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Maintenance Strategies and Spare Parts Inventory Management for Use of Reconditioned Items

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Abstract

The maintenance management of construction equipment occupies a prominent place in the overall strategy for managing the equipment fleet. It is also linked to the management of the stock of spare parts and particularly reconditioned spare parts. Because of the relatively low purchase cost of these, most companies are tempted by this option. The purpose of this article is precisely to study the impact of this category of parts in the stock and also in the optimization of maintenance costs, knowing that to do this; their use must obey certain constraints. It is therefore important to be able to characterize these reconditioned parts by estimating their optimal age, and studying their advantages and also their limits. The determination of the optimal age of reconditioned parts will be such that the total cost of replacement with used parts is at most equal to the total cost of replacement with new parts at the end of the operating period.

Keywords

Strategies, Maintenance, Spare Parts, Reconditioned

1. Introduction

The management of spare parts stocks and supplies is part of the overall problem of material management, particularly the modeling and optimization of the use of construction equipment subject to very often random failures.

In any event, materiel management seeks to ensure that it is in good working order at the time it is used, and this performance indicator (also called availability) can be affected by downtime caused by random events. The latter is as undesirable as they can have serious human and financial consequences. And yet the equipment in working order is also undergoing a predictable degradation, which calls for the permanent use of wear and spare parts (in general). If, in addition, said parts necessary for replacing the defective components are not available, then the equipment is permanently immobilized.

To overcome these disadvantages, spare parts are put in stock to allow rapid replacement of faulty components and ensure business continuity. However, this stockpiling is hampered by the clear constraint of the costs of maintaining these parts, which can significantly increase the rental cost, that is to say, the cost price of the equipment to be maintained. It then becomes sensible to express seriously the equipment, the components for which spare parts have been put in stock within the limits of their economic profitability, knowing that, on the one hand, a shortage can prove very costly to the company and on the other hand, the resources are not infinite. The use of used spare parts is an option taken by most construction companies given their maintenance budget, but it must be done optimally.

2. Position of the Problem

The increasing competitiveness of the various construction projects means that managers are increasingly interested in managing the spare parts stock, which is an important lever in the policy of optimizing the costs of equipment maintenance.

The various models presented allow maintenance actions to be taken into account in the management of spare parts stocks. This joint management results in substantial savings. It should be noted, however, that these models consider that replacements are made with new components (or parts). It might be interesting to study the scenario of the use of reconditioned components (parts) and their impact on the management of spare parts stocks.

This article analyzes the impact of reconditioned spare parts on maintenance strategies and inventory management. In addition to environmental and ecological gains, the use of valued products provides economic benefits. Spare parts recovered by disassembling unused equipment are much cheaper than new or repaired parts [1]. It is important to note, however, that reconditioned parts are not always available, either in the quantity or quality desired. This limits, in some cases, their systematic use as spare parts. Moreover, because the reliability of these reconditioned components is lower than the reliability of a new component, the number of system failures using these components is higher. Therefore, a refined economic analysis is needed to decide whether or not to use reconditioned components.

To do this, we will first deal with the impact of reconditioned parts on maintenance strategies, then in a second phase on inventory management.

3. Reconditioned Parts and Maintenance Strategies

3.1. Advantages and Limitations of Refurbished Parts

The main advantage of using reconditioned parts is their low acquisition cost.

Indeed, used or unused equipment, from which spare parts are obtained, is acquired at low prices. In addition, the process of reconditioning these parts can be reduced to cleaning, testing and packaging operations.

[1] report that salvaged spare parts cost up to 80% less than new parts. It is obviously necessary to ensure when buying reconditioned components, their quality and reliability. In general, sellers offer guarantees that reconditioned spare parts will work properly.

The age of a reconditioned component is an important characteristic to take into consideration when acquiring parts because it has a direct impact on the number of accidental failures, the costs of which are generally very high.

3.2. Determining the Optimal Age of Reconditioned Parts

A component of age x is a component that has operated without failure for x units of time. If $f(t)$ denotes the density function associated with the lifetimes of a new component (*i.e.*, of zero age) then, the density function $f_x(t)$ associated with the lifetimes of a component of age x is given by:

$$f_x(t) = \frac{f(x+t)}{R(x)} \tag{1}$$

The reliability $R_x(t)$ of this component of age x is given by:

$$R_x(t) = 1 - F_x(t) \tag{2}$$

Let

$$R_x(t) = \frac{R(x+t)}{R(x)} \tag{3}$$

For a component with non-decreasing failure rate: $R_x(t) \le R(t)$, $\forall x \ge 0$; $\forall t \ge 0$.

For such a component, we say that its distribution function F is NBU (new better than used) ([2] and [3]).

Similarly, it is possible to show that if the component has a non-decreasing failure rate, then its average residual lifetime decreases with age. In addition, one can determine the average number $M_u(T)$ of replacements at failure by using components in an interval $[0, T]$.

If at each failure, the replacement is made by a component of age x and if the original component (the one that is originally put into operation) is also used of age x at the time of its commissioning operation, then:

$$M_u(T) = M_x(T) \tag{4}$$

where $M_u(T)$ satisfies the renewal equation

$$M_x(T) = \int_0^T \left[1 + M_x(T-y)\right] f_x(y)\,\mathrm{d}y \tag{5}$$

Moreover,

$$M_x(T) = \sum_{n=1}^{\infty} F_x^{(n)}(T) \tag{6}$$

$$M_u(T)=\sum_{u=1}^{\infty}F_x^{(n)}(T) \tag{7}$$

where $F_x^{(n)}$ is the n^{th} convolution $F_x(T)$ with itself.

If the component originally put into operation is new and only the components used for replacements are of age x, then the expression for $M_u(T)$ becomes:

$$M_u(T)=\int_0^T\left[1+M_x(T-y)\right]\cdot f(y)\mathrm{d}y \tag{8}$$

Decision model based on reliability characteristics

If for a mission of duration T, the required reliability threshold is equal to R_L, then the age x of the reconditioned spare parts to be purchased must be such that:

$$R_x(t)\geq R_L \tag{9}$$

where $R_x(T)$ is the reliability of a component of age x for a mission of duration T.

It is then sufficient to find x such that:

$$\frac{R(x+T)}{R(x)}\geq R_L \tag{10}$$

If the determination of the age x of the reconditioned component to be purchased is based on its average residual life MRT then, the age x of the components to be supplied must satisfy the following inequality:

$$\frac{\int_x^{\infty}R(t)\mathrm{d}t}{R(x)}\geq MRT \tag{11}$$

Economic Decision Model

Being less reliable, reconditioned components would fail more often with an increasing frequency with their age. It is then necessary to determine the balance point between the gain made on purchase and the repair costs.

Consider equipment operated over a horizon of length T ($T>0$).

Let $CT_N(T)$ be the total cost of replacements with new parts and $CT_R(T)$ the total cost of replacements with reconditioned parts over the operating horizon T.

Each new part costs C.

Each used part of age x costs $(C-C_{\min})\cdot\mathrm{e}^{-bx}+C_{\min}$.

Where b is a parameter that translates the depreciation rate of the purchase cost according to age x, $C_{\min}$ being the minimum purchase cost of reconditioned parts.

Replacements are made at a unit cost C_R.

Let us determine the optimal age of the reconditioned parts, so that the total cost of replacement by used parts is at most equal to the total cost of replacement by new parts at the end of the operating period (**Figure 1**). In both cases, the original component is new.

$$CT_N(T)=(C+C_R)\cdot M(T) \tag{12}$$

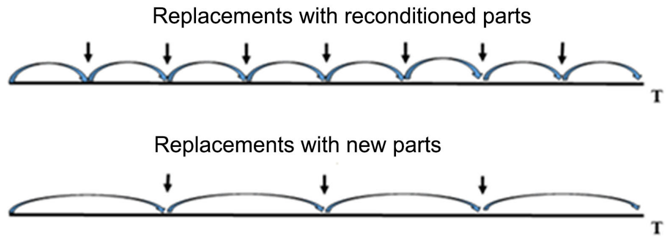

Figure 1. Replacements with new or reconditioned parts.

$$CT_R(T)=\left[(C-C_{\min})\cdot e^{-bx}+C_{\min}+C_R\right]\cdot M_u(T) \tag{13}$$

It is a question of determining the value of x such that:

$$CT_R(T)\le CT_N(T) \tag{14}$$

For any T such that $M_u(T)>0$, this inequality (14) becomes:

$$(C-C_{\min})\cdot e^{-bx}+C_{\min}+C_R-(C+C_R)\cdot\frac{M(T)}{M_u(T)}\le 0 \tag{15}$$

By asking

$$\begin{aligned}\varphi(x)=&(C-C_{\min})\cdot e^{-bx}+C_{\min}+C_R\\&-(C+C_R)\cdot\frac{M(T)}{\int_0^T\left[1+M_x(T-y)\right]\cdot f(y)\,dy}\end{aligned} \tag{16}$$

Age x is obtained by solving the inequality $\varphi(x)\le 0$

Because of the expression of $M(t)$, it is difficult to solve this inequality analytically. It is then necessary to resort to numerical procedures to solve this inequality in the case of any distribution of lifetimes.

To illustrate the use of this model, consider equipment operated over a 15-year horizon ($T=15$) with the following characteristics:

$C = 350$ um, $b = 0.3$; $C_R = 100$ um, $C_{\min} = 50$ um.

$f(t)=t\cdot e^{-t}$ (Gamma – 2 with $\lambda = 1$).

For this particular case, we have: $M(T)=0.5T+0.25e^{-2T}-0.25$

$$M_x(T)=\frac{-x^2-2x-1+\left(x^2+3x+2\right)T+\left(x^2+2x+1\right)e^{\frac{-(x+2)T}{x+1}}}{x^2+4x+4}$$

$$\begin{aligned}\varphi(x)=&(C-C_{\min})\cdot e^{-bx}+C_{\min}+C_R\\&-(C+C_R)\cdot\frac{\left(0.5T+0.25e^{-2T}-0.25\right)\left(x^2+4x+4\right)}{-x^2-2x-1+\left(x^2+2x+1\right)e^{\frac{-(x+2)T}{x+1}}}\end{aligned}$$

By solving the equation $\varphi(x) = 0$, we find the indifference threshold x_L between replacement with new components (parts) and replacement with used components of age x.

In our example, the indifference threshold x_L equals $x_L = 3.09$ years. It is, therefore, profitable to use, for replacements at failure, reconditioned parts whose age is greater than 3.09 years.

The graphical representation of the function $\varphi(x)$ is shown in **Figure 2**. The maximum gain is achieved by using used equipment of age $x^* = 15$ years.

If there is an interval where $\varphi(x)$ is a negative and convex function, then there is a unique and finite optimal age x^* that maximizes the gain from replacing with used components, x^* is the solution of the equation:

$$\frac{\mathrm{d}\varphi(x)}{\mathrm{d}x} = 0 \quad \text{for} \quad x = x^* \tag{17}$$

In summary, it should be noted that the efficient use of reconditioned spare parts is subject to obtaining a compromise between the reduction of maintenance costs and the expected service objectives (reliability or availability).

3.3. Maintenance Strategies Using Reconditioned Parts

The "block type" replacement strategy is one of the best-known and applied maintenance policies thanks in particular to its simplicity of implementation and execution. It suggests using new components to carry out replacements upon failure and at predetermined times kT ($k = 1, 2, 3$, etc.) for preventive replacement. This strategy does not require detailed tracking of repair history [4]. This is why, in some cases, it can lead to a waste of resources since preventive replacements can be carried out shortly after a faulty replacement when the component in operation is almost new.

Several strategies were then developed to allow the reuse of components removed during preventive maintenance or the use of reconditioned parts to carry out replacements upon failure. These strategies can be grouped into three classes:

- The first class includes strategies using minimal repair to failure ([5] and [6]).
- The second class includes strategies that use used parts to replace them when they break down ([7] [8] [9] and [10]).
- The third class includes maintenance strategies that combine minimal repair and the use of used parts.

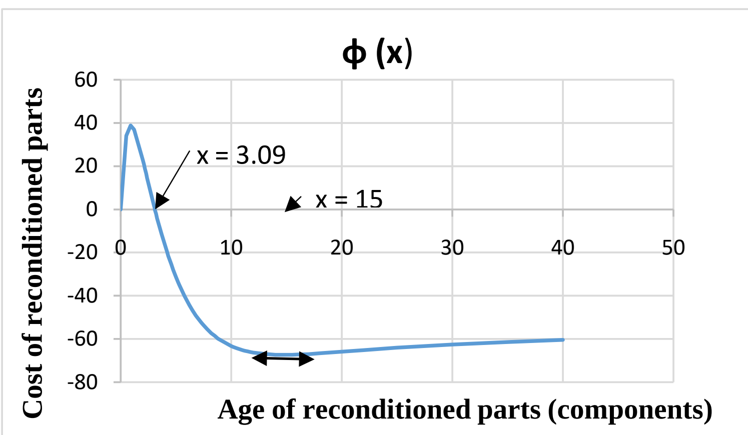

Figure 2. Graphic representation of $\varphi(x)$.

[11] suggests replacing any component that fails with a used one. [4] and [10] divide the preventive replacement cycle of length T into two intervals: $\left[(k-1)T, kT-\delta\right)$ and $(kT-\delta, kT)$. It then proceeds to replacements with new parts at times kT and in the interval $\left[(k-1)T, kT-\delta\right]$. Replacements with used parts of age T take place only if breakdowns occur in the second interval. This strategy avoids having to preventively replace components that are less than δ old.

Rather than being limited to using only used parts of age T like [4] [9] and [10] propose a model which uses all the used parts removed during preventive replacements to carry out replacements at the breakdown.

[7] divide the replacement cycle of length T into three intervals $I_1 = \left[(k-1)T, kT-\delta_1\right]$; $I_2 = \left[(kT-\delta_1), (kT-\delta_2)\right]$; $I_3 = \left[kT-\delta_2, kT\right]$ with $\delta_1 \le \delta_2$. For failures occurring in I_1, replacement is made with new. Replacements with used parts are made for failures occurring in I_2. If a failure occurs in I_3, then no replacement is made and the system remains inactive until the next preventive replacement.

[12] and [13] introduce a model that combines minimal repair and the use of used parts. In the same trend, [14] propose the following strategy:

- Preventive replacement is carried out with new components at times kT;
- (Replacement) upon failure, the cost of a minimum repair is assessed:
  - o If this cost is below a predetermined threshold, then the minimum repair is carried out;
  - o Otherwise, the replacement is made with a used part of age T.

According to the replacement strategies examined, the use of reconditioned parts makes it possible to reduce, in an effective way, the total average cost incurred to carry out preventive and breakdown replacements. Availability gains are also reported.

4. Impact of Reconditioned Parts in Stock

Construction companies often use reconditioned parts or components through their suppliers and dealers. Sometimes also, some can acquire used equipment for the purpose of cannibalization for the recovery of components and reuse them as reconditioned spare parts and add to the traditional mode of supply.

In the classic mode of operation of storage warehouse (**Figure 3**), the requests are satisfied or not depending on the availability of stocks; the store places its orders with its suppliers and is delivered when the supply period expires.

In the operating mode with a return loop of reconditioned parts or recovered from cannibalized equipment (**Figure 4**), the arrivals of these items are naturally random and are added to the quantities received from traditional suppliers.

The problem that then arises is that of determining the quantity to be ordered from suppliers, taking into account the quantities that may come from recovery.

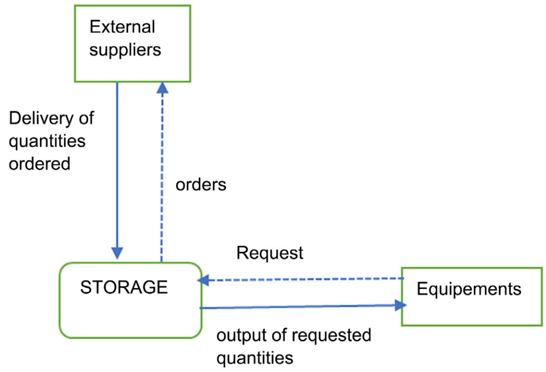

Figure 3. Diagram of transactions in classic inventory management mode.

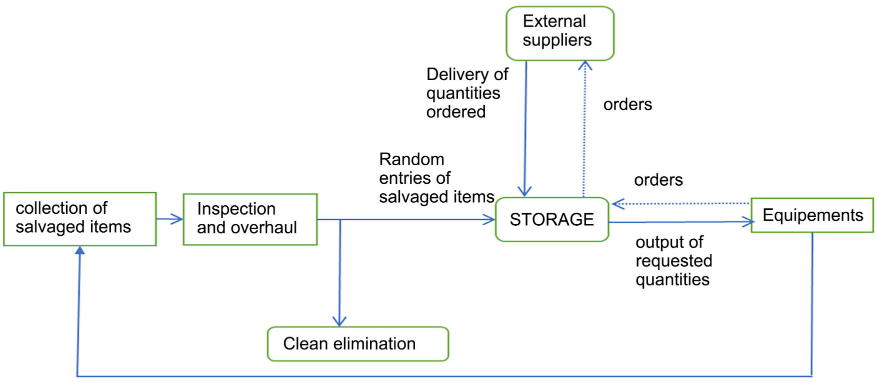

Figure 4. Diagram of transactions in inventory management mode with return.

[15] presents a review of the literature on the contributions to the determination of the parameters of inventory management in the presence of returns. To simplify the problem, it is assumed that reconditioned items are as good as new and that demand can be satisfied by either a new part or a reconditioned part.

The simplest model is the one that addresses the determination of economic quantities to order in the case where the lead time is zero and demand and returns are deterministic and continuous.

[16] was the first to approach this problem by considering a control policy with fixed quantities Q_m of products purchased from the supplier and Q_r of reconditioned products. Each arrival of articles from the supplier is followed by R batches of reconditioned products. Assuming infinite reconditioning and supply capabilities on the part of the supplier, it derives the formulas of Q_m and Q_r similar to Wilson's formula. Several extensions were made to the [16] model, notably by [17] who consider the multi-item case and [18] who are interested in the case with a finite rate of repair.

[19] analyzed the problem more generally by considering that P arrivals from the supplier follow R repackaged batches by including the option of eliminating surplus stocks. Indeed, in an inventory management system with random returns, the arrival of a batch of reconditioned items can cause the stock level to go beyond the maximum stock allowed. It is then necessary to consider the elimi-

nation of this surplus. Some models take this option into account; others do not. [19] demonstrates that, for this control policy, P and R should never be even integers at the same time to guarantee optimality and that the cases $P = 1$ and $R = 1$ are excellent approximations of the optimal policy. It also shows that in most cases, it is optimal either to eliminate all returned items or to recover them entirely. It then derives the expressions of the economic quantities to be ordered.

Several works are also devoted to the study of inventory management when demand and returns are stochastic for both periodic and continuous control policies ([1] [20] [21] [22] and [23]).

[21] consider the case of articles of which a given proportion is returned after a random time of service. The other proportion is considered lost. They model the problem as a stochastic integer program which they transform into a classical lot sizing problem which is solved using the Wagner-Whitin algorithm.

[24] studies a one-item inventory system where the stock level increases with returned items and decreases with demand and considers the disposal option. It shows that the problem is equivalent to a queuing system with a single server. When the demand and the process of returns follow Poisson distributions, it determines the expression of the optimal one-parameter management policy. When the demand and return distributions are general, it approximates the solution.

[22] approach a problem similar to the previous one by taking into account the supposed non-negligible re-machining delays. However, the disposal option is not considered. The demand and the returns are unitary according to a Poisson distribution. The supply control policy with the external supplier is of type (s, Q) and the returned products are recovered (repackaged) as soon as possible. A normal distribution is associated with the stationary net stock to determine the optimal values of s and Q. Muckstadt and Isaac then base themselves on the results obtained in the unitary case to process a 2-level model.

[23] propose an extension of the previous model based on an approximation of the net demand during the supply period to determine the optimal values of s and Q. They also propose an extension to include the disposal option.

[25] use general results from Markovian processes to establish the optimality of the type (s, S) policy when it comes to minimizing the average total cost of management. For this, they show that it is possible to transform the model with returns into its traditional (s, S) equivalent without returns. The main advantage of this approach is that it becomes possible to use traditional resolution algorithms to determine the management parameters (s, S).

When returns and demand follow independent Poisson processes, based on the same transformation principle as before, [15] demonstrates the optimality of the type (s, Q) policy to minimize the average total cost of management.

5. Conclusion

This study shows that the impact of reconditioned and/or recovered parts in maintenance and stock management is a reality. In the construction sector, the subject of this article, spare parts constitute a link between maintenance and stock so that their control becomes an important lever for reducing the unit cost of equipment. And in the specific case of reconditioned spare parts, we are going to be in the context of recovering end-of-cycle or unused equipment were once collected; they are disassembled into components and/or sub-assemblies to be used as parts. Spare parts for other equipment in operation or to various other recovery options. The reconditioned spare parts thus obtained represent an excellent alternative to new parts. And we have just seen under what conditions they can be less expensive while having the characteristics required to ensure the operation of the equipment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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