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A multi-stage remanufacturing approach for life extension of safety critical systems

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Abstract

Life extension of safety critical systems is gaining popularity in many industries due to the increasing demand in world's energy consumption and the strong desire to reduce carbon emissions by different countries. Identification and implementation of a suitable life extension strategy enables safety critical systems to perform their intended functions under stated condition for an extended period of time beyond original design life. In the past, the viability analysis of life extension strategies has been undertaken based on the accumulated knowledge and experience of Original Equipment Manufacturer (OEM), maintenance engineers and inspectors. These approaches involving expert judgement are qualitative in nature and based on conservative assumptions, which may lead to inaccurate conclusion or misleading recommendations to asset managers. Therefore, it is crucial to develop an approach consisting of methods to determine the technical condition of components, estimate the cost of life extension interventions and to analyze carbon footprints. "Remanufacturing" is considered as a suitable end-of-life strategy that can help reduce the overall environmental burden from the product by processing waste materials while at the same time keeping reliability high. Due to the advantages of remanufacturing, it is widely applied for life extension purposes in safety critical industries such as offshore oil and gas, nuclear power, petrochemical, renewable energy, rail transport, aviation, shipping, and electricity distribution and transmission. In this paper, a multi-stage approach is presented to analyze the impact of remanufacturing of safety critical systems on the performance of industrial operations in terms of total cost and carbon footprint. In this approach, the equipment health status is determined by modelling the degradation of the system and then the maintenance costs and carbon footprint are calculated. For the purpose of clarity, the proposed model is applied to an air compressor system and the results are discussed.

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Keywords: Life extension, Remanufacturing, Safety critical asset, Reliability, Maintenance, Greenhouse gases emission.

1. Introduction

Life extension is an end-of-life strategy used to restore the reliability of ageing safety critical systems. The decision whether to extend the service life of assets is often made based on technical and economic analyses [1], i.e. the fitness-for-service (FFS) condition of the asset is assessed alongside economic evaluations of the required intervention. According to Brandt and Mohd Sarif [2], these analyses must demonstrate that the system is safe and reliable for continuous operation beyond original design life.

Extending the service life of safety related systems can help achieve important goals of sustainability—social, environment and economic [3]. Strategies such as remanufacturing, refurbishment, replacement and reuse are identified as suitable end-of-life interventions. Nonetheless, remanufacturing is considered as one of the most suitable life extension options that can help reduce the overall environmental burden from the product by processing waste materials while at the same time keeping reliability high. It is a process often used to recover the value of a product by replacing some components with reprocessed used parts to restore the product to a like-new condition [4]. According to [5–8], remanufacturing involves processes to return an existing system to Original Equipment Manufacturer (OEM)'s functional specifications with warranty. Naeem *et al.* [9] considered remanufacturing as

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a process of rebuilding or reconditioning and overhauling of systems. The study suggested that the aim of remanufacturing is to restore a product to as-good-as-new (AGAN) condition through the use of procedures in a factory environment. Ilgin and Gupta [10] suggested that remanufacturing comprises a series of actions to rebuild or recondition a set of components to like-new condition. The following steps are usually involved in remanufacturing: disassembling, cleaning and washing, machining operations, replacement of parts, assembling and testing [3].

Remanufacturing is often confused with reconditioning, recycling and repair due to similarities in process, however remanufacturing differs from these strategies. Recycling occurs at component level in contrast to raw material level as in the case of remanufacturing [4]. On the other hand, reconditioning process recovers equipment to working condition without equivalent warranty to newly manufactured systems from OEMs, whereas repair involves rectifying specific faults to return damaged equipment to functional status.

The remanufacturing industry in the USA is now a major source of economic wealth and employment and is applied to a wide range of products, such as vending machines, photocopiers, electronics, aircraft parts and automotive components. In 2004, there were 73,000 remanufacturing companies in the USA providing direct employment of 480,000 personnel with annual economic value estimated at $53 billion [7]. Rathore *et al.* [11] investigated whether remanufactured products could be accepted by Indian consumers and how these will fit into the Indian market.

In the past, the evaluation of impact of life extension interventions on asset performance has been based on the accumulated knowledge and experience of OEM, engineers and inspectors. However, experts' judgement and experience do not necessarily lead to optimal solutions due to the complexities of industrial safety critical systems and their degradation processes. Also, existing approaches are not flexible and less structured. Life extension decision making is a dynamic and iterative process requiring cooperation of various parts (elements) of a system. In order to address the shortcomings of the existing approaches, it is required to develop a unified approach for life extension decision making of safety critical systems and economic analysis of corresponding interventions which captures the interactions between various segments within an organization.

In this paper, a multi agent-based architecture is proposed to aid life extension decision making process of safety critical systems. Multi agent-based approach has so far been used in various applications including supply chain management [12, 13], power distribution [14], scheduling [15–18], maintenance planning and optimization [19–22] to ensure pro-activeness, autonomy, interaction, communication, distributed decision making and collaboration among segments of a complex system for efficient decision-making. The rationale behind selecting this approach is to break down the life extension decision making problem into several smaller and simpler problems handled by multiple entities of the asset management organization. The impacts of remanufacturing on the performance of safety critical assets in terms of total cost and the amount of carbon dioxide emissions are analysed and the results are illustrated by a case study of an air compressor system.

The rest of the paper is organized as follows. Section 2 presents the agent-based architecture for life extension decision making problem and its features are explained. In Section 3, the cost functions for maintenance and remanufacturing are derived. Section 4 illustrates the applicability of the proposed approach and finally, Section 5 concludes the paper.

Nomenclature

EHI	equipment health index
C_{PM}	cost of preventive maintenance (PM)
C_{CM}	cost of corrective maintenance (CM)
C_{REM}	cost of remanufacturing
C_D	cost of system downtime
C_M	cost of manufacturing a new safety element
CF_{PM}	carbon footprint due to PM
CF_{CM}	carbon footprint due to CM
CF_{REM}	carbon footprint due to remanufacturing
CF_M	carbon footprint due to manufacturing a new system
X	binary variable {0,1}
RCR	remanufacturing cost rate
$RCFR$	remanufacturing carbon footprint rate
n	number of safety equipment
$f_i(j+1)$	probability that a failure occurring at the instant j+1 stops the safety equipment i from functioning
$R_i(j+1)$	probability that the safety equipment i is remanufactured at the instant j+1
$deg\ (j+1)$	time-dependent degradation condition at the instant j+1
ψ	empirical value
$\gamma_i(j)$	coefficient of the effect of external conditions
$C_m(j)$	total cost of maintenance at the instant j
$CF(j)$	total carbon footprint at the instant j

2. The proposed approach

Extending the service life of industrial safety systems is a complex task because it is often subjected to several constraints such as lack of appropriate procedures, unavailability of qualified personnel, shortage of spare parts and poor logistics support such as inaccessibility to specialized equipment. Due to the uncertainties involved in the life extension decision making, decomposition of the system into several interacting components and considering each component separately may be an effective way of modeling the degradation of safety critical systems. Multi-agent architecture, where the system is decomposed into several interconnecting parts can be a useful approach for estimating the impact of remanufacturing on industrial operations during life extension. We propose a multi agent architecture in which each part of the system consists of one or more autonomous agents as shown in Figure 1.

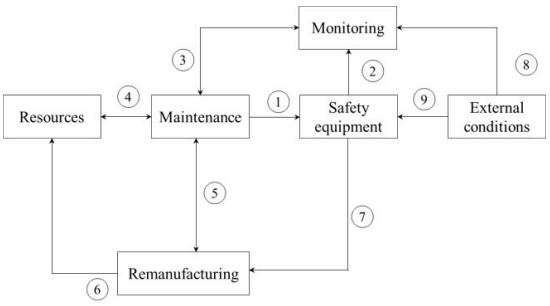


Figure 1. Multi-agent architecture: agents and their interconnections

As shown, the agents included in the life extension decision making problem are: safety equipment, monitoring, maintenance policies, resources (human or technical), external conditions, and remanufacturing. The following subsections explain the role, behavior, composition and the interaction of various agents.

2.1. Safety equipment

A safety equipment is described by a number of factors representing the condition of the components through Equipment Health Index (*EHI*), and the production commodity (e.g. energy, compressed air, oil and gas). Each system is considered autonomous in order to allow each element to interact with other agents such as maintenance, monitoring and external conditions as illustrated in Figure 2.

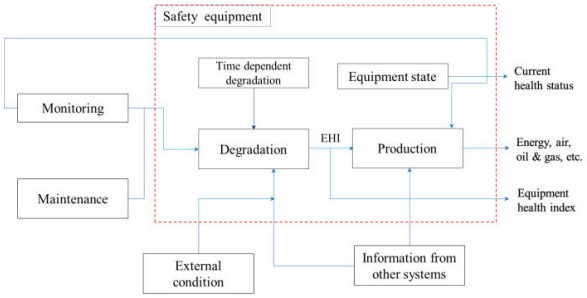


Figure 2. The composition of the safety equipment and its interactions with other agents.

In Figure 2, the composition of the safety equipment and its interactions with other agents are presented. The equipment conditions are based on degradation condition and production level that are influenced by internal variables (e.g. failures that cause downtime and affect production level, preventive maintenance interventions that decrease the degradation rate of the safety equipment) and external variables that are associated with other agents. For example, the weather condition is considered as an external variable affecting the degradation of the safety equipment and resulting in larger failure rate. The maintenance actions improve the degradation condition and production level of the safety equipment. It is assumed that the safety equipment shutdowns during maintenance and remanufacturing processes. However, since the safety equipment is considered to be at the 'wear-out' stage of the so called 'bathtub curve' with an increasing failure rate, the maintenance will bring back the safety equipment to an operating state between as-good-as-new (AGAN) and as-bad-as-old (ABAO), implying *imperfect* maintenance [23].

EHI considers time-dependent degradation varying from 10 (the safety equipment is remanufactured to like-new condition with equivalent warranty to OEM) to 0 (the safety equipment has failed). The *EHI* of a safety equipment decreases with time due to ageing mechanisms such as wear and corrosion due to weather and operational conditions. Therefore, the *EHI* of the safety equipment i at the instant j+1 is expressed as:

$$EHI_i(j+1) = \begin{cases} 0 & if\ \ f_i(j+1)=1 \\ EHI_{\max} & if\ \ R_i(j+1)=1 \\ \gamma_i(j).[EHI_i(j)-\deg(j+1)] & otherwise \end{cases}, \quad (1)$$

where f_i (j+1) represents the probability that a failure occurring at the instant j+1 stops the safety equipment i from functioning. It is assumed to follow the Weibull distribution function. $EHI_{\max}$ is the value of *EHI* when the safety equipment condition after remanufacturing action becomes like-new. In this case, $EHI_{\max}$ is assigned a value of 10. R_i (j+1) is a variable equalling to one if the safety equipment i is remanufactured; otherwise, it will be zero. $deg(j+1)$ represents the status of degradation of the safety equipment in time and is assumed to be proportional to the health condition of the safety equipment, i.e., $EHI_{\max} - EHI(j)$. Then, the degradation model is expressed as:

$$\deg(j+1) = \psi \times (EHI_{\max} - EHI(j)), \quad (2)$$

where ψ represents an empirical value ensuring that *EHI* will equal to zero at the end of life expectancy, e.g. fifty years. The coefficient $0 \le \gamma_i(j) \le 1$ represents the effect of external conditions on the safety equipment degradation and is calculated using the following equation:

$$\gamma_i(j) = \gamma_i^1(j) \times \gamma_i^2(j) \times ... \times \gamma_i^k(j), \quad (3)$$

where k represents the number of different external conditions to be taken into account, including temperature, wind speed, lighting, etc. The values of $\gamma_i^k(j)$ are between zero and one (inclusively) and are predicted empirically based on factors such as geographical location, season of the year, etc.

2.2. External events

The external events may impact degradation status of safety equipment as well as performance of monitoring system. These events represent weather conditions or natural events such as lightning, vandalism, etc. The external event considered in this paper includes the weather effects which depend on variations in meteorological conditions, geographical location of operation, and seasonal changes. The behavior of the external event is defined by a function which predicts weather conditions and determines the impact of weather variations on the functionality of safety equipment.

2.3. Resources

Dahane *et al.* [22] classified the resources required for life extension of safety critical systems into human and material resources. The human resources required for maintenance and remanufacturing actions includes engineers, technicians and administrative staff. Material resources involve logistics support such as service boat, supply vessel, cranes and spare parts. The use of material resources could result in cost and carbon footprint while human resources only incur cost.

2.4. Maintenance policies

The choice of maintenance policy during the extended life period depends on the efficiency of maintenance actions, cost, available resources and operating conditions. These maintenance policies can be categorized into two groups [24]:

- Preventive maintenance (PM): This maintenance policy is largely dependent on the data gathered on performance of the safety equipment via monitoring systems. It is mainly effective where the failure rate of equipment is increasing. Even though PMs can detect most of the sources of faults before they affect the service, there may still be required some reactive maintenance tasks to take place in response to emergency situations.

- Corrective maintenance (CM): This maintenance action is carried out when a failure stops the safety equipment from functioning. This is often an expensive maintenance policy, since it requires hiring service vessels, equipment and a number of sub-contractors and may result in long downtimes.

2.5. Monitoring system

The monitoring system is responsible for data gathering, analysis, planning and scheduling of maintenance activities. Maintenance of the safety equipment is dependent on factors such as degradation level, operational mode, current health status and external conditions. The monitoring system provides information about the safety equipment health status as well as the production levels to ensure that the assets receive timely and reliable maintenance services.

2.6. Remanufacturing

Remanufacturing restores the degradation condition of a safety equipment to like-new condition (i.e. *EHI*=10). Costs of remanufacturing and the associated carbon footprint are taken into account in this study.

3. Cost modeling and carbon footprint assessment

3.1 Cost model

Due to limited resources available for the life extension phase of operation, maintenance cost is considered as a key criterion for decision making. These costs depend on the failure mode, type of maintenance policy, duration for maintenance, weather conditions and the availability of human and material resources. The proposed maintenance cost model interacts with other modules to estimate the total cost of maintenance and associated downtime while safety equipment undergoes scheduled maintenances or remanufacturing. In this cost model, we assumed CM actions are more expensive than PMs and they result in longer downtimes. It is assumed that monitoring system has been already installed and therefore the capital cost of monitoring system is not included. The total of cost maintenance at the instant j over the life extension period, $C_m(j)$ is expressed as:

$$C_m(j) = \sum_{i=1}^{n} [C_{PM_i}(j) \times X_{PM_i}(j) + C_{CM_i}(j) \times X_{CM_i}(j) + C_{D_i}(j) \times X_{D_i}(j)], \quad (4)$$

where n represents the number of safety equipment, $C_{PM_i}(j)$ and $C_{CM_i}(j)$ are the cost of, respectively, PM and CM actions for the safety equipment i at an instant j, $X_{PM_i}(j)$ and $X_{CM_i}(j)$ are binary variables defined as below:

$$X_{PM(CM)_i}(j) = \begin{cases} 1 & \text{If PM (CM) is conducted on safety equipment } i \text{ at the instant } j \\ 0 & otherwise \end{cases} \quad (5)$$

$C_{D_i}(j)$ is the cost of downtime for the safety equipment i at the instant j, and $X_{D_i}(j)$ represents a binary variable that is defined by:

$$X_{D_i}(j) = \begin{cases} 1 & \text{If the safety equipment stops during maintenance action occurring at the instant } j \\ 0 & otherwise \end{cases} \quad (6)$$

On the other side, the total cost of remanufacturing depends on the processes involved in performing the remanufacturing action. The total cost of remanufacturing at the instant j, $C_{REM}(j)$ can be expressed as:

$$C_{REM}(j) = \sum_{i=1}^{n} [C_{REM_i}(j) + C_{D_i}(j) \times Y_{D_i}(j)], \quad (7)$$

where $C_{REM_i}(j)$ represents the cost of remanufacturing at the instant j and is assumed to be linear proportion to cost of manufacturing a new safety element (C_M), i.e. [12],

$$C_{REM_i}(j) = RCR \times C_{M_i}, \quad (8)$$

where $0<RCR<1$ is the remanufacturing cost rate. $Y_{D_i}(j)$ represents a binary variable that is defined by:

$$Y_{D_i}(j) = \begin{cases} 1 & \text{If the safety equipment stops during remanufacturing at the instant } j \\ 0 & otherwise \end{cases} \quad (9)$$

The total cost of maintenance and remanufacturing actions over the life extension period T is calculated as:

$$TC = \sum_{j=1}^{T} [C_m(j) + C_{REM}(j)], \quad (10)$$

where $C_m(j)$ and $C_{REM}(j)$ are given by Eqs. (4) and (7), respectively.

3.2 Carbon footprint assessment

The carbon footprint is determined by calculating the greenhouse gas (GHG) emissions of the safety equipment during maintenance and remanufacturing processes. It includes direct and indirect emissions. In this study, we consider direct emission sources of GHG during the phases of maintenance and remanufacturing. Thus, the total carbon footprint at the instant j, $CF(j)$ is expressed as:

$$CF(j) = \sum_{i=1}^{n} [CF_{PM_i}(j) \times X_{PM_i}(j) + CF_{CM_i}(j) \times X_{CM_i}(j) + CF_{REM_i}(j)], \quad (11)$$

where $CF_{PM_i}(j)$, $CF_{CM_i}(j)$ and $CF_{REM_i}(j)$ represent the carbon footprint due to, respectively, PM, CM and remanufacturing of the safety equipment i at the instant j. The carbon footprint due to remanufacturing action can be calculated using the below equation [11]:

$$CF_{REM_i}(j) = RCFR \times CF_{M_i}, \quad (12)$$

where $RCFR$ is the remanufacturing carbon footprint rate and CF_{M_i} is the carbon footprint due to manufacturing a safety element. Therefore, the total carbon footprint over the life extension period T is expressed as:

$$TCF = \sum_{j=1}^{T} CF(j), \quad (13)$$

where $CF(j)$ is given by Eq. (11).

3.3 Model interactions

In safety critical systems there may exist interactions, communication and exchange of information between different elements. The safety equipment can be affected by external events which impact degradation status and production levels. The monitoring system performs assessment to determine the condition of safety equipment and suggests whether any of the components requires maintenance service. In the case of maintenance, an appropriate maintenance policy is identified and the maintenance resources to undertake the actions are dispatched as needed. The degradation level of the safety equipment is monitored on a regular basis to avoid catastrophic failures. Figure 3 shows the relationship diagram of the safety equipment incorporating the decisions to be made for life extension.

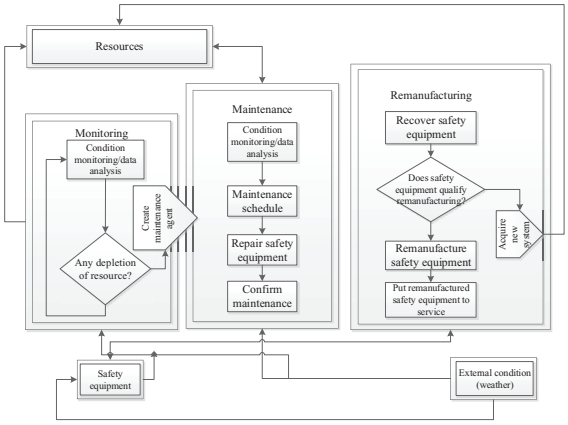


Figure 3. The relationship diagram of a safety equipment for life extension.

When maintenance or remanufacturing task is conformed, the data is recorded and asset returns back to service. Also, the safety equipment cannot be maintained or remanufactured for an infinite time, so there is a threshold of designated life span. At the end of lifetime, the safety equipment is considered for disposal. Table 1 gives the tasks to be carried out and the decisions to be made by each module for life extension of a safety critical asset.

Table 1. Actions and decisions for life extension of safety critical systems.

Decision	Agent	Condition	Actions to achieve decision
Condition data	Monitoring	Data analysis	Extract data and provide results of monitoring
Maintenance scheduling	Monitoring	Duration for maintenance	Determine the next available date for maintenance.
Reliable maintenance action	Maintenance	Degradation level, and availability of resource agent	Arrange maintenance personnel and repair safety equipment
Remanufacturing	Remanufacturing	Availability of resource agent and remanufacturing threshold	Reconditioning of safety equipment and reset of safety equipment degradation level
Degradation	Safety equipment	Weather, degradation level and failure rate	Estimation of safety equipment degradation

4. Illustration by a case

In order to test the applicability of the proposed approach, a case study of 7.5KW industrial air compressor system is provided (Figure 4).



Figure 4. An air compressor system.

The air compressor considered in this study is used to preserve specimen for experiments in the Agrifood laboratories at Cranfield University. A Monte-Carlo simulation (MCS) model is applied to predict the long term impact of maintenance and carbon footprint during the extended lifespan of the air compressor for ten years. The air compressor failures caused a total of 240 hours downtime during the operation cycle of twenty years with a total replacement cost of £25,200. The system degrades with time until the equipment health index (EHI) reaches zero at the end of design life. The results of the analysis are represented in Table 2.

Table 2. Remanufacturing cost and carbon footprint of safety equipment with and without PM

	Without PM	With PM once in a year
Number of failures	3	2
Downtime	240 hours	19 hours
PM cost	0	£392.42
CM cost	£25200	£210
Remanufacturing cost	-	£6878.4
Carbon footprint	640 kg $CO_{2\text{-}e}$	10.49 kg $CO_{2\text{-}e}$

The lack of PM actions increases life extension cost and possibly will affect the economic benefits that may be achieved. A greater discount rate will result in lower remanufacturing cost than the £6878.4. After remanufacturing, the economic health index is assigned the value of 10. This is because there is no considerable difference between remanufacturing action and replacement in terms of improvement of the condition of the air compressor. In the remanufacturing process, 97% of the parts were reprocessed and used while the rest were replaced with new parts. Conducting no PM action during life extension period increases the degradation levels of safety equipment and also increases equipment replacement frequency. On the other hand, implementing PM actions during extended life of operation results in decreased safety equipment degradation, thereby reduction of downtime (in hours) and remanufacturing cost. With an effective PM plan, the air compressor will need to be remanufactured twice in ten years of design lifetime compared to three times being replaced in

the case of no PM action. This makes remanufactured safety equipment economically viable for industrial operations.

From Table 2, the replacement strategy results in higher carbon footprint compared to remanufacturing policy. If the penalty of CO_2 emissions is assumed to be £18 per tonne [25], cost of carbon footprint of a new compressor will equal to £115 while remanufacturing will only cost £0.18. Thus, remanufacturing is not only considered as an economic end-of-life strategy but also as a carbon footprint reduction solution for long term operations.

5. Conclusions and future work

The paper presented an architecture or framework to support life extension decision making of safety critical assets. The proposed approach integrates all elements involved in the life extension decision making, including maintenance management, condition monitoring, remanufacturing and external events that may impact the benefits and costs of life extension process.

In this study, the remanufacturing was suggested as one of the most appropriate strategies for end-of-life of safety related systems and its impacts on industrial operations in terms of total cost and carbon footprint were determined. The results from the analysis showed that remanufacturing can be considered as an effective solution for minimizing total cost and carbon footprint. Furthermore, the use of remanufacturing for life extension delays the replacement of safety equipment, allowing asset managers to save their budget and focus on other investment opportunities.

This study demonstrated that implementing remanufacturing on an industrial air compressor can help achieve technical, economic and environmental benefits simultaneously. Future work will be directed toward analyzing the impact of remanufacturing on a group of safety related systems, since the present analysis focused on a single system. Also, development of an optimization tool for life extension decision making could be an interesting topic of research.

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