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S. Behfard, M.C. van der Heijden, A. Al Hanbali, W.H.M. Zijm

Beta Working Paper series 429

BETA publicatie	WP 429 (working paper)
ISBN	
ISSN	
NUR	804
Eindhoven	August 2013

Last Time Buy and Repair Decisions for Spare Parts

S. Behfard¹, M.C. van der Heijden, A. Al Hanbali, and W.H.M. Zijm
University of Twente, School of Management and Governance, P.O. Box 217,
7500 AE Enschede, The Netherlands

Abstract

Original Equipment Manufacturers (OEM's) of advanced capital goods often offer service contracts for system support to their customers, for which spare parts are needed. Due to technological changes, suppliers of spare parts may stop production at some point in time. As a reaction to that decision, an OEM may place a so-called Last Time Buy (LTB) order to cover demand for spare parts during the remaining service period, which may last for many years. The fact that there might be other alternative sources of supply in the next periods complicates the decision on the LTB. In this paper, we develop a heuristic method to find the near-optimal LTB quantity in presence of an imperfect repair option of the failed parts that can be returned from the field. Comparison of our method to simulation shows high approximation accuracy. Numerical experiments reveal that repair is an excellent option as alternative sourcing, even if it is more expensive than buying a new part, because of postponement of the repair decisions. In addition, we show the impact of other key parameters on costs and LTB quantity.

Keywords: inventory, stochastic processes, spare parts, last time buy, repair

1. Introduction

In this paper, we consider the spare parts supply for advanced capital goods. Examples of these goods are mainframe computer systems, aircrafts, chemical plants, and medical systems. These systems are very expensive and can be in use for a long period (5-30 years). Often, these systems are highly downtime critical, that is, downtime has serious consequences in terms of costs, quality of service, and safety risks.

¹ Corresponding author; phone: +31-53-4894715; e-mail address: s.behfard@utwente.nl

The customers of these systems are often not just interested in acquiring such systems at an affordable price, but far more in a good balance between the resulting Total Cost of Ownership (TCO) and the system availability throughout its lifetime. Often, the support costs for system upkeep during its lifetime constitute a large part of the TCO. For customers however, system use is their core business, and not the system upkeep. Therefore, they often prefer to outsource major parts of system upkeep, either to an OEM or to a specialized service provider, if they can provide a good balance between system uptime and costs of system upkeep. A service contract specifies the services provided and the corresponding service level agreements, such as a maximum problem resolution time, or a minimum system uptime per year. To achieve a high uptime, capital goods are often repaired by replacing failed parts by ready-to-use parts from inventory. Therefore, service providers should offer high spare parts availability.

Due to technological developments and the introduction of new systems, the demand for specific spare parts may significantly drop after some time, causing the manufacturer of these parts to decide that it is not profitable anymore to produce them. This point in time may be many years before the time that service obligations end. As a result, the service provider has to decide how to cover future demand until the end of the service period. This decision is inevitably hard, due to the long remaining period and the high level of uncertainty in demand, arising from uncertainty in the size of the installed base and the parts failure rate.

Placing a large final order, a so-called Last Time Buy (LTB) order, is common in industry. Often, the LTB order quantity is very large to attain a high service level, which also yields high obsolescence levels at the end of the service period. Therefore, companies try to mitigate these risks and the costs involved by considering alternative sourcing options. Examples are (i) repair of failed parts that are returned from the field, (ii) strip phased-out systems for reusable spare parts, (iii) buy second-hand parts on the open market (iv) substitute by a compatible part (v) system redesign avoiding the need of the specific spare part.

A key advantage of using such alternative supply options is that either the decision to supply parts from alternative options can be postponed, thereby reducing the level of uncertainty to deal with ((i), (ii), (iii)), or that an LTB order is not needed at all ((iv) and (v)). Even though companies use these alternative supply options, they lack decision support tools to make rational trade-offs between the various supply options.

In this paper, we construct a model to determine the LTB quantity by making trade-offs between one alternative supply option, namely repair of the failed parts that are returned from

the field. Typically, only a certain fraction of the failed parts will be returned and diagnosed to be suitable for repair, the so-called return yield. In addition, not all repairs are successful. The repair yield here will typically be less than 100%, although it tends to be relatively high provided that a good prior diagnosis is feasible. We assume a pull policy for the repair of failed parts (i.e., repair on demand), as this is known to be effective (Krikke and Van der Laan, (2011)). We aim to minimize the sum of LTB procurement costs, holding costs of ready-to-use parts, repair costs, shortage costs minus the salvage value. In addition, we aim to evaluate service levels in terms of fill rate and probability of not running out of stock. We develop accurate approximations for performance evaluation and efficient heuristics to optimize the key decisions: the LTB quantity and the repair policy (time-dependent inventory levels).

In the next section, we discuss the related literature and specify our contribution. Next, we present our model in Section 3. Section 4 shows the performance analysis and the optimization heuristic when repairs are assumed perfect. Section 5 extends the model to the case with imperfect repairs. We validate the accuracy of our approximations as well as our optimization heuristic in Section 6. There, we also show the impact of the key input parameters in a numerical experiment. Finally, we summarize our main conclusions and give promising directions for future research in Section 7.

2. Literature review

Research on the LTB problem exists in the area of 1) consumer products, and 2) capital goods. For consumer products that have relatively low value, it is an option to replace the failed product by a new or similar product (Pourakbar et al (2012), Van der Heijden and Iskandar (2012)). This is however not a realistic option for advanced capital goods that may have a product value of several millions of euros. Therefore, systems are repaired by replacing failed parts of modules by spares.

The literature within the field of spare parts management is extensive and covers several decades of research (Sherbrooke (2004), Muckstad (2005)). The specific literature in the area of LTB decisions for spare parts can be classified according to the sourcing options that are used to satisfy demand after stopping the production of spare parts. Early papers solely focus on finding the LTB order quantity for several model variants. More recent papers take into account other sources of supply, in particular, the repair of failed parts, the retrieval of parts from dismantling complete systems that are phased-out, setting up dedicated production runs at higher costs, or ordering from the external market at higher prices (if possible). In Table 1,

we give an overview of papers according to this classification and discuss them in more details.

Literature	Supply option				
	LTB	Repair of failed parts	Retrieve parts from dismantling	Perform extra production	External market
Moore(1971)	<input checked="" type="checkbox"/>				
Ritchie, E., Wilcox, P. (1977)	<input checked="" type="checkbox"/>				
Fortuin, L. (1980)	<input checked="" type="checkbox"/>				
Fortuin, L. (1981)	<input checked="" type="checkbox"/>				
Klein Haneveld, W.K., R.H. Teunter. (1998)	<input checked="" type="checkbox"/>				
Hong, J.S., H.Y. Koo, C.S. Lee, J. Ahn. (2008)	<input checked="" type="checkbox"/>				
Teunter, R.H., L. Fortuin. (1998)	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>		
Teunter, R.H., L. Fortuin. (1999)	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>		
Kleber, R., Schulz, T., Voigt, G. (2012)	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>		
Inderfurth, K., Mukherjee, K. (2008)	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Kleber, R., Inderfurth, K. (2009)	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Pourakbar, M., van der Laan, E., Dekker, R. (2011)	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>		
Teunter, R.H., W.K. Klein Haneveld. (2002)	<input checked="" type="checkbox"/>				<input checked="" type="checkbox"/>
Krikke H.R., Laan E. van der. (2011)	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
Kooten J.P.J. van, T. Tan. (2009)	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>			

Table 1: Overview of existing literature on LTB problem for capital goods

Among the papers that consider the *LTB as the only source of supply*, Moore (1971) is the first to propose a method to forecast the all-time-requirement of service parts. His method does not incorporate stochastic demand. As a result, neither safety stocks nor service levels or stock-out costs can be computed. The latter aspects have been analyzed by Ritchie and Wilcox (1977), Fortuin (1980, 1981), Klein Haneveld and Teunter (1998), and Hong et al (2008) for several model variants.

Table 1 shows that retrieving parts from *dismantling phased-out systems* has received the most attention as alternative source in the literature. A key characteristic in this case is the correlation between demand for parts and supply from dismantling: if systems are phased-out and dismantled, the size of the installed base decreases and thus the number of system failures which initiate the demand for spare parts decreases. At the same time, the supply from dismantling increases. Teunter and Fortuin (1998, 1999) assume that dismantling can be done at negligible costs, which justifies the use of a push policy. That is, every returned system is immediately dismantled. They determine a level and dispose the number of the excess parts above that level in order to avoid high inventory levels. Pourakbar and Dekker (2011) propose a model to find the LTB quantity and non-stationary control levels to retrieve parts from phased-out systems, where timing and quantity of the phase-outs are uncertain. Kleber et al (2012) consider buying back failed systems to retrieve spare parts. They study possible benefits of buying back failed systems compared to other sourcing options such as LTB and trade-in campaigns. The option of *extra dedicated production runs* is studied by Inderfurth and Mukherjee (2008), and Kleber and Inderfurth (2009), next to an LTB order and retrieving parts from dismantling. They propose a heuristic to integrate all the three options in decision-

making under specific conditions. Teunter and Klein Haneveld (2002) consider providing spare parts from the external market at a much higher price. They propose two order-up-to level policies based on the ordering time.

Finally, a few papers consider *repair of failed parts* that are returned from the field. In contrast to dismantling, this source may provide a considerable amount of supply early in the remaining service period when the installed base is still large. A drawback is that repair may be more costly or less successful than retrieving parts from dismantled systems that may still function. The correlation between demand and supply differs from that in the dismantling option: if demand is higher than expected, the supply of failed parts suitable for repair is also higher, which has a damping effect on the total uncertainty throughout the remaining service period. Van Kooten and Tan (2009) study the LTB decision under the repair option as the only alternative. They aim to find the LTB quantity to avoid reaching the maximum number of allowed backorders in the system. They assume that repair is always preferred over LTB, if repair is feasible. They consider a push repair policy in which all the failed parts are repaired immediately. This policy may cause significant obsolescence at the end of the service period.

Krikke and van der Laan (2011) consider both repair of parts retrieved from dismantled systems, and repair of failed parts returned from the field as alternative sourcing options. As described above, both sources of supply depend on the size of the installed base, but in a different way. They develop an approximate method to find a near-optimal LTB quantity while satisfying a maximum stock-out probability just before a phase-out occurs. Timing and quantity of the phase-out returns are known, which may be true in specific business situations only. In addition, only at those points in time that phase-outs occur, a decision can be made on using the alternative options. It means that usage from the alternative sources depends on the frequency of phase-out returns. Failed parts and retrieved parts from phased-out systems are assumed to be immediately available for repair within a short repair lead time of one week.

In this paper, we propose an approximate method to find the near-optimal LTB quantity, and determine a near-optimal repair policy. Our contribution to the existing literature is as follows:

- We decide about the quantity and timing of repairs versus LTB based on an *explicit cost trade-off*. To the best of our knowledge, this has not been considered in the literature so far. Therefore, we show that using the repair option may even be profitable when repair is considerably more expensive than buying a new part.

- We consider a *dynamic* decision model allowing for significant return and repair lead times. We combine this with a distinction between *return yield* and *repair yield*. Thereby, we also aim to avoid intermediate stock-outs.
- We evaluate *service levels* (fill rate, probability of running out of stock) and their behavior over the remaining service period. This is relevant, since in practice stock-outs are less acceptable early in the service period than close to the end of the service period.

3. Model description, assumptions, and notation

3.1. Model description

We consider a single part for which a LTB decision should be made, independent of other parts. In order to facilitate the optimization, we discretize time in a finite number of disjoint time intervals, each equal to the review period of the repair process, e.g., a month or a quarter. Demand arises from part failures in the installed base. Replacement parts are supplied from a stock of ready-to-use parts (including the parts acquired as LTB and repaired parts). A failed part is immediately replaced by a ready-to-use part from stock on hand, either a new part or a repaired part. All demand that cannot be satisfied from stock on hand is backordered until ready-to-use parts arrive from the repair process. We assume infinite repair capacity, which means that the repair lead time is not influenced by the load of the repair shop. Figure 1 shows a schematic view of the operational process.

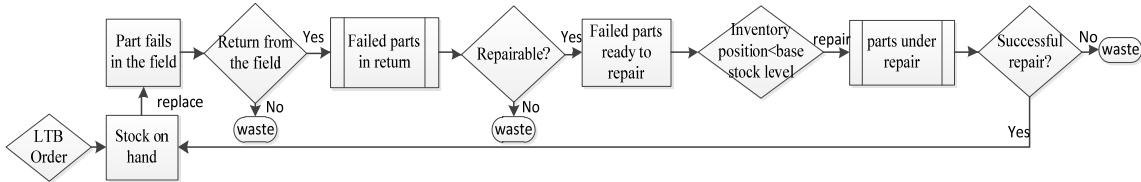


Figure 1: Operational process

A certain fraction of failed parts at time t can and will be returned for repair, which we model by a return yield. The return yield also covers a possible entrance diagnosis upon receipt from the field. Diagnosis is done after receipt, since we are not sure whether all the failed parts returned from the field are suitable for repair. Therefore, any part included in the return yield is ready for repair in principle. In the remainder of this paper, we will just use the phrase “return yield” for ease of presentation. We model the time between part failure and availability of the failed part for possible repair as a deterministic return lead time. We use a *push policy* for the return process, so returns are not delayed until failed parts are actually needed for repair. Although this may not be optimal, the return costs will generally be considerably less than the repair costs for expensive spare parts.

In contrast to the return process, we control the repair process by a *pull policy*, as repair is typically rather expensive. Then, it is not cost effective to repair more parts than what is actually needed to satisfy demand. We use a *base stock policy* for repair, i.e., at each review period we order a number of failed parts to be repaired such that the inventory position (i.e. the sum of new, repaired, and in repair parts) is raised to the time-dependent base stock level s_t (the time dependency of the levels is due to the fact that demand is non-stationary over the planning period. We will argue that a base stock policy is optimal if there are no fixed setup costs for repair and if all repairs are always successful. However, if only a certain fraction of the repairs is successful (repair yield < 1), a base stock policy can be shown to be non-optimal due to uncertainty in the number of successful repairs. In practice, the repair yield will generally be high, because unnecessary and expensive repairs are typically avoided by a preliminary diagnosis. For that reason, we expect the base stock policy to be a good approximation of the optimal policy. This will be affirmed in a small numerical experiment.

We model the time between release of a repair job and job completion by a deterministic repair lead time. In contrast to many other models in the literature and based on what we have observed in practice, we allow both the return lead time and the repair lead time to be large, say several months. The *objective* of our model is to minimize the total relevant costs over the remaining service period between discontinuation of part production (LTB opportunity) and the formal end-of-service date, which may be up to (say) 15 years. The total relevant costs cover procurement of new parts, holding costs of new and repaired parts at the end of each time interval, repair costs of any repair started (whether it is successful or not), shortage costs at the end of each interval, and scrap cost or salvage value of remaining parts at the end of the service period. Further, we compute the time dependent service levels corresponding to the cost-optimal policy, i.e., the cycle service level (probability of no stock-out) and the fill rate (fraction of demand served from stock on hand) at the end of each time interval. In this way, we facilitate a trade-off between costs and service levels in case shortage costs are hard to quantify. The *decision variables* of our model consist of the LTB quantity (Q) and the non-stationary base stock levels (s_t) for the repair process during the remaining service period.

The sequence of the events in each time interval is as follows:

1. At the start of the interval:
 - a. arrival of successfully repaired (ready-to-use) parts,
 - b. arrival of ready-to-repair failed parts that have been returned from the field,
 - c. registration of the inventory position,

- d. decision on the quantity of parts to repair.
2. During the interval: realization of demand.
3. At the end of the interval:
 - a. registration of inventory levels (on hand stock, backorders),
 - b. sending back failed parts from the field,
 - c. computation of service levels (probability of no stock out, fill rate),
 - d. computation of operational costs (repair, holding, shortage).

The typical behavior of the inventory position during the planning period is shown in Figure 2. In contrast to the standard base stock policy, the inventory position after reordering may be *higher* than the base stock level due to the parts remaining from the LTB. However, it may also be lower than the base stock level due to lack of failed parts that can be repaired. Stock-outs may occur at any point in time just before repaired parts arrive from the repair process, as well as near the end of the service period.

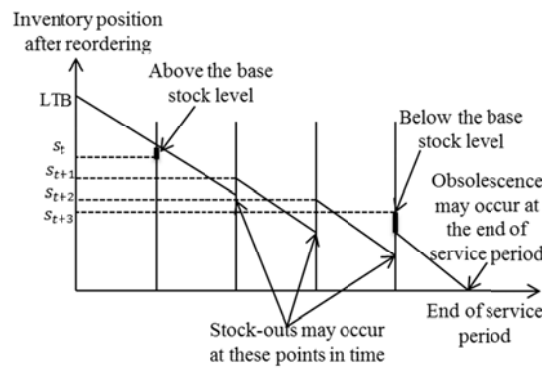


Figure 2: Behavior of the inventory position as function of time

3.2. Assumptions

In addition to model characteristics as described in 3.1, we use the following assumptions:

- Demand is independent over successive time intervals.
- Repair yield is constant over time, since a preliminary quality inspection is being done on the failed parts once they are returned from the field.
- New and repaired parts have the same quality and the same holding costs.
- There is no cost involved for holding the ready-to-repair failed parts as well as non-repairable parts. The extension of the model to consider these costs is straightforward.

3.3. Notation

In the remainder of this paper, we use the following notation:

Input parameters:

t : interval number, $t \in \{1, 2, \dots, T\}$ with T the total number of intervals

- l_2 : return lead time
- l_1 : repair lead time
- h : holding cost per ready-to-use part (new or repaired) at the end of each interval
- c_p : purchasing cost of a new part at the start of the planning period
- $c_{r,t}$: repair cost for each repair started in interval t
- v_s : salvage value per ready-to-use part at the end of the service period
- $c_{b,t}$: shortage cost per ready-to-use part at the end of interval t
- $y_{ret,t}$: return yield, i.e., the fraction of failed parts that are returned from the field at the end of interval t and that are suitable for repair (possibly after a preliminary inspection)
- y_{rep} : repair yield, i.e., the fraction of parts that are successfully repaired
- $p_t(n)$: probability that the demand, D_t , for ready-to-use parts in interval t is equal to n

State variables:

- I_t : inventory position of ready-to-use parts before repair decision at the beginning of interval t
- S_t : inventory position of ready-to-use parts after repair decision at the beginning of interval t
- K_t : number of ready-to-repair failed parts at the beginning of interval t
- OH_t : on-hand inventory of ready-to-use parts at the end of interval t
- BO_t : shortage of ready-to-use parts at the end of interval t

Auxiliary variables:

- D_{t_1,t_2} : accumulated demand in the intervals $\{t_1, \dots, t_2\}$; by convention, $D_{t_1,t_2} = 0$ when $t_2 < t_1$
- $r_t(D_t)$: random number of failed parts that are sent back from the field at the end of interval t , as function of the demand in interval t
- $z(X)$: random number of parts that are repaired successfully, if X repairs have started

Performance indicators:

- β_t : fill rate at the end of interval t
- β : overall fill rate of the planning period
- α_t : cycle service level

Decision variables:

- s_t^* : base stock level of ready-to-use parts at the beginning of interval t
- Q : ready-to-use stock level at the beginning of $t=1$

3.4 Approach

In principle, we can find the optimal repair policy and LTB quantity using stochastic dynamic programming (SDP). There, we find the optimal repair decisions at the beginning of each time interval based on the system state variables at that moment (e.g. ready-to-use, in repair, in return, failed and ready-to-repair parts). However, the state space of this SDP formulation explodes when the demand rates increase, and so do the computation times and the computer memory requirements. Therefore, we apply an approximate method by assuming a base stock

policy for the repair decisions. In Appendix A, we show that this approximation yields a maximum error of 0.9% in total relevant costs based on a small numerical experiment.

4. Performance analysis for perfect repair

It is known from literature that a base stock policy is optimal for dynamic inventory models without fixed ordering costs under general conditions, see Zipkin (2000). In Section 4.1, we summarize the SDP approach to find the base stock levels under infinite supply of failed parts. Next, we argue in Section 4.2 that the same repair policy is optimal for the special case with perfect repair. In Section 4.3, we find expressions for the total relevant costs as function of the base stock levels and the LTB quantity. In Section 4.4, we derive an approximate probability distribution for the inventory position after reordering, which we need to compute the total relevant costs. This is the basis for our algorithm containing a simple numerical search over the LTB quantity to find a near-optimal solution in Section 4.5.

4.1. Optimal base stock levels for infinite source of supply

Following Zipkin (2000), we start with the special case of zero repair lead time. We define the time intervals as stages and the system state as the inventory position before reordering I_t at the start of stage t . The decision in each stage is the base stock level s_t . That is, we order a quantity $\max\{s_t - I_t, 0\}$. We define $V_t(I_t)$ as the minimal expected costs from the start of interval t until the end of the service period given that the inventory position at the start of stage t is I_t . At the end of the planning period, we have the following terminal condition stating that any unused part has salvage value v_s :

$$V_{T+1}(I_{T+1}) = -v_s * I_{T+1} \quad (1)$$

We define $H_t(s_t)$ as the minimum expected relevant costs in the intervals $\{t, \dots, T+1\}$ if we choose s_t as the base stock level and if $I_t = 0$. $H_t(s_t)$ consists of the ordering cost of s_t parts, the expected holding and shortage costs at the end of interval t , denoted by $C_t(s_t)$, and the minimum expected costs from interval $t+1$ onwards. Note that $I_{t+1} = s_t - D_t$:

$$H_t(s_t) = c_{r,t} \cdot s_t + C_t(s_t) + E[V_{t+1}(s_t - D_t)] \quad (2)$$

where $C_t(s_t) = E[h \cdot (I_t - D_t)^+ + c_{b,t} \cdot (D_t - I_t)^+]$. Zipkin (2000) shows that we can find the optimal s_t by minimizing $H_t(s_t)$. Next, we find the value functions $V_t(I_t)$ for all I_t from:

$$V_t(I_t) = -c_{r,t} \cdot I_t + \min_{s_t} \{H_t(s_t) : s_t \geq I_t\} \quad (3)$$

Starting from stage T and moving backward in time, we solve equations (2) and (3) recursively. It is straightforward to extend this approach to strictly positive lead times. Then, a

decision in stage t influences the holding and shortage costs at the end of stage $t + l_1$ (a repair lead time later). Therefore, we can apply the same algorithm, provided that we evaluate the single period costs by $C_t(s_t) = E[h \cdot (I_t - D_{t,t+l_1})^+ + c_{b,t} \cdot (D_{t,t+l_1} - I_t)^+]$. As the first decision is taken at the start of stage $T-l_1$, we find a set of optimal base stock levels

$$s^* = \{s_1^*, s_2^*, \dots, s_{T-l_1}^*\}.$$

4.2. Optimal base stock levels for finite source of supply

Our model differs from the infinite supply model in two ways: (1) the supply of failed parts that are returned from the field in good condition is finite; (2) we have additional supply of parts from the LTB. The first implies that we may not be able to raise the inventory position to its target value; the second means that the inventory position may (strongly) exceed the base stock levels, particularly early in the planning period.

In related literature on models with finite and time-varying (production) capacity, the capacity is modeled either as deterministic, or as random variables which are independent over subsequent intervals, see, e.g., Federgruen and Zipkin (1986), Güllü (1998), and Iida (2002). Under finite capacity, the base stock levels tend to be higher than in the corresponding infinite supply model. The reason is that we should order more when capacity is available to compensate for the fact that capacity may be restricted and insufficient at a later point in time. The key point is that unused (production) capacity is lost. In our model, the latter is not true, because we never scrap failed parts waiting for repair. A failed part in stock can always be repaired in a next interval when it is needed. Therefore, the unused supply of failed parts is never lost and early ordering does not add any value, since we incur more holding costs without avoiding significant shortage costs. As a result, there is no trigger to repair in advance, and so no trigger for higher base stock levels. Therefore, the optimal base stock levels from the infinite supply (capacity) model still apply in our model, see Appendix B for mathematical evidence.

For the computation of the total relevant costs, we have to take into account that the inventory position *after* reordering may differ from the target values s_t^* . It is a random variable S_t that can take on any discrete value within $(-\infty, \max(s_t^*, Q)]$. S_t can exceed the base stock level s_t^* , but it can never be larger than Q (initial ready-to-use stock level) if $Q \geq s_t^*$. In the next section, as a general approach, we derive approximations for the total relevant costs and the related service levels given the initial stock level and the base stock levels. There, we assume that the probability distribution of S_t is already known to us.

4.3. Total relevant costs and fill rates

The total relevant costs consist of holding costs, salvage value, shortage costs, repair costs, and procurement of new parts. Below, we give expressions for each of these cost components, where we use the shortcut notation $X^+ = \max\{X, 0\}$.

Expected on hand inventory:

As the demand in interval 1 will yield receipt of some ready-to-repair parts at the start of interval $2+l_2$, the first time that repaired parts can be available for use is at the start of interval $2+l_2+l_1$, if $2+l_2+l_1 \leq T$. Therefore, repaired parts only arrive in stock at the start of interval $t \in \{l_1+l_2+2, \dots, T\}$. We compute the expected on hand inventory $E[OH_t]$ at the end of interval t by conditioning on the actual inventory position after reordering a repair lead time ago and on the demand during the repair lead time. In time intervals $t \in \{1, \dots, l_1+l_2+1\}$, we only consume from the LTB order, since repairs cannot be completed due to the return and repair lead time. Therefore, the on hand inventory at the end of these intervals depends on the demand only.

$$E[OH_t] = \begin{cases} E[(S_{t-l_1} - D_{t-l_1,t})^+], & l_1 + l_2 + 2 \leq t \leq T, \\ E[(Q - D_{1,t})^+], & 1 \leq t \leq l_1 + l_2 + 1. \end{cases} \quad (4)$$

Expected parts on hand at the end of the service period:

The salvage value is computed based on the parts on hand at the end of the service period $E[OH_T]$.

Expected backorders:

$$E[BO_t] = \begin{cases} E[(D_{t-l_1,t} - S_{t-l_1})^+], & l_1 + l_2 + 2 \leq t \leq T, \\ E[(D_{1,t} - Q)^+], & 1 \leq t \leq l_1 + l_2 + 1. \end{cases} \quad (5)$$

Expected number of repairs:

The usage from the supply and the returned failed parts in previous intervals determine the number of ready-to-repair failed parts K_t at the start of each interval. Defining R_t as the number of repairs started in interval t , we have:

$$R_t = \min\{(s_t^* - S_{t-1} + D_{t-1})^+, K_t\}, \quad (6)$$

$$K_t = K_{t-1} - R_{t-1} + r_{t-l_2-1}(D_{t-l_2-1}). \quad (7)$$

Because there are implicit dependencies among K_t , D_{t-l_2-1} , and S_{t-1} , finding the exact value of $E[R_t]$ is complicated (see Section 4.4.1 for details). As a simple approximation, we use:

$$E[R_t] \cong ((E[S_t] - E[S_{t-1}] + E[D_{t-1}])^+). \quad (8)$$

Aggregating the costs per time interval and adding the purchasing cost for a given value of Q and computed s^* , we find the total relevant costs $TRC(Q, s^*)$ as:

$$TRC(Q, s^*) = Q \cdot c_p + \sum_{t=1}^T h \cdot E[OH_t] - v_s \cdot E[OH_T] + \sum_{t=1}^T c_{b,t} \cdot E[BO_t] + \sum_{t=2+l_2}^{T-l_1} c_{r,t} \cdot E[R_t]. \quad (9)$$

The last term is equal to zero if $l_1+l_2+2>T$. If we have any initial ready-to-use parts before placing the LTB order, we simply deduct its procurement costs when computing $TRC(Q, s^*)$.

Service levels

We compute the fill rates per time interval, the overall fill rate and the cycle service levels as:

$$\beta_t = 1 - \frac{E[BO_t]}{E[D_t]}, \quad (10)$$

$$\beta = 1 - \frac{\sum_{t=1}^T E[BO_t]}{\sum_{t=1}^T E[D_t]}, \quad (11)$$

$$\alpha_t = Pr\{S_t - D_{t,t+l_1} > 0\}. \quad (12)$$

In order to evaluate the above-mentioned performances, we need the probability distribution of S_t . In the next subsection, we derive approximations for this distribution.

4.4. Probability distribution of S_t

S_t depends on the availability of ready-to-repair parts and the base stock levels. In Section 4.4.1, we derive recursive stochastic equations for S_t . As these equations appear to be hard to solve, we derive a simple approximation for the probability distribution of S_t (first approximation) in 4.4.2, which we improve in 4.4.3 (second approximation).

4.4.1. Recursive equations for S_t

The inventory position before reordering at time t is equal to $S_{t-1} - D_{t-1}$. So, we aim to start $(s_t^* - S_{t-1} + D_{t-1})^+$ repairs. As this may not be feasible due to finite supply of failed parts, the actual repair quantity is R_t , given in equation (6). The following stochastic recursion shows the actual inventory position after reordering:

$$S_t = S_{t-1} - D_{t-1} + R_t, \quad \text{where } S_1 = Q. \quad (13)$$

Now, we have three equations (6), (7), and (13) and the complexity is in the term $r_{t-l_2-1}(D_{t-l_2-1})$, since S_t depends on D_{t-l_2-1} as well. Therefore, the three random variables S_t , K_t , R_t are correlated, and we must find the conditional joint distribution of S_t and

K_t given D_{t-l_2-1} . This correlation cannot be easily determined. Therefore, we derive an approximation. The recursive evaluation is an option only if $l_2=0$, which is not a realistic case.

4.4.2. First approximation of S_t

To find the approximate probability distribution of S_t , with related random variable \hat{S}_t , we use the cumulative demand in the intervals $\{1, \dots, t-1\}$ and the cumulative supply of ready-to-repair failed parts in the intervals $\{1, \dots, t-1-l_2\}$. We distinguish three cases:

Case 1: Demand in the first $t-1$ intervals was low, such that the inventory position without any repair from the beginning until $t-1$ exceeds the target level s_t^* :

$$\hat{S}_t = Q - D_{1,t-1}, \quad \text{if } Q - D_{1,t-1} > s_t^*. \quad (14)$$

Case 2: The supply of ready-to-repair failed parts is not sufficient to raise the inventory position to the target level s_t^* . Therefore, the inventory position is equal to the maximum inventory position if *all* the ready-to-repair parts have entered repair:

$$\hat{S}_t = Q - D_{1,t-1} + \sum_{i=1}^{t-l_2-1} r_i(D_i), \quad \text{if } Q - D_{1,t-1} + \sum_{i=1}^{t-l_2-1} r_i(D_i) < s_t^*. \quad (15)$$

Case 3: The supply of ready-to-repair failed parts is sufficient to reach the target level s_t^* . Therefore, there is a need to repair only the required number of parts:

$$\hat{S}_t = s_t^*, \quad \text{if } Q - D_{1,t-1} \leq s_t^* \leq Q - D_{1,t-1} + \sum_{i=1}^{t-l_2-1} r_i(D_i). \quad (16)$$

We refer to Appendix C for details on the evaluation of the stochastic equations (14)-(16).

The key approximation lies in the Cases 1 and 3. In fact, we assume that the inventory position at the start of interval t can only exceed s_t^* if the cumulative demand in the first $t-1$ intervals is less than $Q - s_t^*$ and no repair has been started before. This is correct when the base stock levels are constant or increasing in time. However, if the base stock levels are strictly declining (or declining in part of the planning period) there are other sample paths leading to an inventory position exceeding s_t^* which is not covered under Case 1.

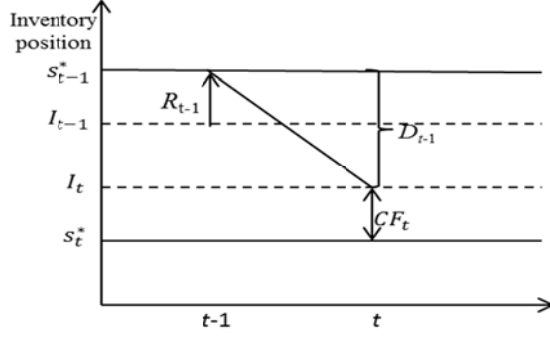


Figure 3: Inventory position above the base stock level (before reordering)

Figure 3 shows an example with $s_t^* < s_{t-1}^*$ (common in an end-of-service situation), where the inventory position before reordering I_{t-1} is less than s_{t-1}^* and $\hat{S}_{t-1} - D_{t-1} > s_t^*$. This means that the inventory position before reordering at the start of interval t may exceed s_t^* , even though $Q - D_{1,t-1} \leq s_t^*$ and based on the three-case categorization inventory position even *after reordering* cannot exceed s_t^* . In this case, we have $(Q - D_{1,t-1} + \sum_{n=2+l_2}^{t-1} R_n > s_t^*)$, where $\sum_{n=2+l_2}^{t-1} R_n > 0$ which means repairs had already been started. By neglecting these possibilities, we underestimate the probability mass for Case 1 and overestimate the probability mass mainly for Case 3. In principle, it may also happen in Case 2 but with negligible probability. Preliminary numerical experiments, in which we compared our approximations to simulation, revealed that this first approximation may cause significant errors in the total costs evaluation for *declining* repair policies. Therefore, in the next subsection we introduce a random variable that partly corrects for this phenomenon.

4.4.3. Second approximation of S_t

The previous arguments in 4.4.2 show that we have to move probability mass from Case 3 to Case 1. We define a random variable CF_t , as the gap between the inventory position *before reordering* and the *base stock level* s_t^* at time t , insofar it is non-negative. We define \tilde{S}_t as the actual inventory position after reordering by adding a correction variable to \hat{S}_t , i.e. $\tilde{S}_t = \hat{S}_t + CF_t$. Note that, since we focus on Case 3 for strictly positive CF_t , $\hat{S}_t = s_t^*$. In order to find the underestimated probabilities, we need to know the probability distribution of CF_t . Hence, $Pr\{CF_t = f\}$ for $f > 0$ exactly states the underestimated probability at $\hat{S}_t = s_t^* + f$ in the first approximation. In order to find $Pr\{\tilde{S}_t = s_t^* + CF_t\}$, we add the underestimated probability (i.e., $Pr\{CF_t = f\}$), to the probability for the same inventory position under Case 1 (i.e., $Pr\{\hat{S}_t = s_t^* + f\}$). We refer to Appendix D for details. After finding the second approximation \tilde{S}_t , we plug the new probability distribution into (4), (5), (8), and (9).

4.5. Algorithm to find the near-optimal LTB quantity

Now that we are able to evaluate the total relevant costs for a given base stock policy and LTB quantity, we apply a numerical search over a range of Q values to find the minimum $TRC(Q, s^*)$ and the near-optimal Q^* . Altogether, this yields the following algorithm:

Step 1: Determine the base stock levels $s^* = \{s_1^*, s_2^*, \dots, s_{T-l_1}^*\}$ (Section 4.1). Initialize $Q = \max\{s_1^*, s_2^*, \dots, s_{T-l_1}^*\}$ and the current value of TRC as very large ($\rightarrow\infty$)

Step 2: Determine the distribution of the actual inventory position after reordering for the base stock policy as found in Step 1 and for the current value of Q using (14),..., (16).

Step 3: Compute total relevant costs TRC_{new} for the given Q and the repair policy using (9).

Step 4: If $TRC_{new} > TRC$, set the near-optimal LTB quantity as $Q^* = Q - 1$. Otherwise, set $TRC := TRC_{new}$, $Q := Q + 1$, and go to Step 2

Step 5: compute the service levels for the Q^* using (10), (11), (12).

This algorithm presumes that the cost function has a single minimum. Although we were not able to prove this, a numerical experiment revealed no example with multiple local minimums. Note that in case of large values for Q , we can improve the efficiency of our algorithm by using a better numerical search procedure, e.g., bisection.

5. Adjustments for imperfect repair

5.1. Approach

It is known from literature that the optimal repair policy is not necessarily a base stock policy when the repair is imperfect, see Henig & Gerchak (1990) and Zipkin (2000). Nevertheless, a base stock policy is a good approximation under our problem settings, see Appendix A. Referring to the arguments from Section 4.2, we conclude that we can still use the base stock levels from the infinite supply model. To include the impact of imperfect repairs, we use order inflation as suggested in Zipkin (2000). It means that with y_{rep} as repair yield and order quantity R_t , we should order R_t / y_{rep} at the beginning of interval t (rounded to an integer).

For approximate evaluation of the inventory position after reordering, we include the effect of failed repairs *immediately after reordering* in the inventory position. That is, a repair order with size R_t contributes to the inventory position as a random variable $z(R_t)$, being the number of successful repairs if R_t repairs have been started. The realization of $z(R_t)$ is only

known after repair completion. As in the case with perfect repair, first we find the first approximation \hat{S}_t and then correct it by means of a correction variable.

5.2. Probability distribution of S_t

As in 4.4.2, we distinguish three cases for the first approximation \hat{S}_t , which are identical to those in 4.4.2. Case 1 is exactly the same as (14). However, here we should include uncertainty in the repair process in Cases 2 and 3, where we start to repair:

Case 2: We take the product of the repair yield and the return yield as a single yield factor. Similar to (15) we find:

$$\hat{S}_t = Q - D_{1,t-1} + z \left[\sum_{i=1}^{t-l_2-1} r_i(D_i) \right], \quad \text{if } Q - D_{1,t-1} + z \left[\sum_{i=1}^{t-l_2-1} r_i(D_i) \right] < s_t^*. \quad (17)$$

Case 3: The key point in this case is the assumption that we can reach the base stock level only in expectation:

$$E[\hat{S}_t] = s_t^*, \quad \text{if } Q - D_{1,t-1} \leq s_t^* \leq Q - D_{1,t-1} + z \left[\sum_{i=1}^{t-l_2-1} r_i(D_i) \right]. \quad (18)$$

The major complexity is in the third case where we need to include the additional uncertainty in \hat{S}_t , in which s_t^* can only be reached in terms of $E[\hat{S}_t]$. This additional uncertainty only exists over the amount in the repair pipeline, i.e., the quantity that has been ordered in the last l_1 periods (repair lead time). We define the random variable \hat{Y}_t as the actual inventory position after reordering in *Case 3*. \hat{Y}_t can be higher, equal or even less than s_t^* due to the inflated number of repair orders and uncertainty in the repair outcome. Therefore, we need to find the distribution of \hat{Y}_t where the uncertainty of repair process is included. Then, we need to include it in the distribution of the first approximation. For doing so, we need to condition on: $Q - D_{1,t-1} \leq s_t^* \leq Q - D_{1,t-1} + z \left[\sum_{i=1}^{t-l_2-1} r_i(D_i) \right]$. This condition makes sure that we focus on the *Case 3*, otherwise it may overlap with the outcomes in the other two cases.

To find the probability distribution of \hat{Y}_t , we compute the first two moments and fit it to a discrete distribution as in Adan et al (1995). Then, we add the resulting probabilities from all possible outcomes of \hat{Y}_t to the resulting probabilities for the same outcomes of \hat{S}_t (under Cases 1, 2). For *Case 3*, we just use the probability at $\hat{Y}_t = s_t^*$ (see Appendix E for details).

To find the correction variable, we follow the same procedure as in 4.4.3. We compute the total relevant costs as in the perfect repair model, except for the repair costs that should be

inflated by the repair yield factor, i.e. $E[R_t]$ is replaced with $E[R_t]/y_{rep}$ in equation (9). Then, the algorithm in 4.5 still applies to find the near-optimal LTB quantity.

6. Validation and sensitivity analysis

We first validate our heuristic by comparison with the results of discrete event simulation. Next, we perform a sensitivity analysis of the performance on the key input parameters.

6.1. Accuracy of approximation

To assess the accuracy of our approximations, we constructed a discrete event simulation model in Plant Simulation. We consider an experiment of 256 problem instances. For each near-optimal solution, we compared the key performance indicators (cost components as mentioned in Table 5 and service levels) to the simulation results. In all instances, the planning period between LTB and end of service is equal to 10 years, divided in 60 intervals of 2 months. The price of a new part is € 1000, and any left part at the end of the service period has no value. The holding costs per piece equal 25% of the new part price per year. For simplicity, we assume that repair cost and shortage cost per part are constant over time. We vary the other key input parameters as stated in Table 3. Even though some scenarios are less realistic, we included them in the experiment to check the approximation accuracy for a large range of problem instances. Table 4 shows four yearly demand patterns arising from the choice of total mean demand (50 or 200) and the variability of demand. To show high and low variability, we consider Negative binomial and Poisson distribution. For the Negative binomial distribution, we assume an increasing coefficient of variation (CV) in order to introduce a higher variability in the later intervals:

Varying parameters	Value 1	Value 2
Repair cost per part	50% of the new part price	150% of the new part price
Shortage cost	1500	25000
per part/interval	(low overall fill rate < 80%)	(high overall fill rate > 98%)
Total expected demand	50	200
Demand distribution	Poisson	Negative binomial
Return yield	0.6	0.9
Repair yield	0.6	0.9
Return lead time	1 (2 months)	3 (6 months)
Repair lead time	2 (2 months)	4 (6 months)

Table 3: Varying parameters in the numerical experiment

Year	1	2	3	4	5	6	7	8	9	10
Mean demand 1 (50)	9	8.50	8	7	5.70	4.40	3	2	1.40	1
Mean demand 2 (200)	38	35	32	28	22	17	12	9	5	2
CV(NegBin)	1	1.05	1.10	1.20	1.45	1.80	2.20	2.50	3	3.50
Variance/Mean (Poisson)	1	1	1	1	1	1	1	1	1	1

Table 4: Yearly demand patterns

All combinations yield $2^8 = 256$ problem instances. For each instance, we find the near-optimal LTB quantity and repair policy, and compare the estimated performance to results from simulation with 100,000 replications, see Table 5 below.

	High overall fill rate		Low overall fill rate	
	Average error	Maximum error	Average error	Maximum error
Total cost	0.3%	0.7%	0.5%	1.1%
Shortage costs	9%	20%	2%	5%
Obsolescence costs	1%	2%	2.50%	5%
Repair cost	2%	4%	4.2%	5.5%
Holding costs	0.2%	0.8%	0.5%	1.6%

Table 5: Relative error of the proposed heuristic compared to simulation

The error in the total costs is small for all problem instances. In most cases, shortage costs are slightly overestimated, while holding and salvage value are slightly underestimated. However, there seem to be significant errors for individual cost components, see e.g. the large maximum relative error in the shortage costs for the cases with high fill rate. In these cases, the absolute value of the shortage is typically *very small*, and so the relative error is large. For example, a 20% shortage cost error arises from an approximate fill rate of 0.995 versus a simulated fill rate of 0.996, which is typically accurate enough (or in terms of shortage quantities: 0.2 versus 0.25). The maximum error in the obsolescence cost and repair cost arises in cases with low overall fill rates (<0.80), while for advanced capital goods very high overall fill rate is necessary.

To examine whether our method finds the correct LTB quantities, we performed a numerical search with our simulation model. We find that our method gives the optimal quantity in 95% of the cases. In the other cases, we found only one unit difference, usually in cases where the total cost difference between the two solutions is very small.

6.2. Sensitivity analysis

We study the impact of key parameters such as repair cost, return and repair yield, return and repair lead time, and demand variability on the performance indicators to explore any structural results. We use a similar demand pattern as before where the demand follows a

negative binomial distribution with total mean equal to 50. The shortage cost is set to 25000, corresponding to an overall fill rate of approximately 98%.

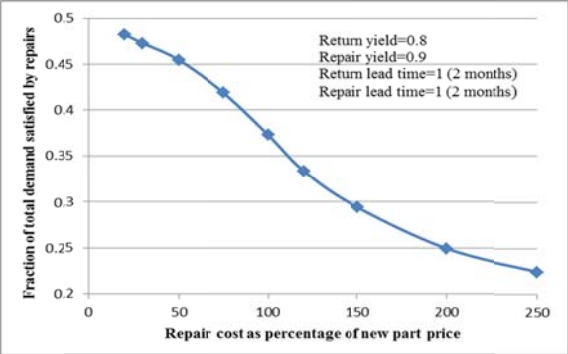


Figure 4: Impact of repair cost on the number of repairs

In Figure 4, we study the impact of repair cost on the fraction of the total demand satisfied by repairs. It shows that we may still use the repair option to fill a significant fraction of demand when the repair cost is considerably higher than the price of a new part. This is the effect of postponement of the repair decisions. With a certain probability, we do not need to repair, and then the sourcing costs are negligible. If we procure a new part at the start of the planning period, it may happen that we do not use it. In the latter case, we incur scrap costs at the end and holding costs over the entire planning period, next to the procurement costs. Therefore, expensive repair may be a better option. For the remaining sensitivity analysis, we set the repair cost to 120% of the new part price to show the impact of yield and lead times when repair is less attractive from costs point of view. For lower repair costs, the impact is higher.

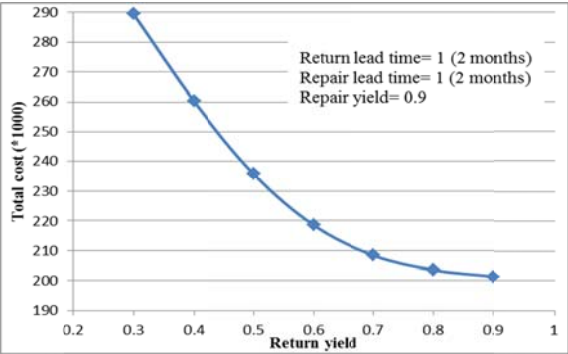


Figure 5: Impact of return yield on total costs

Figure 5 shows how the return and repair yield influence the total costs. A relatively high repair and return yield leads to significant reduction in total costs, even if the repair costs are higher than the price of a new part. It is also remarkable that the decrease in the total costs diminishes when the yield increases. Because of the high repair costs, we need fewer parts for repair than we can retrieve from the field and repair successfully.

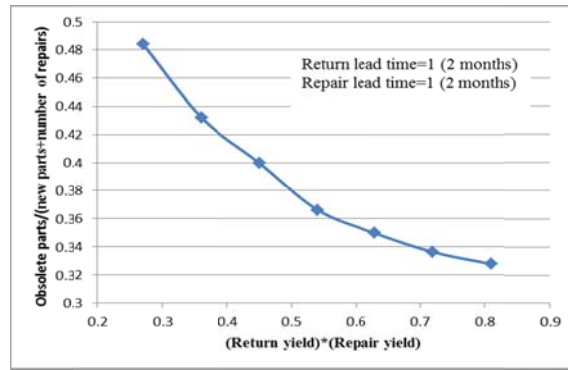


Figure 6: Impact of repair decisions on obsolete parts

Figure 6 shows the impact of yield on obsolete parts at the end of the service period. When return and repair yield are increasing, the number of obsolete parts at the end of the service period is decreasing due to postponement of the repair decisions as discussed before. The large number of obsolete parts at the end of the service period (as an extreme case in this figure) arises from enormous uncertainty in the demand, very high fill rate, and expensive repair cost which yields to larger LTB order at the beginning.

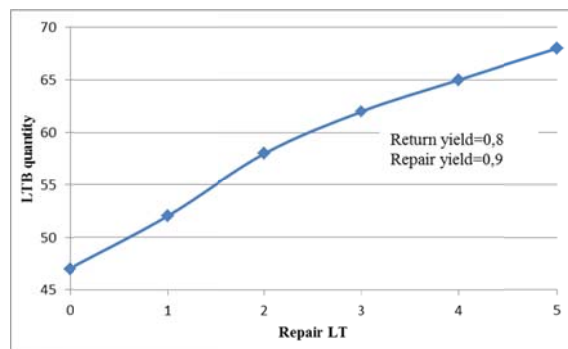


Figure 7: Impact of repair lead time on LTB quantity

In Figure 7, we study the impact of the repair lead time on LTB quantity. For the lead time larger than zero, we fix the return lead time to 1 interval (2 months) and increase the repair lead time. It shows that lead time has significant impact on LTB quantity, particularly in case the repair yield is high. We will see the same affect if we fix repair lead time and vary the return lead time. This shows the importance of including the lead times explicitly in the model. We also noticed that allocation of the total lead time over the return and repair process has little impact on LTB quantity with maximum 3 units difference in this specific instance (e.g. instead of return lead time=1 and repair lead time=1, we may use repair lead time=2 and return lead time=0). Nevertheless, for accurate results we should consider lead time for each process separately.

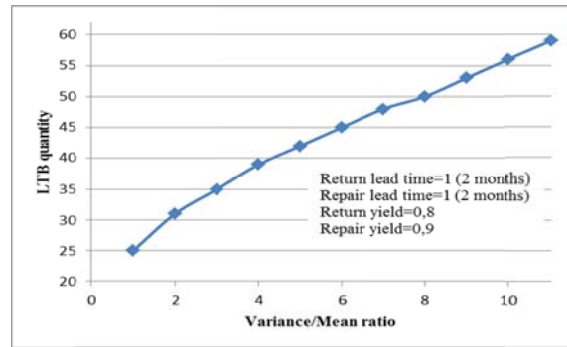


Figure 8: Impact of demand variability on LTB quantity

The impact of the demand variability on the LTB quantity is shown in Figure 8. We increase variance to mean ratio per interval to see how the LTB quantity changes. Variability has relatively significant impact on LTB quantity even for high return and repair yield with short lead times. It means that we need an accurate estimation of the mean demand and variance in order to reduce the required LTB quantity in real cases. We observed in industry that the average demand in the generated forecasts is typically overestimated (biased forecast), while there is not much information about its variability.

7. Conclusions and directions for further research

In this paper, we developed a model to determine the optimal Last Time Buy quantity when supply of spare parts is discontinued and repair of failed parts is possible as alternative sourcing option. Using stochastic dynamic programming to solve the model exactly is not an efficient method for large-scale problems. Therefore, we proposed an efficient heuristic method assuming a base stock policy for repair decisions. We checked the accuracy of our approximation in a numerical experiment and. Then, we studied impact of key parameters on the performance indicators. According to the observed results, we can draw the following conclusions: 1) alternative supply is worth considering even though it is considerably more expensive than the primary source (buying new parts), 2) integration of the LTB decision and repairs has significant impact on reduction of total costs and obsolete parts at the end of the service period while avoiding intermediate shortages, 3) a base stock policy is a good repair policy even for imperfect repairs, 4) the variability of demand has significant impact on LTB quantity; it is important to have an accurate life cycle demand forecasting method.

Our work can be extended in several ways as follow:

- Include the decision when to return failed parts from the field, which results in a two-echelon model,

- Include dispose-down-to level policy for failed parts,
- Modify the formulas for continuous distribution in order to model fast moving parts,
- Include other source of supply as retrieving parts from phased-out systems.

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Appendix A: Impact of using a base stock policy under imperfect repair

In order to see impact of using a base stock policy instead of the optimal repair policy, we conduct an experiment of 16 problem instances. For each instance, we find the LTB quantity and the total relevant costs from both SDP and our approximate method. In all instances, the planning period is equal to 10 intervals. The price of a new part is €10. The holding cost is €2 per part per interval. The repair lead time is one interval. For ease of computation, we use zero return lead time. We vary return yield, repair yield, shortage cost and repair cost as in Table A.1. Table A.2 shows the demand pattern:

Varying parameters	Value 1	Value 2
Repair yield	0.6	0.9
Return yield	0.6	0.9
Shortage cost per part per interval	€ 50	€ 200
Repair cost per part	€ 8	€ 12

Table A.1: Varying parameters

Interval	1	2	3	4	5	6	7	8	9	10
Mean demand (Poisson distribution)	10	9	8	7	6	5	4	3	2	1

Table A.2: Demand pattern

We find that SDP and our approximation using a base stock policy yield the same LTB quantity for all instances. The average error in terms of total relevant costs is 0.9%, whereas the average error is 0.5%. The maximum error arises in cases with low repair yield.

Appendix B: Optimality of infinite supply base stock levels for finite supply models

First, we show that under which condition it is beneficial to order one unit more than the levels found from the model with infinite capacity s_t^* . Then, we show that in our case, this condition does not hold and therefore there is no trigger to order more in advance.

It is beneficial to order one unit more if extra expected holding costs are lower than reduction in expected shortage costs:

$$\begin{aligned}
 & h. \left(E[s_t^* + 1 - D_{t,t+l_1}]^+ - E[s_t^* - D_{t,t+l_1}]^+ \right) \\
 & < b. \left(E[D_{t,t+l_1} - s_t^*]^+ - E[D_{t,t+l_1} - s_t^* - 1]^+ \right)
 \end{aligned} \tag{B.1}$$

We use the following expression to replace the second term in each side of (B.1):

$$E[s_t^* - D_{t,t+l_1}] = E[s_t^* - D_{t,t+l_1}]^+ - E[D_{t,t+l_1} - s_t^*]^+ \tag{B.2}$$

After replacement, we end up with the following condition:

$$E[s_t^* + 1 - D_{t,t+l_1}]^+ - E[s_t^* - D_{t,t+l_1}]^+ < \frac{b}{b+h} \quad (\text{B.3})$$

$$E^*[OH_t] - E[OH_t] < \frac{b}{b+h}$$

$E^*[OH_t]$ is the expected on hand inventory while we order one unit more than the base stock level. According to Zipkin (2000), $(\frac{h}{b+h})$ is the stock-out probability when we order s_t^* parts according to the optimal base stock policy under infinite supply. Therefore, the probability that we do not run out of stock is $(\frac{b}{b+h})$. In all cases that we do not run out of stock, we have one unit more on hand if we order $s_t^* + 1$ units. Therefore, the extra expected on hand inventory equals $(\frac{b}{b+h} \cdot 1)$, which means $OH_t^+ - OH_t = \frac{b}{b+h}$. It is in contradiction with (B.3). If we consider more intervals ahead, the same argumentation holds and extra quantity in the expected on hand inventory will be accumulated in subsequent intervals and becomes even more: $OH_t^+ - OH_t \geq \frac{b}{b+h}$.

This argumentation holds in our case, since we are able to order in the current interval or postpone it to any of the next intervals when it is needed (due to not scraping ready-to-repair failed parts). In addition, repair cost is not computed with discount factor.

Appendix C: Distribution of S_t with perfect repair

The first approximation for the actual inventory position after reordering \hat{S}_t has a probability distribution on the interval $(-\infty, \max(s_t^*, Q)]$ (Section 4.4.2). To facilitate the computations, we only compute the probabilities $Pr\{\hat{S}_t = x\}$ for $x \geq LB_t$, where $Pr\{\hat{S}_t \leq LB_t\} = \varepsilon$ with ε a very small value (we used $\varepsilon = 10^{-6}$).

Based on the three possible cases described in 4.4.2, we find $Pr\{\hat{S}_t = y\}$. For simplicity of notation, we assume that the return yield is independent of time. Extension to a time dependent return yield is straightforward. We denote by $\rho = \{1 - y_{ret}\}$ the fraction of failed parts that are *not returned* from the field or that are *not good enough* for repair. $W_{j,\rho}(i)$ denotes the probability that from j failed parts, at most i parts are *not available* for repair. We define $w_{j,\rho}(i)$ as the corresponding density function. We denote by $q_{t_1,t_2}(n)$ the probability that the accumulated demand in the intervals $\{t_1, \dots, t_2\}$ is equal to n .

Case 1:

The inventory position without any ordering exceeds the target level s_t^* :

$$Pr\{\hat{S}_t = y\} = q_{1,t-1}(Q - y), \quad \text{if} \quad s_t^* < y \leq Q. \quad (\text{C.1})$$

Case 2:

The inventory position is equal to the maximum inventory position if *all* ready-to-repair parts have entered repair. The first two terms in (C.2) show the accumulated demand in the two subset of intervals $\{1, \dots, t-l_2-1\}$ and $\{t-l_2, \dots, t-1\}$ that we have to distinguish because of the return lead time. In the second subset of intervals, only failed parts in the intervals $\{1, \dots, t-l_2-1\}$ can be available for the repair. By definition, the probability that $(Q - y - n_2)$ parts from n_1 failed parts have *not* been returned in good condition equals $w_{n_1, \rho}(Q - y - n_2)$. Then, there are insufficient ready-to-repair parts to raise the inventory position to the base stock level s_t^* :

$$Pr\{\hat{S}_t = y\} = \sum_{n_2=0}^{Q-y} \sum_{n_1=Q-y-n_2}^{\infty} q_{1,t-l_2-1}(n_1) \cdot q_{t-l_2,t-1}(n_2) \cdot w_{n_1, \rho}(Q - y - n_2), \quad (\text{C.2})$$

$$\text{if} \quad y < s_t^*.$$

Case 3:

There are sufficient ready-to-repair failed parts to raise the inventory position to the base stock level s_t^* . The probability that maximum $(Q - y - n_2)$ parts from n_1 failed parts have not been returned in good condition is $W_{n_1, \rho}(Q - y - n_2)$ by definition:

$$Pr\{\hat{S}_t = s_t^*\} = \sum_{n_2=0}^{Q-y} \sum_{n_1=Q-y-n_2}^{\infty} q_{1,t-l_2-1}(n_1) \cdot q_{t-l_2,t-1}(n_2) \cdot W_{n_1, \rho}(Q - y - n_2), \quad (\text{C.3})$$

$$\text{if} \quad y = s_t^*.$$

Appendix D: The distribution of the correction variable CF_t

As explained in Section 4.4.3, we define CF_t as the gap between the inventory position *before reordering* and the *base stock level* at time t , insofar it is nonnegative. CF_t can be strictly positive only under Case 3 in the first approximation. Based on the assumptions in the first approximation the justification is as follows: when $\hat{S}_t > s_t^*$, *no repair* has been started yet and the initial ready-to-use parts are still being consumed. When $\hat{S}_t < s_t^*$, demand was so high (or the number of ready-to-repair failed parts is so low) that even after reordering the inventory position cannot reach s_t^* , therefore the probability of positive CF_t is negligible.

A two-moment approximation for the distribution of CF_t does not yield accurate results, since it does not behave as one of the distributions used in Adan et al (1995). Therefore, we find its distribution by conditioning on \tilde{S}_{t-1} and D_{t-1} :

$$CF_t = (\hat{S}_{t-1} + CF_{t-1} - D_{t-1} - s_t^*)^+ \quad (D.1)$$

$$\tilde{S}_{t-1} = \hat{S}_{t-1} + CF_{t-1}$$

Note that for $\hat{S}_{t-1} \leq s_{t-1}^*$, $CF_{t-1} = 0$ and for $CF_{t-1} > 0$ we already have considered $Pr\{\hat{S}_{t-1} = s_{t-1}^*\}$ while computing $Pr\{CF_{t-1} = i > 0\}$. Also \tilde{S}_{t-1} and D_{t-1} are mutually independent. Using the stochastic equation in (D.1) we find for $f > 0$. :

$$\begin{aligned} Pr\{CF_t = f\} &= \sum_{y=s_t^*+1}^{s_{t-1}^*} Pr\{\hat{S}_{t-1} = y\} \cdot p_{t-1}\{D_{t-1} = y - f - s_t^*\} \cdot Pr\{CF_{t-1} = 0\} \\ &+ \sum_{i=1}^{s_t^* - s_{t-1}^*} Pr\{CF_{t-1} = i\} \cdot p_{t-1}\{D_{t-1} = s_{t-1}^* + i - s_t^* - f\} \end{aligned} \quad (D.2)$$

Note that τ is the first time interval that $s_t^* < s_{t+1}^*$, since the correction variable appears only when base stock level is declining (in case that repair policy is strictly declining over entire period $\tau = 2$). Now, for each $\hat{S}_t > s_t^*$ in the first approximation with the probability $Pr\{\hat{S}_t = y\}$, we add the probability from correction $Pr\{CF_t = y - s_t^*\}$. As a result, we find the second approximation as follows:

$$Pr\{\tilde{S}_t = y\} = \begin{cases} Pr\{\hat{S}_t = y\} & \text{if } y < s_t^* \\ Pr\{\hat{S}_t = y\} \cdot Pr\{CF_t = 0\} + Pr\{CF_t = y - s_t^*\} & \text{if } y > s_t^* \\ 1 - \sum_{i=-\infty}^{s_t^*-1} Pr\{\tilde{S}_t = i\} - \sum_{j=s_t^*+1}^{\max\{Q, s_t^*\}} Pr\{\tilde{S}_t = j\} & \text{if } y = s_t^* \end{cases} \quad (D.3)$$

For $y < s_t^*$, we just use probabilities from the first approximation since there is no correction involved.

Appendix E: Distribution of S_t with imperfect repair

We use a similar approach as for the model with perfect repair (Appendix C). Case 1 is identical to (C.1), since no repair started. Case 2 is identical to (C.2), but we take the product of the repair yield and the return yield as a single yield factor: $\rho = \{1 - y_{ret} \cdot y_{rep}\}$. We mainly have to revise Case 3.

Case 3:

In this case, the (stochastic) amount in the repair pipeline is equal to $(s_t^* - S_{t-l_1-1} + D_{t-l_1-1, t-1})^+ / y_{rep}$. The last two random terms are mutually independent, since the demand included refers to different (adjacent) periods.

This order quantity can be translated into an increase in the inventory position equal to $z\{(s_t^* - S_{t-l_1-1} + D_{t-l_1-1,t-1})^+ / y_{rep}\}$. This random variable exactly represents the variability in the inventory position due to the failed repairs. The output (successful repairs) corresponding to this repair quantity is $z\{(s_t^* - S_{t-l_1-1} + D_{t-l_1-1,t-1}) / y_{rep}\}$, and only this amount is included in the inventory position given by:

$$\hat{S}_t = \hat{S}_{t-l_1-1} - D_{t-l_1-1,t-1} + z\{(s_t^* - \hat{S}_{t-l_1-1} + D_{t-l_1-1,t-1}) / y_{rep}\} \quad (E.1)$$

i.e., the quantity that we had a lead time l_1 ago minus the demand in the last l_1 periods plus the output of the process of ordering up to s_t^* in expectation.

For convenience, we use the shortcut notation U_t :

$$U_t = \left\{ \hat{S}_{t-l_1-1} - D_{t-l_1-1,t-1} \mid Q - D_{1,t-1} \leq s_t^* \leq Q - D_{1,t-1} + z \left[\sum_{i=1}^{t-l_2-1} r_i(D_i) \right] \right\} \quad (E.2)$$

$$\hat{Y}_t = \left\{ \hat{S}_t \mid Q - D_{1,t-1} \leq s_t^* \leq Q - D_{1,t-1} + z \left[\sum_{i=1}^{t-l_2-1} r_i(D_i) \right] \right\} \quad (E.3)$$

So, we have that: $\hat{Y}_t = U_t + z\{(s_t^* - U_t) / y_{rep}\}$. If we ignore that $(s_t^* - U_t) / y_{rep}$ is real-valued, and if $z\{(s_t^* - U_t) / y_{rep}\}$ has a binominal distribution with success rate y_{rep} , we find for the unconditional mean and variance of \hat{Y}_t :

$$E[\hat{Y}_t] = s_t^* \quad (E.4)$$

$$Var[\hat{Y}_t] = Var\{E[\hat{Y}_t | U_t]\} + E[Var(\hat{Y}_t | U_t)] = (1 - y_{rep}) \cdot (s_t^* - E[U_t])$$

We use a two-moment approximation for the discrete distribution of \hat{Y}_t as in Adan et al (1995). Next, we combine this approximate distribution with the first approximation \hat{S}_t . In order to do so, we need to estimate $E[U_t]$ which is not easy to compute due correlations between demands in adjacent periods. As an approximation, we can take into account the most important part of the condition that indicates repairs should have been started, namely: $Q - D_{1,t-1} \leq s_t^*$. Then, we have:

$$EU_t \cong \{\hat{S}_{t-l_1-1} - D_{t-l_1-1,t-1} \mid D_{1,t-1} \geq Q - s_t^*\} \quad (E.5)$$

We rewrite the conditional part $D_{1,t-1} \geq Q - s_t^*$. Then, we can derive a new expression for U_t by looking to the lower bound of $D_{t-l_1-1,t-1}$, since $D_{t-l_1-1,t-1}$ exists in the both sides of the expression in (E.5):

$$\begin{aligned}
U_t &= \{\hat{S}_{t-l_1-1} - D_{t-l_1-1,t-1} | D_{t-l_1-1,t-1} \geq Q - s_t^* - D_{1,t-l_1-2}\} \\
&= \min\{\hat{S}_{t-l_1-1} - D_{t-l_1-1,t-1}, \hat{S}_{t-l_1-1} - Q + s_t^* + D_{1,t-l_1-2}\} \\
&= \hat{S}_{t-l_1-1} - \max\{D_{t-l_1-1,t-1}, Q - s_t^* - D_{1,t-l_1-2}\}
\end{aligned} \tag{E.6}$$

It can be easily found that:

$$E[U_t] \cong E[\hat{S}_{t-l_1-1}] - E[\max\{D_{t-l_1-1,t-1}, Q - s_t^* - D_{1,t-l_1-2}\}] \tag{E.7}$$

Finally, we replace $E[U_t]$ computed from (E.7) into (E.4) to find $Var[\hat{Y}_t]$ and use it in the two-moment approximation of \hat{Y}_t .

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