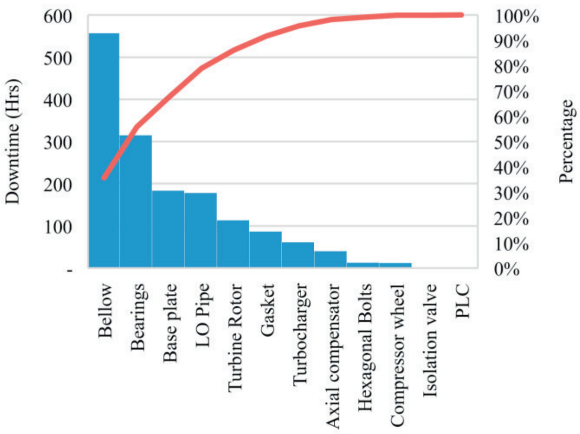

Fig. 3. Pareto chart for turbocharger components.

4.3. Model parameters extraction

Table 1 summarizes the time to the first failure and the time to the next failure for each of the components selected as critical in the turbocharger subsystem. The computation of the time to the initial failure was done with an assumption of the analysis commencement of January 2011. Time to next failure (TNF), was derived by fitting a distribution to the data, thereby estimating the distribution's parameters using Input Analyzer-Arena software. The Weibull distribution estimate represented as WEIB (α, β) with shape parameter β and scalar parameter α while exponential distribution has the mean.

Table 1. Component Initial failure and TNF values

Component	Time to first failure (Hrs)	Time to Next Failure TNF (Hrs)
Others	5,944.30	67 + EXPO(1.09e+003)
Bellows	2,579.28	24 + WEIB(1.73e+003,0.506)
Bearings	263.80	161 + EXPO(3.52e+003)
Base plate	10,909.53	16 + WEIB (832,0.651)
LO Pipe	85.80	23 + WEIB (846,0.673)
Turbine Rotor	2,046.62	1.21e+003 + EXPO(1.64e+003)

Table 2 summarizes the mean time to recover (MTTR), recovery rate and the probability of utilization for the various recovery actions. Time utilized under the preventive maintenance (overhaul) had a uniform distribution of minimum 20 hours and maximum 28 hours as depicted from the preventive maintenance schedule manual.

Table 2. Recovery actions MTTR and probability values

Recovery Action	MTTR (Hrs)	Recover Rate per Hr (μ)	Probability
Replace	12.64	0.07911	0.630
Repair	29.94	0.03340	0.190
Reuse	5.01	0.19960	0.110
Recondition	9.07	0.11025	0.070

The impact factors (ε) adopted for the 'replace' action was 0.80, 'repair' 0.6559, 'recondition' 0.4339, 'reuse' as 0.405 and 'overhaul' as 0.95. This was derived from proportionating the respective total TNF, comparing with replace as 0.80 under the assumption that attaining AGAN status is difficult in deteriorating systems due to introduction of errors like diagnosis, tooling, human related errors, and so on.

4.4. Model

The model mimicking the operation of the turbocharger subsystem was developed, where the performance measurements were turbocharger availability and maintenance time which were studied as response variables. Process analysis was done to uncover the effect of recovery actions to the turbocharger availability and maintenance time. See fig 4 of the simplified schematic model block representation.

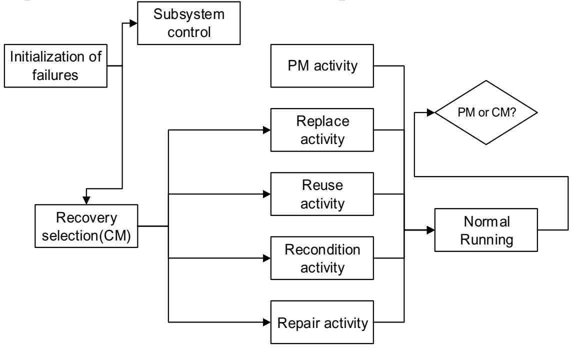

Fig. 4. Schematic block representation of discrete event simulation model

4.5. Analysis of results

The process analysis involved varying the ε values of the various EOU activities like replace (0.8-0.95), reuse (0.3-0.6), recondition (0.4-0.7), repair (0.55-0.8) and MTBO (7,000–12,000 hours). Fig 5 depicts the effects of MTBO to the turbocharger availability, where an increase in MTBO leads to a decrease in the availability of the turbocharger.

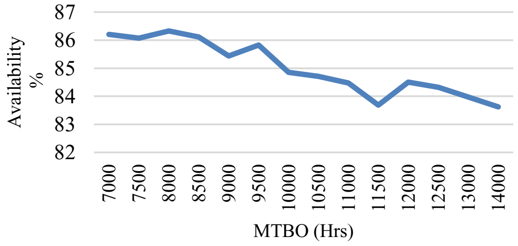

Fig. 5. Turbocharger availability with MTBO

Similarly, it was found that Low MTBO causes a relatively lower maintenance time for the turbocharger system. An optimal MTBO is seen to be between 8000 and 9500 hours.

Table 3, illustrates the computed average main effects of recovery actions using a 2^5 full factorial design on the availability and maintenance time. Increase in MTBO from low to high, with other actions remaining constant, will decrease the availability by 2.02% and increase the maintenance time by 589.68 hours on average. While an increase in ε for replace action will increase availability by 3.46% and decrease repair time by 3,431.16 hours averagely.

Table 3. Computed main effects of recovery actions

Measurement	Over -haul	Reuse	Replace	Recondition	Repair
Turbocharger Availability	-2.02	1.15	3.46	1.02	1.48
Maintenance Repair Time	589.7	-1121.7	-3431.1	-986.5	-1456.5

Similarly, Table 4 depicts a sample of interactions, for example the interaction between reuse and replace actions will increase the availability by a factor of 0.30% and decrease the repair time by 294.32 hours. This shows the effect of reuse moderately depends on the level of effect of replace activity.

Table 4. Computed sample interactions of recovery actions

Measurement	Overhaul + Reuse	Reuse + Replace	Overhaul + Replace	Overhaul + Repair + Reuse + Replace
Turbocharger Availability	0.08	0.30	-0.24	0.16
Maintenance Repair Time	-87.13	-294.32	262.76	-162.59

5. Discussion

As depicted in Fig. 1, the plant relies mainly on component replacement, which directly renews the component, thereby extending the functionality and life of the subsystem as is expected. The high frequency of replace may be associated to an elaborate strategy implemented by the power plant due to its remote location. This could also be connected to components that can only be replaced whilst other recovery activities cannot be carried out on them, such as bearings. Reuse frequency could be attributed to cannibalization, lack of spares and delays in sourcing. Repair action frequency is not comparable to the first two actions, which may impute lack of skills as well as use of outsourced maintenance options where lower repair treatment is promoted.

Fig. 3 illustrates the individual contribution of the components making the turbocharger subsystem to the downtime. Based on the criteria of downtime contribution, the bellows, bearings, base plate, LO pipe and turbine rotors are selected as critical components, representing 86% of the total downtime. Consequently, most of the turbocharger challenges will be resolved if they are addressed, thereby lengthening the operational time of the turbocharger subsystem and thereby boost the plant availability.

The time to next failure as seen in table 1, manifests varied distribution estimate fitting for respective components. Turbine rotor, bearing and others, generate an exponential distribution presumably due to random causes of failures and implementation of high replacement strategy which in the end tends to bring the TNF to a near steady state. This could be attributed to high use of replace action. Bellow, LO pipe and base plate generate a Weibull distribution, attributable to the aging and wear out effect. The three components exhibit shape parameter $\beta > 1$, which indicates components are on the wear out life, therefore advisable that regenerative strategies be implemented to extend life before EOU. The components have their hazard rate increasing due to more intense restorative strategies implemented that have high impact on the RUL. This in turn reduces the TNF. Contrary, the replacement strategy has a lower impact on the RUL due to the strategy characteristics where the component renewal is near AGAN, accordingly lengthening the life of the subsystem before a failure.

Repair had a higher MTTR than replacement, attributable to low frequency use of repair strategy, challenges in strategy execution for example, diagnosis, tooling, spares and so on. Similarly, high MTTR for replacement action could infer challenges like spares unavailability and long sourcing lead times. Reuse had the lowest MTTR, implying a good to fit strategy, howbeit requires to be validated, to reduce the downtime of the turbocharger. This can be attributed to factors such as availability of cannibalization source units, which may have been decommissioned earlier, ease of carrying out the action and an elaborate strategy of repairing failed replaced components, which are afterwards warehoused for future reuse opportunities.

While analysing the main effects as seen in Table 3, the replacement action has the strongest effect on both response variables. Enhanced replacement strategy in this model improves the availability and reduces the maintenance time with an average effect of 3.46% and 1,121.16 hours respectively. This is attributed to the high restorative impact of replacement; hence the life of the component is lengthened consequently reducing the time required for maintenance and improves the power plant availability. Repair, reuse and recondition follow in terms of strength of effect on both performance measures. On the contrary, the strong effect of replacement action, would need to be investigated, as this could occur at the expense of increased costs due to spare stock holding which will be a subject in the section of our future study. Mean time between overhaul has a negative effect on the performance measures. This is corroborated by figure 5, where an increase in MTBO from the low to high value as earlier indicated, would reduce the turbocharger availability and increase maintenance time by an average of 2.02% and 589.68 hours respectively. This can be attributed to high failures of the components occurrence before PM where renewal of all components is done. Extension of MTBO will cause components to reach end of serviceable life earlier, thereby reduce the life and longevity of the subsystem. The other recovery actions showed an increased availability and decreased maintenance time as their respective effects which consequently lead to a longer operational life of the component and subsystem, plus reduced maintenance and recovery costs.

Table 4 indicates sample interaction results, for example, reuse effect on availability, moderately depend on the effect of the replace action. Component replacement has a positive effect at high reuse but negative effect at low reuse. While reviewing the impact on maintenance time, effect of reuse to some extent depends on the effect of replace, where replace has a negative effect at high reuse but positive effect at low reuse. This means minimal use of reuse while implementing replace will improve the availability and reduce the maintenance time and vice versa.

6. Conclusion and future work

The study which, as alluded earlier, is the initial exploration of the on-going research of optimizing remanufacturing and maintenance strategies linked with circular economy, has uncovered various product recovery strategies under CE used in the power plant set up and analysed the effects of the activities towards affecting the component's useable life and delay of EOU. The study has shown that the replacement activity has the strongest effect on both the turbocharger availability and maintenance time, suiting such a remotely located power plant. Presence of interactions of the various maintenance activities impacting the response variables are also evidenced. Following this initial study, enhanced optimization of specific different recovery strategies to subsystem availability and maintenance time in terms of its individual contribution with a possibility of costs incorporation is proposed for future work.

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