A decision-making framework to integrate maintenance contract conditions with critical spares management

David R. Godoy, Rodrigo Pascual, Peter Knights

Abstract

Maintenance outsourcing is a strategic driver for asset intensive industries pursuing to enhance supply chain performance. Spare parts management plays a relevant role in this premise since its significant impact on equipment availability, and hence on business success. Designing critical spares policies might therefore seriously affect maintenance contracts profitability, yet service receivers and external providers traditionally attempt to benefit separately. To coordinate both chain parties, we investigated whether the spare components pool should be managed in-house or contracted out. This paper provides a decision-making framework to efficiently integrate contractual conditions with critical spares stockholding. Using an imperfect maintenance strategy over a finite horizon, the scheme maximizes chain returns whilst evaluating the impact of an additional part to stock. As result, an original joint value–preventive interval and stock level– sets the optimal agreement to profitably allocate the components pool within the service contract. Subsidization bonuses on preventive interventions and pooling costs are also estimated to induce the service provider to adjust its policy when needed. The proposed contractual conditions motivate stakeholders to continuously improve maintenance performance and supply practices, thus obtaining higher joint benefits.

1. Introduction

Maintenance outsourcing is a strategic means to improve business performance. Outsourcing creates value through the use of external resources by and for companies to acquire and sustain competitiveness [1]. The maintenance function is a main driver of outsourcing since it has excellent potential to achieve cost benefits and enhance performance among partners [2]. This business purpose is meaningful for asset intensive industries – such as mining, aeronautic, or defence – which face substantial investment in maintaining complex equipment and high demand on system availability. For these firms, the main reasons to contract out maintenance tasks rather than perform them in-house are focusing on core business, accessing highly specialized services at competitive costs, and sharing risks [2–5]. When dealing with outsourcing, effective supply chain coordination allows achieving a rewarding situation for all stakeholders [3]. Accordingly, a model capable of coordinately optimizing performance can lead to successful maintenance contracting strategies in capital intensive environments.

Spare parts management has a critical role toward operational efficiency of asset intensive industries. Equipment criticality is defined by the most relevant assets that efficiently and safely sustain production [6]. The operation of such equipment is consequently supported by critical spare parts [7]. Major spare components are related to considerable investment, high reliability requirements, extended lead times, and plant shutdowns with important effects on operational continuity [8]. A method to prevent production loss events is having inventories at hand, especially when either target service levels or backorder penalties are large [9]. This is the case of capital intensive firms, wherein critical spares storage is directly linked to business success due to the impact of stock-outs on assets utilization [7]. As an example, the aviation supply chain holds a remarkable US$ 50 billion in spare inventories to provide availability service [10]. Efficient critical spares stockholding is therefore essential for companies in which success strongly depends on equipment performance.

Maintenance contracts profitability can be significantly affected by critical spares policies. Particularly, the stock of critical repairable spares can be interpreted as a pool of components from where replacements are satisfied [7]. Consistently with the serious impact on operational and financial performance, managing the pool of critical spare components becomes a key to improve profits within the service contract. Nevertheless, as it depends
on the decision-maker’s position, both supply chain parties – service receiver (client) and external provider (agent) – traditionally intend to maximize benefits separately. If the client controls the spare parts pool, there are scarce incentives for the provider to avoid an indiscriminate use of components aside from regular restraints. Conversely, if the agent administers the pool, rational use of components turns reasonable. Critical spares stockholding is a supply chain lever to keep maintenance outsourcing viable for the parties involved.

In order to coordinate the contracting parties, we investigated whether or not the client should outsource the management of the pool of spare components to the agent. This paper provides a decision-making framework to profitably integrate the contractual maintenance strategy with critical spares stockholding. The scheme is based on a joint value – preventive interval and stock level – that maximizes the supply chain returns whilst evaluating the impact of an additional part to stock. Using an imperfect maintenance strategy over a finite horizon, the model leads to an optimal decision to allocate the critical spare components pool within the outsourcing contract. An interesting link is thus created between maintenance performance indicators and supply chain practices.

Having introduced the importance of allocating critical spare parts management within maintenance service contracts for asset intensive industries, the rest of the paper is organized as follows. Section 2 states the differences between the enriched concept of the present paper and relevant existent researches. Section 3 describes the model formulation to integrate maintenance and spares supply indicators. Section 4 presents a case study in the mining industry, which holds substantial spares inventories to ensure system performance. Finally, Section 5 provides the main implications of applying the joint model to coordinate the outsourcing strategy under an asset management perspective.

3. Model formulation

Consider a system belongs to a fleet of equipment whose operation is supported by a pool of repairable components. The proposed model optimizes the management decisions of critical spare components within the outsourcing service contract. The formulation is presented in three sections as follows: (i) preventive maintenance (PM) policy under the contractual conditions scheme, (ii) service level associated with the stock of critical spare parts, and (iii) decision-making model to integrate PM interval with optimal spares inventory to maximize global profits. The terms “client” and “agent” will henceforth be adopted to indicate service receiver and external provider, respectively.

3.1. Contractual preventive maintenance policy

Let the maintenance of the fleet system be contracted out by the client to the agent. For sake of self-containment, relevant maintenance contract conditions – such as imperfect maintenance and finite contract horizon – developed in [3,4,19] are described in detail. The scheme is set by the following conditions.

- The interval between preventive interventions (PM interval) is $T$.
- The agent is free to select the age $T$ at which PM will be performed.
- Direct costs and length of PM are, respectively, $C_p$ and $T_p$.
- Direct costs and length of corrective interventions are, respectively, $C_r$ and $T_r$.
- The basic service fee to the agent is $p$.
- The net revenue of the client after production costs is $r$.
- The agent sets a minimum expected profit $\pi$ to participate in the game.
- The finite horizon is as the contract lasts from the beginning of a system life cycle to the end of the $n$-th overhaul.

The system has a Weibull distribution with shape parameter $\beta > 1$.  

\[ \beta > 1. \]
The inclusion of imperfect maintenance into the failure rate is based on the system improvement model [19]. Each PM intervention restores the system condition according to
\[
h_k(t) = ah_{k-1}(T-T)+(1-\alpha)h_{k-1}(t)
\]
where \( t \) denotes lifetime, \( k \) corresponds to the index of the \( k \)-th preventive action, and \( \alpha \in [0,1] \) is the maintenance improvement factor.

Before the first preventive intervention, the failure rate is
\[
h(t) = h_0\beta^\alpha - 1, \quad t < T.
\]

The expected number of failures \( H \) after \( n \) overhauls is
\[
H(nT) = \sum_{i=0}^{n} \left( \frac{n!}{i!} \alpha^i(1-\alpha)^{n-i} \right) h_0(t) dt
\]
where \( h_0 \) is the maintenance preventive policy described in the above-mentioned section. Estimation of system availability as a function of critical spare parts stock is adapted from the inventory model for repairable items developed in [18]. For sake of conciseness, a one component case is treated but the extension to multicomponents is straightforward. The approach is as follows.

- The system belonging to the fleet of equipment requires \( i \) types of repairable spare components.
- The fleet size is \( N \) and the multiplicity of each type of spare components in the equipment is \( z_i \).
- Stock level of critical spare parts is \( S \).

### Table 1

Values of \( \kappa \) as inclusion of imperfect maintenance and finite horizon.

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<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>( n^2(1-\alpha) + na )</td>
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<tr>
<td>3</td>
<td>( m(n-1)(n-2)(1-\alpha)^2 + 3m(n-1)(1-\alpha) + n )</td>
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</table>

- Turn-around time, as the workshop repair cycle from removal of a component until readiness to use, is \( T_{ar} \).
- The concept of spare components service level allows incorporating the preventive maintenance policy described in the abovementioned section. Estimation of system availability as a function of critical spare parts stock is adapted from the inventory model for repairable items developed in [18]. For sake of conciseness, a one component case is treated but the extension to multicomponents is straightforward. The approach is as follows.

3.2. Spare components service level

The expected number of failures \( H(nT) \) for repairable items developed in [18]. For sake of conciseness, a one component case is treated but the extension to multicomponents is straightforward. The approach is as follows.

- The system belonging to the fleet of equipment requires \( i \) types of repairable spare components.
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We propose the following approach to incorporate the impact of PM interval on the critical spare parts demand to work. The expected number of failures for any non-homogeneous Poisson process.

\[
\lambda(t) = \frac{N\lambda}{MTBI(t) + T_p R(t) + T_c (1 - R(t))}
\]

where \( R(t) \) is the reliability function at \( T \) and \( MTBI(T) = \int_0^T R(t) dt \) is the mean time between interventions.

Expected backorders with spares stock level \( S \), the unfilled number of demands for not having sufficient inventory, is

\[
EBO(S) = \sum_{j=1}^{\infty} (1 - S)(\beta_j)(T_{ar})(\sum_{j=1}^{\infty} \frac{1}{j!})
\]

Expected service level of equipment given by spares stock is then

\[
A_S(S) = \prod_{j=1}^{\infty} \left( 1 - \frac{EBO(S)}{NE_0} \right) \frac{1}{j!}
\]

where the aim is to maximize equipment availability, or analogously to minimize expected backorders, as a function of the optimal investment in critical spare part inventories.

This service level usually corresponds to the fraction of time that equipment can operate because of critical spare parts that are at hand. Nevertheless, in this indicator it has been included the maintenance policy from the critical system under contracting. In the next section, both maintenance contracts conditions and spare components service level are linked as an integrated approach.

3.3. Optimal integration of maintenance policy with spares service level

The following model provides a decision-making framework to optimally decide whether the spare components pool should be managed by the client or the agent. Taking this premise into account, the system availability of interest is that which integrates the maintenance preventive policy with the spares service level, so that

\[
A(nT,S) = 1 - \prod_{j=1}^{\infty} (1 - A_S(S)) \prod_{j=1}^{\infty} (1 - A_M(S))
\]

where \( A_M(nT) \) is given by Eq. (7) and \( A_S(S) \) by Eq. (10).

Expected global cost of spares inventory \( C_G(S) \) during the contract is

\[
C_G(S) = C_i(S) + C_h(S) + C_d(S)
\]

where

- \( C_i(S) = n_i(S_0 + \sum_j S_j)CRF \) is the discounted acquisition cost of investment in spare parts, where \( n_i \) is the new spare acquisition cost, \( i \) is the discount factor, and

\[
CRF = \left( \frac{(1+i)^nT + T_p}{(1+i)^nT + T_p - 1} \right)
\]

is the capital recovery factor across the contract horizon \( n(T+T_p) \).
- \( C_h(S) = n_h(S_0 + \sum_j S_j)\) is the holding cost for keeping inventories at hand, where \( n_h \) is the holding cost rate.
- \( C_d(S) = \sum_j S_j (1 - A_S(S)) N_j \) is the downtime cost given by the production loss period, where \( \sum_j S_j \) is the downtime cost rate.

This model is capable of efficiently integrating critical spare parts stockholding with outsourcing contracts design. The main options to
handle the spare components pool within the maintenance service contract are presented in the following subsections.

3.3.1. Option 1: client manages the pool of spare parts

Option 1 sets the contractual framework in which the client agrees to manage the pool of spare components. In this scenario, although agreement restraints, there are no major incentives for the agent to avoid an indiscriminate use of components. Following the lead of [3] and [4], profits for the supply chain can be adapted as follows.

Let \( \Pi_c(nT, S) \) be the expected profit for the client. As the client manages the pool, its profit is affected by the entire spares global cost; that is, acquisition cost, holding cost, and downtime cost. Hence, this profit is

\[
\Pi_c(nT, S) = rA(nT, S) - p - C_d(S). \tag{13}
\]

Moreover, let \( \Pi_a(nT, S) \) be the expected profit for the agent. Under this scenario, the profit for the agent is only affected by the service fee and the preventive maintenance cost. That is

\[
\Pi_a(nT, S) = p - C_m(nT). \tag{14}
\]

3.3.2. Option 2: agent manages the pool of spare parts

Option 2 sets the contractual framework in which the agent agrees to manage the pool of spare components. If so, a policy based on rational use of components turns suitable for the agent. Profits for the supply chain are the following.

Although the client does not cover the entire spares global cost, its benefit is still impacted by the related downtime cost. The expected profit for the client is therefore

\[
\Pi_c(nT, S) = rA(nT, S) - p - C_d(S). \tag{15}
\]

As the agent manages the pool, its benefit is affected by both acquisition cost and holding cost. The expected profit for the agent is hereby

\[
\Pi_a(nT, S) = p - C_m(nT) - (C_c(S) + C_h(S)). \tag{16}
\]

Ultimately, the total expected profit for the service chain \( \Pi(nT, S) \) valid for both Option 1 and Option 2 is

\[
\Pi(nT, S) = rA(nT, S) - C_m(nT) - C_c(S). \tag{17}
\]

Using this framework, the chain coordination can be achieved by selecting the optimal joint value \([T, S]\) that maximizes \(\Pi(nT, S)\). This policy profitably allocates the spare components pool, while both contracting parties obtaining higher benefits than pursuing single objectives separately.

3.4. Coordination mechanisms for optimal joint values

Coordination mechanisms can be used to ensure a cooperative setting under the above-mentioned Option 1 and Option 2. Following the lead of [3] and [4], subsidization bonuses on both PM intervals and spares pooling costs can be adapted to set parties’ joint values \([T, S]\) with the one of the supply chain.

3.4.1. Cost subsidization under Option 1

When the PM interval of the agent is higher than optimal \( T \) of the supply chain, the client agrees to subsidize the direct cost of PM to create an incentive for the agent. If let \( \Delta C_p \) be the PM subsidization bonus, the new preventive cost is

\[
C'_p = C_p - \Delta C_p. \tag{18}
\]

The expected profit for the client adding the PM bonus effect is

\[
\Pi_c(nT, S) = rA(nT, S) - p - C_d(S) - \frac{n\Delta C_p}{T + T_p} \tag{19}
\]

\[
= rA(nT, S) - p - C_d(nT) - \frac{\Delta C_p}{T + T_p} \tag{20}
\]

The expected profit for the agent adding the pooling bonus effect is

\[
\Pi_a(nT, S) = rA(nT, S) - p - C_m(nT) - \Delta C_u - \frac{n\Delta C_p}{T + T_p} \tag{22}
\]

\[
= p - C_m(nT) - \frac{\Delta C_p}{T + T_p} - \Delta C_u \tag{23}
\]

With the optimal selection of \( \Delta C_u \), the agent is encouraged to adjust its PM interval as needed for chain coordination.

3.4.2. Cost subsidization under Option 2

Since under Option 2 the agent manages the pool, another mechanism is needed to cope with its extra acquisition and holding costs. Although similar to the aforesaid PM bonus, this model is rather based on subsidizing the spares pooling cost. The scheme creates an incentive for selecting the optimal stock level of the chain, while it keeps the benefits of adjusting the PM interval. Let \( \Delta C_u \) be the inventory subsidization bonus, the new acquisition cost is thus

\[
c'_u = c_u - \Delta c_u. \tag{21}
\]

The expected profit for the client adding the pooling bonus effect is

\[
\Pi_c(nT, S) = rA(nT, S) - p - C_d(S) - \frac{\Delta C_p}{T + T_p} - \Delta C_u \left( S_0 + \sum_j S_j \right) \tag{22}
\]

The expected profit for the agent adding the pooling bonus effect is

\[
\Pi_a(nT, S) = p - C_m(nT) - (C_c(S) + C_h(S)) - \frac{\Delta C_p}{T + T_p} + \Delta C_u \left( S_0 + \sum_j S_j \right) \tag{23}
\]

The cost subsidization models for Option 1 and Option 2 induce the agent to optimally perform both maintenance and stockholding services. Such policy ensures maximum supply chain performance.

4. Case study

In the following case study, the critical components of interest are principal alternators of a fleet of haul trucks operating in a copper mining company. This client contracts out the fleet maintenance service to a specialized agent attempting to ensure high equipment performance. The parameters for the preventive

<table>
<thead>
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<th>Table 2: Parameters for the joint maintenance-stockholding model.</th>
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<tbody>
<tr>
<td>Management area</td>
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<tr>
<td>Preventive maintenance strategy ( h_0 )</td>
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<tr>
<td>( r )</td>
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<tr>
<td>Spare components stockholding ( N )</td>
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<td>( T_{at} )</td>
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maintenance strategy and spare components stockholding are shown in Table 2.

Fig. 1 shows the system availability resulting in merging of both the availability related to maintenance strategy and the spare stockholding service level. Higher service level can be provided as the spare stock level increases, but higher investment is required. Moreover, the optimal PM interval \( T \) changes over the associated spare stock range. Under the proposed framework, the system availability \( \Pi(nT, S) \) is clearly a performance indicator of interest and thereby it is used to coordinate the chain profits during the contract.

Figs. 2 and 3 reveal the differences in profits depending on the allocating position of the critical spare components pool. The results of the aforementioned Option 1 and Option 2 are obtained by solving Eqs. (13–17) as follows. When the agent manages the pool, the joint values \([T, S]\) are \([18 \times 10^3, 0]\) for the agent and \([11 \times 10^3, 3]\) for the client. The corresponding single profits are \(\Pi_a(nT, S) = US\, 287,888\) and \(\Pi_c(nT, S) = US\, 935,142\). Conversely, when the agent manages the pool, the joint values are \([18 \times 10^3, 0]\) for the agent and \([10 \times 10^3, 10]\) for the client. The respective single profits are \(\Pi_a(nT, S) = US\, 287,888\) and \(\Pi_c(nT, S) = US\, 1,149,772\). It is considered that \(\pi\) is set to fulfill the profit constraint \(\pi\). Before subsidization, the corresponding profits for the supply chain by using optimal parties \(T^*\) intervals are \(\Pi(nT^*, S) = US\, 1,169,230\) and \(\Pi(nT^*, S^*) = US\, 1,211,243\) for Option 1, and \(\Pi(nT^*, S) = US\, 1,169,230\) and \(\Pi(nT^*, S^*) = US\, 1,206,436\) for Option 2. However, the optimal supply chain joint value \([T^*, S^*]\) is \([15 \times 10^3, 3]\), which leads to a higher profit \(\Pi(nT, S) = US\, 1,219,018\). Therefore, the optimal duration of the contract is \(n(T^* + T_p) = 5(15 + 1) \times 10^3 = 80 \times 10^3\) (h).

From the previous results, it is clear that taking into account the entire supply chain is the best possible scenario. As anticipated, the agent must be motivated to adjust its PM interval and stock as needed for chain coordination. To achieve this result, the cooperative mechanisms described in Section 3.4 are used. Under Option 1, the interval of the agent is certainly higher than desired, thus the client subsidizes the PM cost. In this case, \(\Delta C_p = 2.853\) sets the agent’s PM interval with the optimal interval of the chain, namely from \(T = 18 \times 10^3\) to \(15 \times 10^3\). Under Option 2, it is clear that the agent attempts to keep the stock level as low as possible since the extra acquisition and holding costs. Hence, the client decides to subsidize those significant inventory costs. In this case, \(\Delta C_p = 55.030\) sets the stock level with the optimal stock of the chain.

After subsidization, profits for the whole supply chain by using optimal single intervals align with the maximum value \(\Pi(nT, S) = US\, 1,219,018\). Nonetheless, as expected, the single profits change across options. For example, the client’s profit decreases from US$935,142 (Option 1) and US$1,149,772 (Option 2) to US$915,065 due to the subsidization mechanism, and the agent’s profit increases from US$287,888 to US$303,953. For further details on changes for both subsidization options, Figs. 4 and 5 denote a sensitivity analysis for those optimal joint values that maximize the profit for the entire channel. Note that after the application of both bonuses, the joint values of agent and

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Fig. 1. System availability by integrating \(T\) and \(S\).

Fig. 2. Study of optimal \(T\) and \(S\) when the client manages the pool of spare components.

Fig. 3. Study of optimal \(T\) and \(S\) when the agent manages the pool of spare components.
contractor align with the optimal joint value of the supply chain \([15 \times 10^2, 3]\). Hence, the desired coordination is achieved. As demonstrated, the supply chain benefit is higher than those single profits obtained by the contracting parties. Consequently, the proposed framework motivates both chain parties to improve their maintenance and supply services continuously.

5. Conclusions

This paper has introduced a model for defining the optimal manager of the pool of components within outsourcing services. A decision-making framework has been provided to integrate preventive maintenance with critical spares stockholding for contract profitability. Using an imperfect maintenance strategy over a finite horizon, the allocation scheme induces the parties involved to perform maintenance and supply activities cooperatively, rather than a separated non-optimal way. This aim is achieved by setting an original joint value consisting of the preventive maintenance interval and the spare parts stock level that maximizes the total expected profit for both client and agent.

It has been found that the joint values reach the supply chain coordination for the two options under study, when the client administers the spare components and when the agent is the pool manager. However, there are scenarios where the expected profit is not sufficient to drive changes in the policy. To provide an incentive to set parties’ joint values with the optimal benefit of the supply chain, subsidization bonuses on both additional PM performed and spares pooling costs are practicable methods. The procedure to estimate such bonuses has been developed.

Finally, we have demonstrated that the model is capable of coordinately optimizing business performance for the entire supply chain. Both client and agent are encouraged to continually improve their maintenance services and supply practices, thus obtaining higher joint benefits compared to those single profits when no coordination occurs. Accordingly, this research has built an interesting bridge between the decision areas of preventive maintenance strategy and spare parts management.

Acknowledgments

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