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Technical Paper

Optimizing upgrade and imperfect preventive maintenance in failure-prone second-hand systems

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ABSTRACT

Upgrade operations are improvement actions that can be carried out on recovered end-of-life systems to rejuvenate them and make them fit for subsequent lifecycles. These operations are costly but improve the reliability of these second-hand systems and consequently can reduce their maintenance costs. In this paper, a mathematical model for the joint determination of the optimal acquisition age, upgrade level, and imperfect preventive maintenance strategy is developed for a second-hand system. The system is acquired and upgraded, if necessary, before being put into operation and preventively maintained each time its reliability reaches a minimum required reliability threshold. Preventive maintenance actions are imperfect and modeled using the hybrid hazard rate approach. Optimality conditions are derived and discussed for general cost structures of the acquisition and upgrade actions. A test case is provided to illustrate the validity of the proposed approach. Numerical experiments and sensitivity analysis are also conducted to investigate the interactions between the upgrade level decisions, the optimal maintenance policy decisions and the total costs incurred during the lifetimes of these refreshed second- hand systems.

1. Introduction

In the past decade, concerns for sustainability have led to the adoption of legislation to force the collection and recovery of end-of-life products, and electronics in particular. This has generated a stream of parts and products that can be reconditioned/refreshed to be reused on assembly lines or in maintenance activities. Many well established e-commerce platforms such as Amazon and EBay facilitate the posting and the sale of used products. The used product market is a lucrative business and has become increasingly attractive. It covers a wide range of used products from mobile phones and transportation engine parts, up to heavy industrial machinery. This new source for components raises many interesting decision-making questions and research problems some of which have been extensively studied by researchers. For example, closed-loop supply chain design and management models, optimal inventory control policies for returned products, and remanufacturing production planning strategies have flourished during the past decade [1–6].

However, important research questions relating to quality, reliability, maintenance engineering and warranty policies for remanufactured systems that will be reintroduced into the market as second-hand or refreshed products have been largely ignored [7,8].

In order to generate demand for reconditioned or second-hand products, manufacturers or dealers/brokers have introduced a combination of initiatives to promote and infer the quality of their products. These initiatives include significant price reductions, generous warranty coverage (same coverage as new systems, free preventive maintenance in the first year of the refreshed system), upgrade of recovered systems before resale [9]. Usually, end-of-life (EOL) products are recovered, sorted and tested before remanufacturing and reuse. Upgrade activities are carried out to bring the recovered systems to better condition and thus effectively reducing their age [10,11]. The cost of this rejuvenating/refreshing action depends on the improvement level carried out and is an expense that can increase the sale price of the reconditioned systems. However, the age reduction provides better reliability that can translate into better performance during operational lifetime. Therefore, trade-offs have to be made to find the best upgrade level for a given age of used products recovered.

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Second-hand systems (SHS) also need to be appropriately maintained to extend their lifetimes and ensure expected performance levels. The combination of upgrade and maintenance actions if well planned and implemented should help second-hand systems perform nearly as well as new systems, while ensuring that resources are not overused by the production of new products and systems.

The purpose of this paper is to introduce a joint upgrade and non-periodic maintenance model with imperfect preventive maintenance (PM) actions for SHS. In the next section, a brief literature review on the upgrade and maintenance models for SHS and imperfect maintenance models is presented and the shortcomings of the current state of the literature are summarized.

2. Literature review

This literature review is divided into two sections: one for the upgrade and maintenance models dealing with SHS and the other for imperfect maintenance models.

2.1. Review of upgrade and maintenance models for second-hand systems

There is a large body of literature devoted to the modeling of maintenance policies and many survey papers have also been published on the subject [12–22]. All the above mentioned works are devoted to new products. The literature dealing with maintenance of second-hand products (SHP) is severely lacking as highlighted by [23,8].

Chattopadhyay and Murthy [24] proposed a probabilistic warranty model for second-hand equipment from the seller's point of view. In their paper, two warranty policies (free replacement and pro-rata) models for second-hand equipment were considered, but they ignored the maintenance cost component. To perform their analysis, the expected warranty costs are computed for monolithic components and systems of components both with known and with uncertain initial ages. To complete the latter approach, Lo and Yu [25] considered a quality management policy for second hand equipment with extended producer responsibility. They proposed warranty models for second hand equipments from the buyers' point of view. They provided a practical application to used cars. In another work, Chattopadhyay and Murthy [26] studied two reliability improvement problems for used items sold with free replacement warranty policy. In their paper, an upgrade is performed on the item before its sale and only minimal repairs are considered during the warranty period. Naini and Shafiee [27] proposed a joint optimal price and upgrade level model for a warranted second-hand product. They presented an application of their model to solve a second-hand electric drills re- manufacturing problem. Chari et al. [28] and [9] developed mathematical models to determine optimal warranty policies with replacements carried out with reconditioned parts. They did not consider any upgrade or PM actions. Recent reviews of quality, reliability, maintenance and warranty issues for these second-hand products appeared in [7,29].

In the existing literature, very few papers explicitly addressed the PM of used items. Pongpech et al. [30] proposed a mathematical model to determine the optimal upgrade and preventive maintenance actions that minimize the total expected maintenance and penalty costs for used equipment under lease. In their model, the PM actions lower the rate of occurrence of failures: the PM actions cannot worsen the failure rate. Yeh et al. [31] proposed two periodical age reduction preventive maintenance (PM) models for a SHP with known age and a pre-specified length of usage. Their objective is to obtain the optimal number of PM actions and the optimal degree of each PM action such that the total expected maintenance cost is minimized. They did not consider any upgrade action. Kim et al. [32] formulated a periodic inspection/upgrade model under free non-renewable warranty policy with a fixed length of warranty period for a second-hand product and jointly determined the optimal number of inspections required and an optimal improvement level to minimize the expected total warranty cost from the perspective of the dealer during the warranty period. They did not include PM actions in their formulation. Shafiee et al. [33], proposed an optimization model to maximize the manufacturer's expected profit. A mathematical formulation with specific cost-structures of acquisition, upgrade and the warranty costs is developed. The optimal expected upgrade level to be performed on the EOL system is determined when minimal repairs are performed at failure. No PM actions are considered. More recently, Sidibé and his co-authors in [34,35] adapted the basic age replacement policy (ARP) developed for new systems to the case of second-hand systems (SHS) that are being used in an environment that is more severe and damaging than during their first life. They modeled the expected cost rate and derived an optimal replacement policy. They did not consider any upgrade operation.

2.2. Imperfect maintenance models

In production and service systems, it is often required to ensure minimum interruptions due to machine failures. PM actions are used to perform maintenance on systems in order to avoid failures and costly downtime. As noted by Lin et al. [36], traditional PM models assume that the system after PM is either *as good as new* (i.e., perfect PM or replacement) or *as bad as old* (i.e., minimal repair). The more realistic and generalized approach is to assume that the system after PM lies somewhere between as good as new and as bad as old, which is called imperfect PM. For example, opening a machine to repair one component may result in damaging other components leading to an increase of the slope of the failure rate function. Another reason is that lack of resources or time may not permit to maintain the system as best as possible. As a consequence, the PM actions occur at an increased frequency (i.e., the intervals between consecutive PM actions reduce as time passes as shown in Fig. 1). At one point, these PM actions are so frequent that it is better to replace the system, hence the interest in finding the optimal number N of PMs before replacement.

The effect of PM actions can be modeled based of their impact on the failure intensity function (or failure rate function) [37]:

(a) Failure intensity/rate adjustment (e.g., [38,39]).
(b) Deceleration of the deteriorating process (e.g., [40]).
(c) Age reduction (e.g., [41,42]).

Hybrid PM models are obtained by combining any two of the three types above (e.g., [43,36]). The hybrid hazard rate approach proposed by [36] combines failure rate adjustment and age reduction approaches. It is a more general and realistic case as it allows the PM action to reduce the effective age to a certain value but also to change the slope of the hazard rate function. Indeed, if the hazard rate function