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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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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.

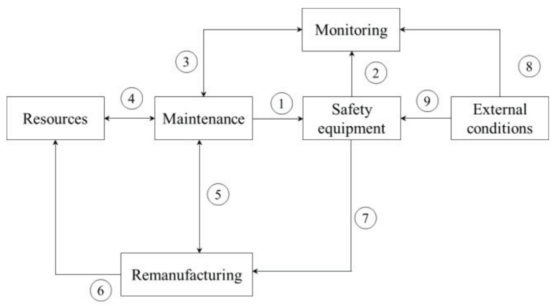

Figure 1. Multi-agent architecture: agents and their interconnections