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REVIEW PAPERS

Spares provisioning strategy for periodically replaced units within the fleet retirement period

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Abstract Within aviation enterprises, the process of dismantling an aircraft at the end of its life is referred to as parting-out. Obviously, the asset value of the units and materials parted out from the retired airframes can be considerable. The benchmarked best practice within the aviation industry is to dismantle the retired aircraft and use the parted-out spares to support the remaining fleet or to offer them on the surplus market. Part-out-based spares provisioning (PBSP) has been a major focus of attention for aviation companies. The PBSP approach is a complex task that requires a multidisciplinary and integrated decision-making process. In order to control the stock level and fulfil the decision criteria within PBSP, it is necessary to make decisions on the termination, at specific times, of both the parting-out process and the maintenance and repair actions performed on the units. This paper considers repairable units and introduces a computational model to identify the applicable alternatives for repair termination times that will minimize the number of remaining spares at the end of the retirement period, while fulfilling the availability requirement for spares during the PBSP period, at the lowest possible cost. The feasible alternatives are compared with regard to their respective costs, and the most cost-effective solution is selected. The cost model uses estimates of future maintenance requirements, the turn-around times, and the cost of the various maintenance tasks, the future spares consumption, and the estimated salvage of spares from retired aircraft. The output of the model is a set of applicable alternatives which satisfy the availability requirements for spares for the active fleet. The method is illustrated using a case study performed on the Saab-105 training aircraft.

Keywords Provisioning · Spare parts · End-of-Life · Maintenance · Retirement · Parting-out · Repairable units · Stock level · Dismantling · Aviation · Life-cycle cost

Abbreviations

CM	Corrective maintenance on units
PBSP	Part-out-based spares provisioning
PM	Preventive maintenance on units
POM	Parting-out maintenance
POD	Parting-out discard
PO	Parting-out process
POS	Parting-out storage
SEK	Swedish crowns
USD	US dollars

Mathematical notation

$C(t_1, t_2, t_3, t_4)$	Cost function associated with termination times for CM, PM, POM and POS
C_{CM}	Cost for a CM action
C_{PM}	Cost for a PM action
C_{POM}	Cost for a POM action
C_{PO}	Cost for a PO action
D_i	The demand for units during month i, due to CM and PM actions

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D	Total demand for units for the whole retirement period, T, due to CM and PM actions
G_i	Number of units received for storage from POS actions for month i
i	Repair termination (month), $i = 1, 2\ldots, T$
$I_{CM,i}, I_{PM,i}, I_{POM,i}, I_{POS,i}$	The status of CM, PM, POM and POS actions, either stopped (0) or on-going (1)
$I_{j,i}$	Matrix describing status of CM, PM, POM and POS with termination times (t_1, t_2, t_3, t_4) for month i
j	PBSP control gates: CM, PM, POM and POS, $j = 1, \ldots, 4$
M_{CM_i}	Number of successfully repaired units during month i, due to CM actions
M_{PM_i}	Number of successfully maintained units during month i, due to PM actions
M_{POM_i}	Number of units entering the repair shop during month i, due to PO actions
M'_{POM_i}	Number of successfully maintained units during month i, due to POM actions
M_{POS_i}	Number of units received for storage during month i, due to PO actions
M_{DOP_i}	Number of units discarded during month i, due to PO actions
N_{CM_i}	Expected number of corrective maintenance actions during month i (a stochastic measure)
N_{PM_i}	Number of preventive maintenance actions during month i (a deterministic measure)
$N_{PO,i}$	Number of parted-out units from retired aircraft during month i
p_1	The probability of a successful repair of units on starting a CM action
p_2	The probability of a successful repair of units on starting a PM action
q_1	The probability that the parted-out unit will be classified as a unit for POM
q_2	The probability that the parted-out unit will be classified as a unit for POS
q_3	The probability that the parted-out unit will be classified as a unit for POD
R_i	Number of units received for storage from the repair shop during month i
S_0	Initial stock level at the start of the retirement period
S_i	The stock level for the non-controlled scenario in month i
S_i^*	The stock level for the controlled scenario in month i
S_T	The stock level for the non-controlled scenario at the end of the termination period, i.e. $i = T$
T	Retirement period (months)
t_1, t_2, t_3, t_4	Termination times (months) for CM, PM, POM and POS actions
U_i	Total number of units received for storage during month i in the non-controlled scenario, from CM, PM, POM and POS actions
U_i^*	Total number of units received for storage during month i in the controlled scenario, from CM, PM, POM and POS actions
w_1	The probability that units coming from POM actions will be discarded at the repair shop
Ω	Repair lead time, associated with CM, PM and POM actions
$\mathcal{O}$	Order or magnitude of an algorithm or a number

1 Introduction and background

Provisioning the maintenance stock is one of the most important functions for the operational success of any asset-intensive industry, such as the aviation industry. The goal of maintenance stock management in aviation is to find a cost-effective stock provisioning, allocation and management system. The main purpose in aviation is to provide upon demand the parts required to maintain a fleet of aircraft, and to achieve a specific level of aircraft availability. According to Díaz and Fu (1997), approximately one third of all assets correspond to stocks. In a survey conducted by Aero Strategy (2010), the average value of the maintenance spares stock per aircraft was reported to be equal to 1.9 million USD, with the weighted average holding cost being estimated to be 21.5%. A properly managed stock also ensures that the human capital of the maintenance personnel is efficiently utilized.

Keeping a reasonable stock service level or “fill rate”, coupled with efficient maintenance practices, ensures a high level of fleet readiness. Key profits can be increased by the improvement of logistics and maintenance performance through more efficient stock management for costly components whose faultless functioning is crucial in asset-intensive industries (Braglia and Frosolini 2013).

Therefore, stock management and spare parts provisioning within the production, operation and maintenance phase of the product lifecycle have attracted a large volume of research. Many researchers have studied the joint-optimization of maintenance and stock provisioning policies for spare part logistics (see e.g. Kiesmuller and Zimmermann 2018; Chen et al. 2006; Geiger et al. 2007; Scarf and Cavalcante 2012; Ilgin and Tunali 2007; Wang et al. 2008; Wang 2011, 2012; Zeng and Wang 2010; Liu et al. 2013; Lynch et al. 2013; Zahedi-Hosseini et al. 2017; Zhang and Zeng 2017). In addition, Ferreira and Wang (Ferreira and Wang 2012) proposed a hybrid of simulation and analytical models for spare parts optimization, taking into account the residual life of equipment estimated by using condition monitoring techniques. Liao and Rausch (2010) addressed the issue of a joint production and spare parts stock control strategy driven by condition-based maintenance (CBM). It can be noted that most maintenance policies assume that failed or used components are replaced with identical units. Actually, such a hypothesis neglects the possible obsolescence of components and the existence of alternative components and suppliers, which affects stock forecasting (Mercier and Labeau 2004). Some researchers have considered the obsolescence problem in their optimization models (see e.g. Arcelus et al. 2006). The design of a spare parts stock by its very nature involves risk management. It is a multi-phase task to meet the associated economic and technical requirements. A typical target is to optimize the size of the stock by balancing the costs against the stock-out risk (Hagmark and Pernu 2006). To this end, Bharadwaj et al. (2009) introduced a risk-based methodology for spare parts stock optimization, and Hagmark and Pernu (2006) studied the risk evaluation of a spare parts stock by stochastic simulation. Many others have studied the optimization of spares allocation for multi-echelon spare parts stock systems (see e.g. Alkhamis and Ahmed 2005, 2006; Cheng et al. 2008; Levner et al. 2011; Li et al. 2009; Nowicki et al. 2012; Sun and Zuo 2010; Sun et al. 2013; Wang and Kang 2009). In addition, several research studies have dealt with the classification of spare parts to facilitate decision making (see e.g. Braglia et al. 2004; Cavalieri et al. 2008; Zheng et al. 2010; Bacchetti and Saccani 2012; Molenaers et al. 2012; Roda et al. 2012), spare part allocation becomes a further critical aspect when dealing with performance based logistics during end-of-life, discussed by Hur et al. (2018).

It should be noted that most of the literature in this field covers the operation and maintenance phase of the equipment lifecycle, where the main source of spares provisioning is the part removed from the operational fleet due to preventive and corrective maintenance (PM and CM), as well as the purchase of new parts. When a fleet of aircraft reaches the retirement phase, which is the case considered in this paper, the fleet will be scrapped gradually during a specified period, during which the number of operational aircraft will gradually decrease. In this context, the remaining fleet should still be kept at a defined level of availability, and spares provisioning and storage are still required to support the maintenance and operation of the remaining fleet, preferably at a minimum cost and risk.

In many cases, a retired aircraft contains valuable spares that retain some operational or monetary value. The benchmarked best practice within the aviation industry is to use these spares to support the remaining fleet or to offer them on the surplus market. The process of dismantling aircraft systems and collecting the valuable spares is called the parting-out process (see Block et al. 2014).

To achieve cost-effective spares provisioning strategies during a phase-out scenario, a part-out-based spares provisioning (PBSP) programme was developed by Block et al. (2014). A spares management framework was proposed for the phase-out scenario, the prerequisites for a PBSP management programme were detailed, and associated key decision criteria for an effective phase-out management process were presented.

Figure 1 illustrates the dynamics of a typical PBSP programme. During normal operation, aircraft rotables will be removed from operational aircraft due to CM and PM actions. If the condition of a rotable shows that restoration or repair is not economically viable, the unit is classified as non-fixable and is discarded. Otherwise, the unit proceeds for further investigation and inspection at the repair shop. For normal operation, decision gates 1 and 2 in Fig. 1 concern decisions as to whether it is worth repairing a failed unit, or performing preventive maintenance on the unit. A detailed investigation at the repair shop level may show that the most effective decision is to discard the unit, for safety, operational or economic reasons. The units that receive a successful repair will be tagged as serviceable and sent to storage.

As shown in Fig. 1, once the retirement period has started and the parting-out process has commenced, the useful spares are removed from the retired aircraft. Decision gate 3 concerns which spares are worth reclaiming. In this process, the total volume of parted-out spares (during the PO) from the retired aircraft is put directly into storage

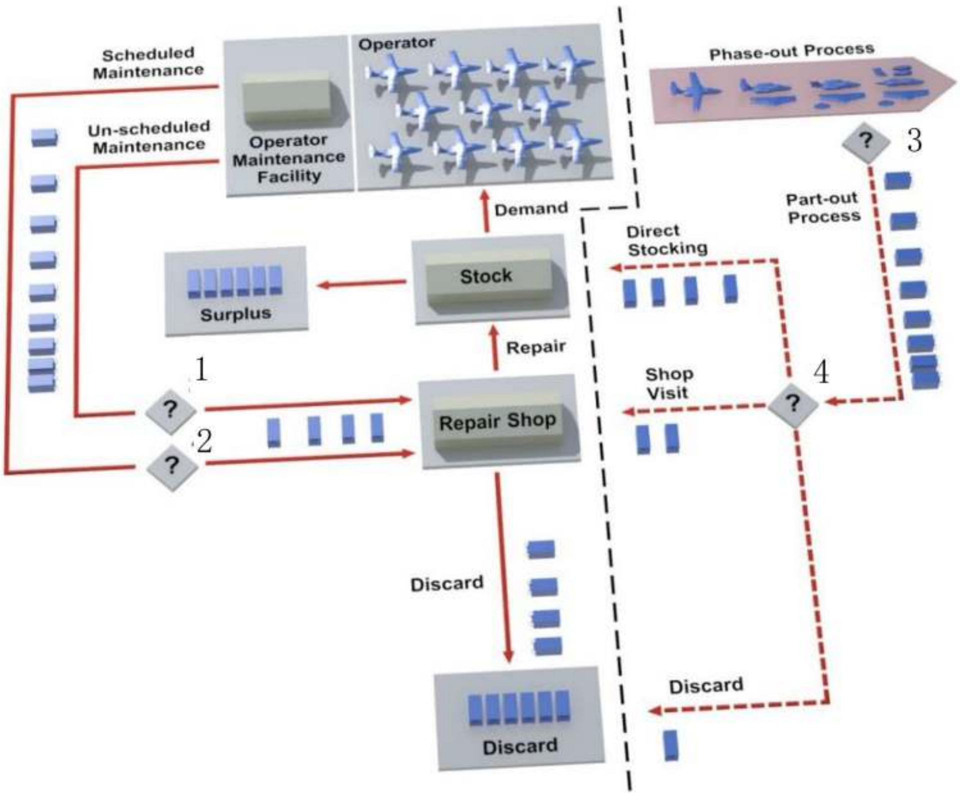


Fig. 1 Schematic diagram of the PBSP dynamics and decision gates: (1) stop corrective maintenance (CM) and (2) stop preventive maintenance (PM); (3) stop the parting-out process (PO), i.e. stop parting-out storage (POS), meaning stop sending units directly to storage; (4) stop parting-out maintenance (POM)

(parting-out storage, POS), sent for repair (parting-out maintenance, POM) and then put into storage, or discarded (POD) when not in a state in which they are worth keeping or repairing, see decision gate 4.

When the PBSP is taking place, the stock fill rate will increase due to the spares received through the parting-out process (PO), i.e. the units sent to storage owing to POS and POM, as well as the spares received through the repair actions due to the scheduled maintenance (PM) and unscheduled maintenance (CM) of the operational fleet. At the same time, the number of operational aircraft will decrease over the retirement period, and obviously the demand for spares will normally decrease.

The increase in the fill rate and the simultaneous decrease in the demand for parts will lead to an excessive level of spares in stock. In a real-life context, the implementation of an effective PBSP should be governed by the preferences of the PBSP manager, which in the case of this study were as follows:

- minimizing the stock level to a certain level, e.g. one unit, at the end of the full retirement period,
- minimizing the risk of back-orders throughout the retirement period,
- minimizing the total cost of stocks and provisioning.

In order to fulfil these preferences, the methodology presented in this paper requires the termination, at specific times, of the parting-out process (PO), the sending of parted-out units directly to storage (POS), and repair actions performed on the units received at the repair shops owing to CM and PM, as well as the parted-out units that need to be repaired (POM).

The CM, PM, POM and POS activities are referred to as *PBSP control gates,* which will either be open or closed. A CM activity involves the restoration of a failed unit to a sufficiently functioning state so that the unit can be re-installed and used in the operational aircraft fleet. A PM activity maintains units in operation according to a predetermined maintenance schedule based on calendar time, cycles, operational hours or other operational parameters. A PO activity includes the actual process of reclaiming units from retired aircraft. A reclaimed unit may be sent for a POM activity, including the maintenance tasks necessary to restore that unit to an adequate state for operational use. A second option for a reclaimed unit is a POS activity, which includes visual inspection and sending the unit to storage as an additional asset for the operational fleet. Finally, the third option for reclaimed units is to discard them, referred to as part-out discard (POD), an activity which involves a visual inspection of units before sending them for discard.

The termination times for the PBSP control gates are conditions that are predefined in the proposed computational model, and these times will arrive in consecutive order. The PM and CM will always be stopped at the same time as or earlier than the POM. Additionally, the POM will always be stopped at the same time as or before the POS. This implies that the termination times for the PO and POS must occur at the same time, i.e. there will therefore be a maximum of four termination times (t_1, t_2, t_3, t_4) to be considered in the model. These conditions reduce the total number of possible solutions, see Sect. 2.2.

For example, an applicable solution for such termination times for the CM, PM, POM and POS which fulfils the above conditions can be represented by (t_1, t_2, t_3, t_4). Using the results from the presented case study, one obtains the respective termination times (27, 25, 53, 63), given in months counted from the start of the retirement period. As seen, the termination of the POM precedes that of the POS, and since there is no reason to continue the parting-out process after both the POM and POS have been terminated, the PO is also stopped in month t_4, which in this case is month 63.

The identification of feasible and effective alternatives for the repair termination times is a combinatorial problem by nature. Dividing the whole retirement time horizon into T months, there are T^4 possible choices of months for closing the four PBSP control gates (CM, PM, POM and POS). It should be noted that when T is large, e.g. 100 months, the total number of possible combinations is quite large (in this particular case 100^4, i.e. 100 million combinations). Therefore, the proposed methodology involves taking all the possible solutions and then discarding the infeasible alternatives. The availability of spares and the risk of back-orders in each time period are computed for all the T^4 possible choices of months, to avoid both under-stocking and overstocking.

However, identifying the applicable and effective solutions by searching among *all* the combinations of possible solutions, including both feasible and infeasible solutions, would be time-consuming. Therefore, finding a solution to this combinatorial problem requires the use of an algorithm, starting from an initial state (e.g. using the time since overhaul and the maintenance history) and an initial input (e.g. using the operational time and the initial stock) which existed prior to entering the phase-out period. In this study, branch-and-cut techniques were used to help identify and prune away the infeasible solutions, i.e. those solutions which could not satisfy the total spares demand.

The applicable and feasible alternatives are compared with regard to their respective costs, and the most cost-effective solution is selected. The cost model considers the estimated future maintenance requirements (for PM and CM), the turn-around times, the cost of the various maintenance tasks, the future spares consumption, the salvage of spares from retired aircraft, etc. The output of the model is a set of applicable alternatives which satisfy the availability requirements for spares for the active fleet.

The method is illustrated using a case study with data from a unit (the cooling turbine) from a Saab-105 trainer fleet. In the computational model, a number of conditions and simplifying assumptions have been applied. As mentioned above, the termination times arrive in consecutive order.

Furthermore, the number of faults and maintenance actions are calculated by monthly increments. Another simplification is that, if a preventive maintenance action is due to be performed on a unit during a certain month, the unit in question is replaced at the beginning of the month, and the probability for corrective maintenance (failure) is then calculated for the replacement unit over the whole month, rather than calculating an exact replacement date and estimating the failure probabilities for both units before and after this date. Another condition is that, once a termination has taken place, i.e. a PBSP control gate has been closed, this termination applies for the whole remaining phase-out period and is not reversed again in the model.

The rest of this paper is organized as follows. In Sect. 2, the computational model is described and the non-controlled scenario is presented in Sect. 2.1, followed by a presentation of the controlled scenario in Sect. 2.2. The algorithm used for finding feasible repair termination alternatives is presented and illustrated in Sect. 2.3, and finally the cost function is presented in Sect. 2.4. A case study on the cooling turbine in a Saab-105 Fleet is presented to illustrate the proposed computational model in Sect. 3. The results of the case study are discussed in Sect. 4. Finally, Sect. 5 concludes this paper and points out the future direction.

2 Proposed model for spare part provisioning in the retirement period

The PBSP programme is planned over a discrete time domain $\{1, 2, \ldots, T\}$, where the time resolution is set to monthly increments and T is the total length of the retirement period. A PBSP programme aims at determining the admissible maintenance schedule given complicated maintenance strategies. The key object is to ensure that there is no back order if a spare unit is required and maintain a desired number of the redundant units. Particularly, let S_i denote the stock level of the spare part and D_i denote the demand of the spare part. Both S_i and D_i are dynamically depending on the maintenance strategy and they shall satisfy the constraint $D_i \leq S_i \leq D_i + \Delta$ for all $i = 1, 2, \ldots, T$. Our task is then to find out the appropriate stock levels $S_1, \ldots, S_T$ over the whole time domain. Moreover, the operational fleet generates repair actions due to unscheduled maintenance (CM) and scheduled maintenance (PM), representing the demand due to CM and PM, see Node 1 in Fig. 2.

The estimation of the PM events of an aircraft system is quite straightforward and is based on the defined frequencies and intervals tabulated in the maintenance planning document offered by the manufacturer. The major challenge is the estimation of the CM events, i.e. the failure events of repairable units, which are highly dependent on the reliability performance of the units in the operational field. In the study presented in this paper, the CM estimations were made using the non-parametric approach of the mean cumulative function (MCF) (see Block et al. 2013).

In Fig. 2, the flow of units from operational and retired aircraft is illustrated. A number of units reclaimed from retired aircraft are sent directly to storage (POS), sent to the repair shop (POM) or discarded (POD) with the predefined probabilities q_1, q_2 and q_3, respectively, as shown in Fig. 2. Furthermore, for a unit entering the repair shop due to a POM action, there is the probability $(1 - w_1)$ that the unit will be repaired and sent to storage.

For a unit sent to the repair shop due to a CM action there is a probability, p_1, that the unit will be successfully repaired and thereafter sent to storage. The corresponding probability of repair and storage for a unit sent to the repair shop due to a PM action is denoted by p_2. The numbers of units being successfully repaired and sent to storage after CM, PM and POM are added up in Node 2, see Fig. 2. The predefined probabilities are measured or defined based on the experience of experts in the operation and maintenance field.

In addition, the total number of units sent to storage in month i (including the units sent directly to storage (POS)) is given in Node 3, see Fig. 2. The flow of units finally determines the stock levels for the non-controlled scenario and the controlled scenario, respectively, see Fig. 2 and Sects. 2.1–2.3.

2.1 Non-controlled spares provisioning management

In the PBSP programme, the total demand for units, D, is generated by the PM and CM activities performed on the still-operational aircraft fleet during the whole retirement period, see Node 1 in Fig. 2. The total demand for the whole retirement period T is formulated in Eq. 1 as follows:

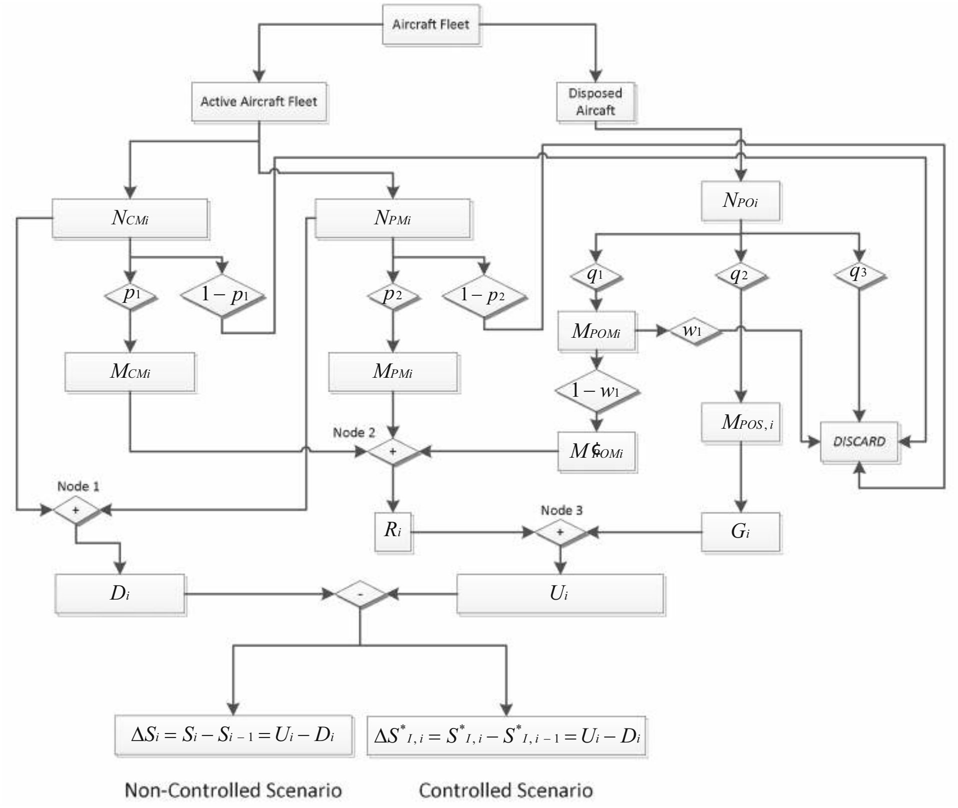
$$D = \sum_{i=1}^{T} D_i, \tag{1}$$

where D_i represents the demand for units for month i, due to both PM and CM actions, see Fig. 2.

The monthly demand D_i is formulated as:

$$D_i = N_{CM_i} + N_{PM_i}, \tag{2}$$

Fig. 2 Flow of spares during the retirement period



where $N_{CM,i}$ is the expected number of CM actions for month i, and N_{PM_i} refers to the monthly number of PM actions performed. N_{CM_i} is stochastic in nature, while N_{PM_i} is a deterministic value, because PM actions are predetermined through a fixed maintenance schedule.

As shown in Fig. 2, there is a probability p_1, that the units entering the repair shop due to a CM action will be successfully repaired and sent to storage, while the probability that the units sent to the repair shop for a PM action will be successfully maintained is p_2. The total number of successfully repaired units sent to storage due to a CM action, for month i, is M_{CM_i}, and the corresponding number coming from PM actions is M_{PM_i}.

$$M_{CM_i} = N_{CM_{i-\Omega}} \cdot p_1$$
$$M_{PM_i} = N_{PM_{i-\Omega}} \cdot p_2,$$

where Ω represents the repair lead time associated with PM, CM and POM actions, i.e. the time from the moment when the logistic manager places a repair order to the moment when the unit is placed in storage.

As shown in Fig. 2, units reclaimed from retired aircraft are assigned to one of the following three categories:

- units sent for maintenance at the repair shop (POM) with the probability q_1,
- units sent directly to storage (POS) with the probability q_2,
- units sent directly for discarding (POD) with the probability $q_3 = 1 - (q_1 + q_2)$.

The number of reclaimed units entering the repair shop due to a POM action, $M_{POM_i,}$ is estimated as follows:

$$M_{POM_i} = N_{PO_i} \cdot q_1,$$

where N_{PO_i} represents the units parted out from retired aircraft during month i. However, there is a probability, w_1, that the units sent to the repair shop due to a POM action cannot be maintained successfully and will be discarded. The number of successfully maintained units sent to storage during month i, M'_{POM_i}, is estimated as follows:

$$M'_{POM_i} = M_{POM_{i-\Omega}} \cdot (1 - w_1).$$

Furthermore, the number of units received for storage due to a PO action, M_{POS_i}, is estimated by:

$$M_{POS_i} = N_{PO_i} \cdot q_2.$$

The number of units discarded due to a PO action, M_{POD_i}, is estimated by:

$$M_{POD_i} = N_{PO_i} \cdot q_3.$$

Consequently, the number of units received for storage during month i from the repair shop, R_i, is calculated as follows:

$$R_i = M_{CM_i} + M_{PM_i} + M'_{POM_i}. \tag{3}$$

Similarly, the number of units received directly for storage from parting-out during month i, G_i, is:

$$G_i = M_{POS_i}. \tag{4}$$

Consequently, the total number of units received for storage during month i, U_i, is:

$$U_i = R_i + G_i. \tag{5}$$

The stock level for the non-controlled scenario in month i is estimated as follows:

$$S_i = S_0 + \sum_{v=1}^{i} (U_v - D_v), \tag{6}$$

where S_0 is the initial stock level at the start of the retirement period.

2.2 Controlled spares provisioning management

To fulfil the objective of PBSP completely, the controlled scenario is needed. In this scenario, at specific times (the PBSP control gates), one ceases to part out units and send them directly to storage (POS), and one stops performing maintenance actions on the units received at the repair shops owing to CM, PM and POM.

The status of the PBSP control gates is binary, either closed (0) or open (1), at any particular time, depending on the termination of the respective activity flows of the units.

Once a termination has taken place, i.e. once a PBSP control gate has been closed, it stays closed for the rest of the retirement period and is not reopened in the model. The status of the PBSP control gates in month i can be described as $(I_{CM_i}, I_{PM_i}, I_{POM_i}, I_{POS_i})$, where $i = 1, \ldots, T$.

The possible termination times (t_1, t_2, t_3, t_4) associated with CM, PM, POM and POS actions during month i in the time domain $1 \le t_1, t_2, t_3, t_4 \le T$ is presented through the following matrix:

$$I(t_1, t_2, t_3, t_4) = (I_{j,i}) \in \{0, 1\}^{4 \times T}, \tag{7}$$

where $I_{j,i} \ge I_{j,i+1}$ and $I_{j,t_j} > I_{j,t_j+1}$ for all $j = 1, 2, 3, 4$ and $i = 1, 2, \ldots, T$.

The total number of units received in storage during month i, U_i^*, is estimated as follows:

$$U_i^* = (I_{CM_i}, I_{PM_i}, I_{POM_i}, I_{POS_i}) \begin{bmatrix} M_{CM_i} \\ M_{PM_i} \\ M_{POM_i} \\ M_{POS_i} \end{bmatrix}, \tag{8}$$

where $(I_{CM,i}, I_{PM,i}, I_{POM,i}, I_{POS,i})$ is the i^{th} column of the matrix $I(t_1, t_2, t_3, t_4)$.

The set of values defined by $(M_{CM_i}, M_{PM_i}, M_{POM_i}, M_{POS_i})$ represents the number of units sent to the repair shop and units coming directly from parting-out to storage. Considering the termination times (t_1, t_2, t_3, t_4), the stock level on a monthly basis, S_i^*, is estimated as follows:

$$S_i^* = S_{i-1,I}^* + U_{i,I}^* - D_i. \tag{9}$$

When T becomes large, the number of possible solutions becomes unmanageable. For example, when the retirement period is set as $T = 96$ months, which is the case in this paper (Sect. 4), the total number of repair termination alternatives will be approximately $96^4 \approx 84 \cdot 10^6$. Consequently, the major challenge is to identify the applicable repair termination alternatives.

However, the viable solutions are limited to those satisfying the following three conditions.

(i) The POM must be stopped before the POS, i.e. $t_3 \leq t_4$. This will reduce the total number of possible solutions from T^4 to $T^3(T+1)/2$, which is still $\mathcal{O}(T^4)$. Additionally, the PM and CM will be stopped before the POM, i.e. $t_1 \leq t_3$ and $t_2 \leq t_3$. If this measure is taken, the number of solutions will be reduced to the following number: $T(T+1)^2(T+2)/12$.

(ii) The number of spares in stock per month, S_i^*, must be greater than the demand for every month i, D_{i+1}, to eliminate the risk of back-orders.

$$S_i^* > D_{i+1}, (i = 1, \ldots, T-1). \tag{10}$$

In addition, if any PBSP control gate (CM, PM, POM or POS) is closed in month t_i, the total number of available spares should fulfil the total demand D, which means that $S_T > 0$.

(iii) To ensure that no overstocking takes place, the difference between the stock level, S_i^*, and the sum of D_j during the retirement period should not exceed a safety margin, Δ, for any month i. This can be expressed as:

$$\left(S_i^* - \sum_{j=i+1}^{T} D_j \right) \leq \Delta (i = 1, \ldots, T). \tag{11}$$

2.3 Search algorithm

In order to limit the search and find applicable solutions, a search algorithm was developed, in Matlab 9.2 (R2017a). The algorithm was developed in such a way that it would facilitate and expedite the computation process by limiting the search for applicable solutions. See Fig. 3 for the flowchart and the corresponding steps and conditions.

The proposed algorithm is a global search algorithm with pruning. Roughly speaking, the search algorithm is a four-step *for-loop*, which is similar to the naive algorithm. The difference between the developed algorithm and the naive algorithm is that the estimate of $\hat{S}_T$ is obtained as an upper bound for the total number of solutions during the retirement period, before the next *for-loop* in the proposed algorithm. This estimate will rule out some obviously infeasible solutions and narrow the searching domain of the algorithm. As shown in the case study, this technique will improve the computational efficiency greatly.

The algorithm starts at $t_1 = 1$, and then the upper bound estimate $\hat{S}_{T,1}$ is expressed as:

$$\hat{S}_{T,1} = S_0 + \sum_{v=1}^{t_1} M_{CM,v} + \sum_{v=1}^{T} M_{PM,v} + \sum_{v=1}^{T} M_{POM,v} + \sum_{v=1}^{T} M_{POS,v} - D. \tag{12}$$

At this step, only t_1 is known and, therefore, if the upper bound cannot meet the requirement, i.e. $\hat{S}_{T,1} > 0$, the algorithm will test the next $t_1 \rightarrow t_1 + 1$. Otherwise, it will continue searching for t_2 from $t_2 = 1$.

Given t_1 and t_2, an updated estimate is then as follows:

$$\hat{S}_{T,2} = S_0 + \sum_{v=1}^{t_1} M_{CM,v} + \sum_{v=1}^{t_2} M_{PM,v} + \sum_{v=1}^{T} M_{POM,v} + \sum_{v=1}^{T} M_{POS,v} - D. \tag{13}$$

This is then used to perform further pruning with the algorithm. Furthermore, the search starts from $t_3 = \max(t_1, t_2)$, which ensures fulfilment of the condition that the termination times for PM and CM should happen before the termination time of POM, i.e. $t_3 \geq t_1$ and $t_3 \geq t_2$ are fulfilled.

Given t_1, t_2 and t_3, an updated estimate is obtained to prune away the infeasible solutions as follows:

$$\hat{S}_{T,3} = S_0 + \sum_{v=1}^{t_1} M_{CM,v} + \sum_{v=1}^{t_2} M_{PM,v} + \sum_{v=1}^{t_3} M_{POM,v} + \sum_{v=1}^{T} M_{POS,v} - D. \tag{14}$$

Furthermore, t_4 is started from $t_4 = t_3$, which ensures that t_4 is larger than any other termination time, $t_1, t_2, t_3 \leq t_4$, i.e. that the PM, CM and POM are terminated before the POS is terminated. In the last step, however, a check needs to be performed concerning the defined conditions (ii) and (iii) for all the months.

First, the stock level in the last month in the retirement period is given as follows:

$$S_T^* = S_0 + \sum_{j=1}^{4} \sum_{v=1}^{t_j} M_{v,j}. \tag{15}$$

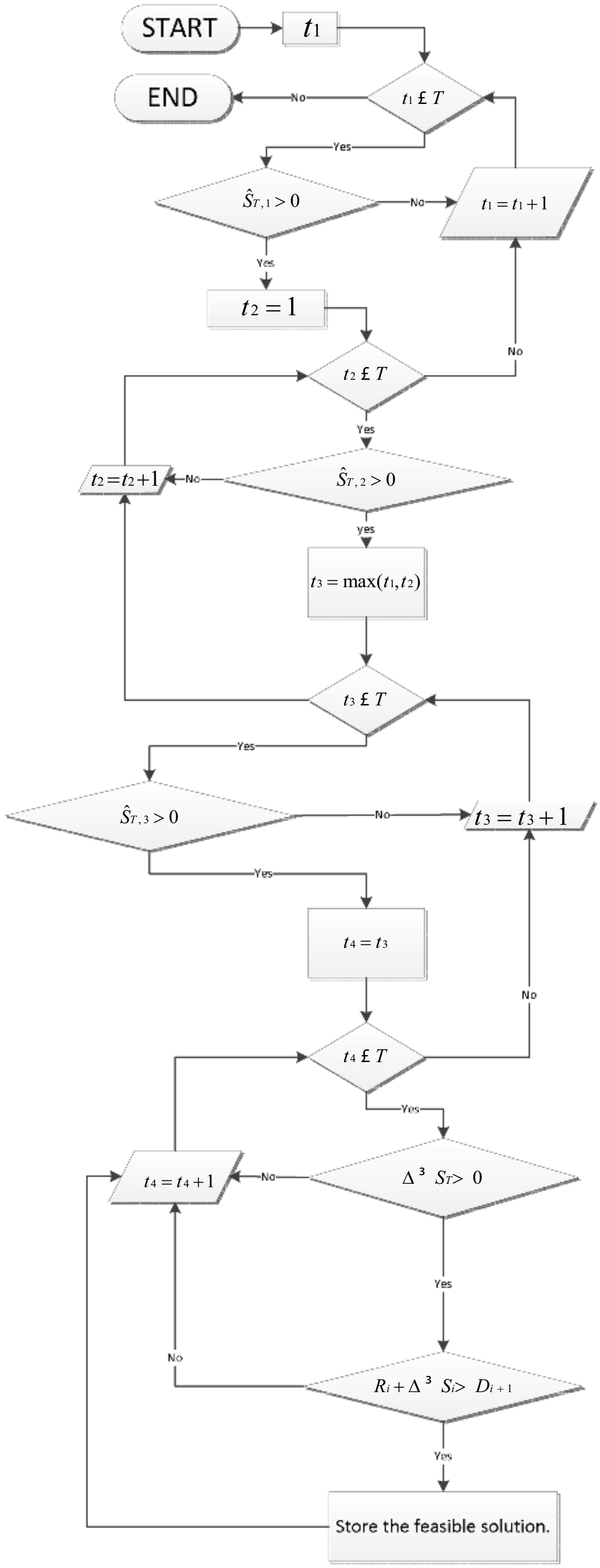


Fig. 3 Flowchart for the search algorithm

Moreover, by checking that the stock level S_i^* at the end fulfils the requirement, if $\Delta \geq S_T^* > 0$ is fulfilled, the stock level for each month i is as follows:

$$S_i^* = S_0 + \sum_{j=1}^{4} \sum_{v=1}^{\min(t_j, i)} M_{v,j} - \sum_{v=1}^{i} D_v. \tag{16}$$

In addition, conditions (ii) and (iii) must be checked for the stock levels from month 1 to month $T - 1$ as follows:

$$R_i + \Delta \geq S_i^* > D_{i+1}, \quad i = 1, \ldots, T - 1. \tag{17}$$

If the above conditions are fulfilled for every month, the solution is feasible and recorded. Finally, all the feasible solutions, the corresponding stock levels and the total cost are recorded. When the applicable repair termination alternatives are identified, the most cost-effective alternative should be selected to be incorporated in the PBSP programme.

Furthermore, if the target is to find the plan with the lowest cost, the cost for the different actions should also be utilized in the pruning procedures, since the cost is monotone in all the t_j. We can also store the current lowest cost and branch the possible solutions with a higher cost. Actually, the cost may not be the only key decision factor, as is argued in Sect. 4, "Discussion and Conclusions".

2.4 Cost model for spares provisioning management

In order to identify the cost of the applicable solutions, a cost model is proposed. This cost model considers the costs associated with corrective and preventive maintenance, as well as the costs for removing the units from the aircraft being retired and restoring the reclaimed units to an operational condition. The applicable alternatives are compared with regard to their total cost, and the most cost-effective one is selected.

The cost function C for any given matrix $I(t_1, t_2, t_3, t_4)$ is defined as follows:

$$\begin{aligned} C(I) = {} & C_{CM} \sum_{i=1}^{T} I_{CM_i} \cdot M_{CM,i} + C_{PM} \sum_{i=1}^{T} I_{PM_i} \cdot M_{PM_i} \\ & + C_{POM} \sum_{i=1}^{T} I_{POM_i} \cdot M'_{POM,i} + C_{PO} \sum_{i=1}^{T} I_{POM_i} \cdot M_{POM_i} \\ & + C_{PO} \sum_{i=1}^{T} I_{POS_i} \cdot M_{POS_i} + C_{PO} \sum_{i=1}^{T} I_{POS_i} \cdot M_{POD_i}, \end{aligned} \tag{18}$$

where C_{CM} and C_{PM} are the costs for performing the CM and PM, respectively, and C_{POM} denotes the cost for the maintenance necessary to restore a parted-out unit to the condition of a serviceable unit. The actual cost for parting out a unit from retired aircraft is denoted by C_{PO}. This cost is associated with the units reclaimed for POM and POS and the units sent for discard (POD). Note that in Eq. 19, the termination time for sending parted-out units for discard is the same as the termination time for sending reclaimed units to storage (POS).

Since I is determined by t_1, t_2, t_3, t_4, rewrite Eq. (20) as follows:

$$\begin{aligned} C(t_1,t_2,t_3,t_4) = {} & C_{CM}\sum_{i=1}^{t_1} I_{CM_i}\cdot M_{CM,i} + C_{PM}\sum_{i=1}^{t_2} I_{PM_i}\cdot M_{PM_i} \\ & + C_{POM}\sum_{i=1}^{t_3} I_{POM_i}\cdot M'_{POM,i} + C_{PO}\sum_{i=1}^{t_3} I_{POM_i} \\ & \cdot M_{POM_i} + C_{PO}\sum_{i=1}^{t_4} I_{POS_i}\cdot M_{POS_i} \\ & + C_{PO}\sum_{i=1}^{t_4} I_{POS_i}\cdot M_{POD_i}. \end{aligned} \tag{19}$$

2.5 Case study on the cooling turbine system in a Saab-105 fleet

A case study was conducted on the cooling turbine unit installed in the 90 aircraft in a Saab-105 fleet, this to illustrate and validate the proposed PBSP search algorithm approach. There is one cooling turbine per aircraft, and it is the main unit of the environmental control system that delivers cooling air for the electronics and the cockpit. This unit was selected because it is associated with a relatively high maintenance volume and cost.

The Saab-105 aircraft is a two-seat twin-engine training aircraft which is used by the Swedish Armed Forces, and which is planned to be phased out within a period of 8 years, i.e. $T = 96$ months. As a part of the phase-out schedule, ten aircraft will remain operational at the end of the retirement period, due to practical considerations concerning flight training continuity. The phase-out plan was defined at a strategic level to be implemented over 96 months, as shown in Fig. 4. Identifying which aircraft are to be discarded and when is, of course, influenced by a number of factors, which are discussed in Bacchetti and Saccani (2012).

The predefined input values used in the computational model are tabulated in Table 1, and the initial stock level was set to $S_0 = 20$ in the studied case. As mentioned above, reclaimed units will be sent to the repair shop (POM) with the probability $q_1 = 0.30$, will be sent directly to storage (POS) with the probability $q_2 = 0.50$, or will be discarded with the probability $q_3 = 0.20$. The still-operative fleet generates CM and PM actions continuously, and the probability of repairing a unit sent for a CM action is $p_1 = 0.85$, while the probability of repairing a unit sent for PM is $p_2 = 0.85$. Furthermore, the cost associated with each activity and the lead time (TAT) are presented in Table 1.

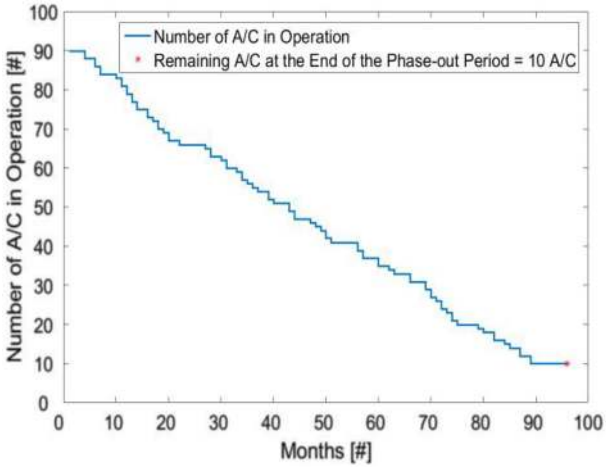


Fig. 4 Phase-out schedule for the Saab-105

As shown in Fig. 5, the total demand is 27 units for CM and 51 units for PM (a total of 78 units) during the whole retirement period. As mentioned earlier, a fraction of these units will be discarded according to the q values. When the retirement period starts, the number of operational aircraft decreases according to the retirement plan (see Fig. 4), which affects the demand for spares, and the corrective and preventive maintenance volumes will normally decrease as well.

The proposed methodology applied for the non-controlled scenario is referred to as alterative **A.** Within the non-controlled scenario, the parting-out process is not terminated and continues to the end of the retirement period (month $T = 96$). In this case, 80 cooling turbines are planned to be reclaimed from retired aircraft during the retirement period.

Figure 6 shows the expected number of reclaimed units to be sent to the repair shop, sent to storage, and sent for discard during the retirement period ($T = 96$ months), as well as the expected frequency of these actions. As shown, the expected numbers of units to be directed to the repair shop, to storage and for discard are equal to $POM = 22, POS = 43\text{and}POD = 15$ units.

When the PBSP is taking place, the stock fill rate will increase due to the parts received through the parting-out process (PO), i.e. the units sent to storage due to POS and POM, as well as the spares received through the maintenance actions due to the scheduled maintenance (PM) and unscheduled maintenance (CM) of the operational fleet. At the same time, the number of operational aircraft will decrease over the retirement period, and the demand for spares will normally decrease.

Table 1 Initial data entering the retirement period

	Maintenance interval (Fh)	TAT (Ω)—(Month)	Cost (SEK)	Probability of repair success
CM	N/A	3	C_{CM} = 30,000	$p_1 = 0.85$
PM	1010	2	C_{PM} = 50,000	$p_2 = 0.85$
POM	N/A	2	C_{POM} = 40,000	$q_1 \cdot (1 - w_1) = 0.30 \cdot (1 - 0.15) \approx 0.26$
POS	N/A	N/A	C_{PO} = 5000	N/A

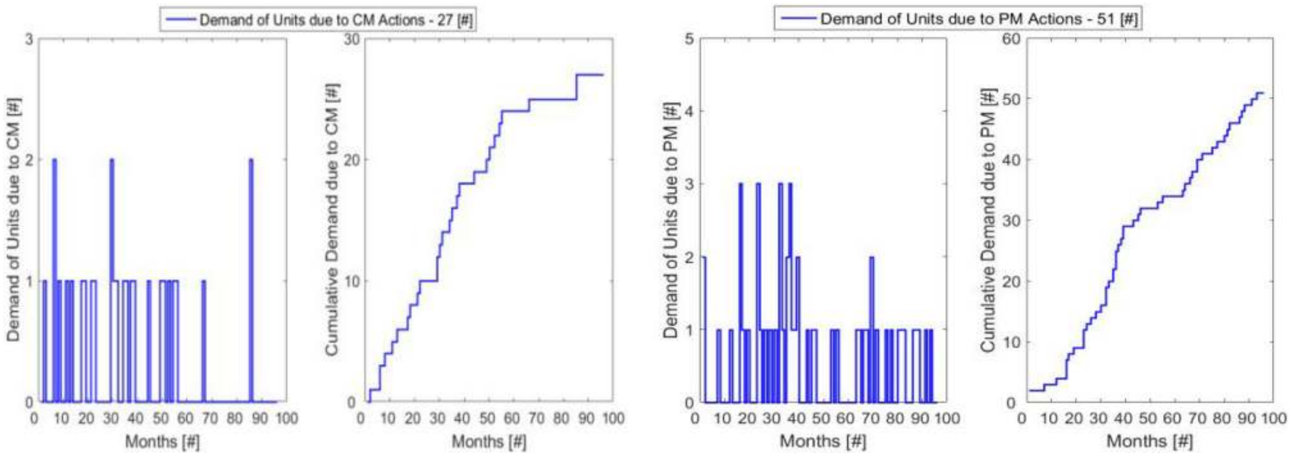


Fig. 5 Demand for units generated by the operational fleet due to CM and PM

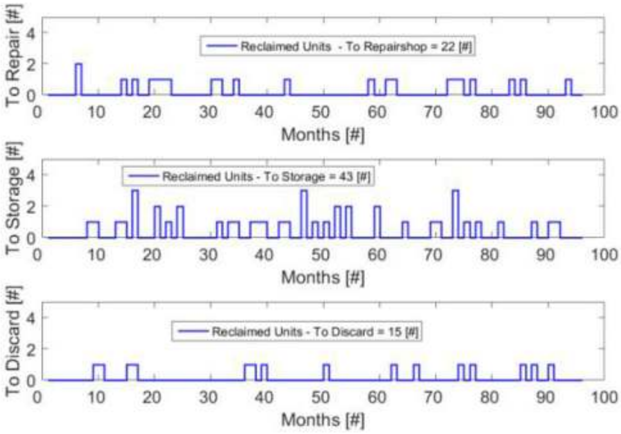


Fig. 6 Expected number of reclaimed cooling turbines to be sent to the repair shop, to storage and for discard, and the expected frequency of these actions

Figure 7 shows the variation of the stock level in the non-controlled scenario. The monthly stock level in the non-controlled scenario is computed using Eq. 6 in Sect. 2.1, and the final stock level in the last month is calculated by letting $i = T$ (the last month) in Eq. 6. As shown in Fig. 7, when applying the non-controlled scenario, there will be 69 cooling turbines in stock at the end of the retirement period.

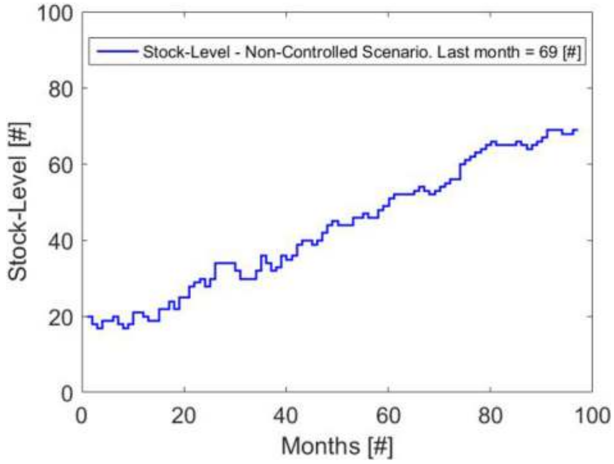


Fig. 7 Variation of the stock level in the non-controlled scenario

Furthermore, the cumulative cost of applying the non-controlled scenario is presented in Fig. 8. As shown, the total cost of applying the non-controlled scenario (alternative **A**) is estimated to be 4.6 MSEK. Obviously, the increase in the fill rate and the simultaneous decrease in the demand for parts will lead to an excessive level of spares in stock. This high stock level at the end of the retirement period represents an unwanted capital investment through unnecessary maintenance and storage.

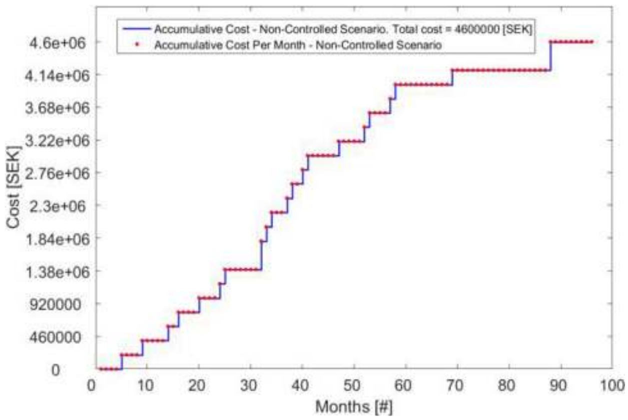


Fig. 8 Cumulative cost for the non-controlled scenario

In order to control the stock level and reduce the total cost, the controlled scenario method is applied to terminate the CM, PM, POM and POS actions. Applying the controlled scenario, the computational models and proposed algorithm were used to identify the set of termination alternatives that would fulfil the PBSP requirement. To control the risk of back-orders for spares, the safety margin for the minimum number of units in stock was set to $\Delta = 1$. The computation shows that there are *129,212* applicable solutions that can be used to fulfil the PBSP programme preferences.

Figure 9 presents a set of arbitrarily selected applicable alternatives and their corresponding stock levels for each month. The stock level in the controlled scenario is calculated according to Eq. 10 in Sect. 2.2, and in this case study the stock level at the end of the retirement period was set to be one remaining unit.

As can be seen from Fig. 9, the results vary to quite a large extent from solution to solution, i.e. there are solutions with a rather low stock level continuously and solutions with an increased stock level at the beginning and a rapidly decreasing stock level at the end of the retirement period. Besides the stock level and cost, several other criteria may be considered in selecting repair planning alternatives. For example, an operator may be interested in closing down the repair shop at the earliest possible stage, perhaps because the operator would want to end the contracts with its subcontractors in order to protect against additional costs.

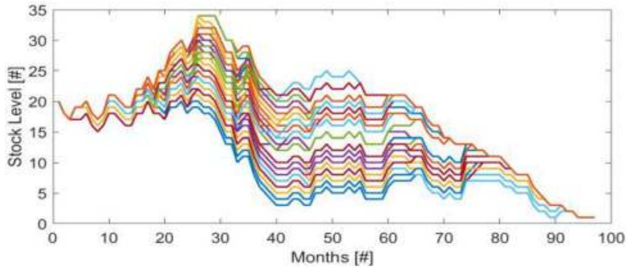


Fig. 9 The stock levels of 100 randomly selected applicable solutions

Figure 10 shows, with a higher resolution, the termination times for CM, PM, POM and POS for two applicable solutions selected arbitrarily (alternative # *46676 and 87387*). When the termination period begins, there is a relatively large difference between the demand and the actual stock level. This difference decreases as soon as the closing of the PBSP control gates initiates. In Fig. 10 one can observe that, in the presented alternative *# 46676*, the stock level starts to decrease when both the PM and CM terminate in month 9 and 17, respectively, and the stock level decreases continuously after the POM is terminated in month 53. The same pattern can also be seen for alternative *# 87387*.

Additionally, as shown in Fig. 10, the termination times are relatively scattered. In alternative # *46676*, there are 44 months between the PM and POM termination times, but there are only 28 months between those times for alterative # *87387*. Such a variation in the gap between termination times for PM, CM and POM complicates the planning for the termination of maintenance contracts in that the planning time horizon for terminating maintenance contracts will be unpractically long. Furthermore, the difference between the stock levels for alternatives 46,676 and 87,387 and the demand is quite high at the beginning of the retirement period. The advantage of these alternatives is the additional safety margin, but they involve an unnecessary binding of capital. As the results in Fig. 10 show, applying the proposed PBSP methodology and the associated computational models and algorithm not only fulfils the availability requirements and the demand for spares during the whole phase-out period, but also reduces the total number of units in stock at the end of the phase-out period $(S_T = 1)$.

In Fig. 11 the termination times for CM, PM, POM and POS for all the *129,212* applicable solutions are presented. As is evident, the termination times for CM and PM can occur relatively early, in months $\sim$ 1–60. The reason is that the number of active aircraft is decreasing, which means that fewer units are coming from a CM or PM action over time.

The results in Fig. 11 also show that the termination times for POS actions are relatively late, in month $\sim$ 35–95. The reason why POS can continue to the end of the phase-out period is that there is a continuous flow of units coming from POS during the whole phase-out process, and that there is no lead time connected to POS, while there is a lead time for CM, PM and POM. Concerning POM actions, the results show that the termination times can also occur rather late in the retirement period, between months $\sim$ 20 and 90. It should be noted that in the case of

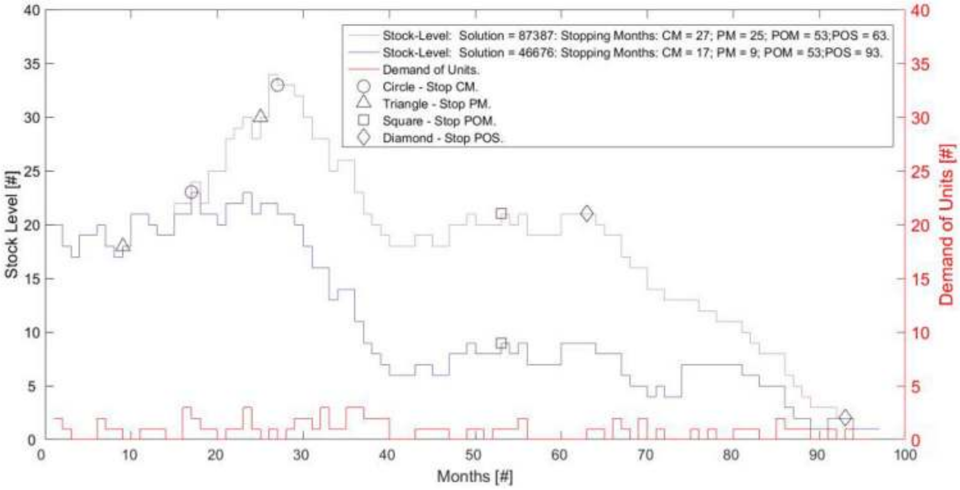


Fig. 10 Two randomly selected applicable solutions and their stock levels for the retirement period

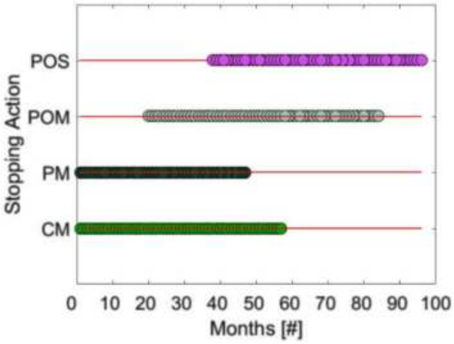


Fig. 11 Range of the termination times for CM, PM, POM and POS for the whole plethora of repair termination alternatives

POM, there is a continuous flow of units coming during the whole retirement period which is unaffected by the fact that the active fleet of aircraft is decreasing. Since there is a turn-around time for POM, it is not possible to collect units up to the end of the retirement period.

In order to identify the most economically applicable alternatives when applying the controlled scenario, the cost associated with each applicable alternative is calculated using the proposed cost model presented in Sect. 2.4. In Fig. 12, the costs associated with the applicable alternatives are presented. In this figure, the alternatives are sorted based on their costs to enable identification of the alternatives with the lowest and highest costs.

Within the controlled scenario, there are 36 applicable alternatives resulting in the minimum cost of 765,000 SEK, referred to as alternative group B (see Table 2). As shown in Table 2, the CM actions should be terminated in month 32 for all the 36 alternatives, while there are two termination alternatives for the PM actions, month 1 and 2, three alternatives for the POM actions, months 16, 17 and 18, and, finally, six alternatives for terminating the POS actions, months 91-96.

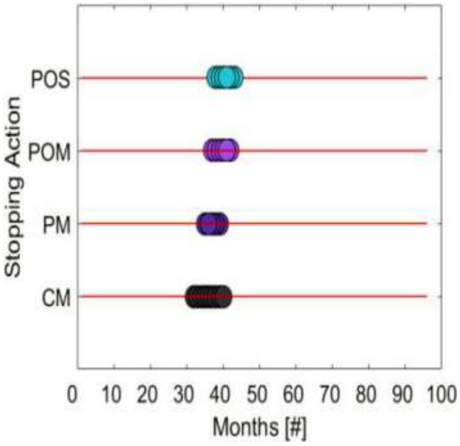


Fig. 12 The costs associated with the applicable solutions

The highest cost within the controlled scenario was incurred by three alternatives, referred to as alternative group C, and that cost is 1,888,500 SEK (see Table 3).

Furthermore, when implementing a PBSP programme, it is also of interest to identify those applicable alternatives that allow CM, PM and POM to be terminated at approximately the same time. Such alternatives provide the possibility of terminating all the associated maintenance contracts at the same time. Figure 13 presents the solutions that have a maximum mutual gap of six months between the CM, PM and POM actions. In this case, the number of applicable alternatives is 64, and within this set of alternatives there are 15 alternatives associated with the lowest cost of 1,750,000 SEK, and three alternatives associated with the highest cost of 1,850,000 SEK; these two sets of alternatives are referred to as alternative group D and E, respectively.

Table 4 lists the termination times for alternative group D, associated with the minimum cost of *1,750,000 SEK*.

Table 2 Termination times for CM, PM, POM and POS actions for alternatives within alternative group B

	Alternatives																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Termination times—group B																		
CM action	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
PM action	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
POM action	33	33	33	33	33	33	34	34	34	34	34	34	35	35	35	35	35	35
POS action	91	92	93	94	95	96	91	92	93	94	95	96	91	92	93	94	95	96

	Alternatives																	
	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Termination times—group B																		
CM action	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
PM action	2	2	2		2	2	2	2	2	2	2	2	2	2	2	2	2	2
POM action	33	33	33	33	33	33	34	34	34	34	34	34	35	35	35	35	35	35
POS action	91	92	93	94	95	96	91	92	93	94	95	96	91	92	93	94	95	96

Table 3 Termination times for CM, PM, POM and POS for alternative group C

	Alternatives		
	1	2	3
Termination times—group C			
CM action	34	35	36
PM action	38	38	38
POM action	38	38	38
POS action	38	38	28

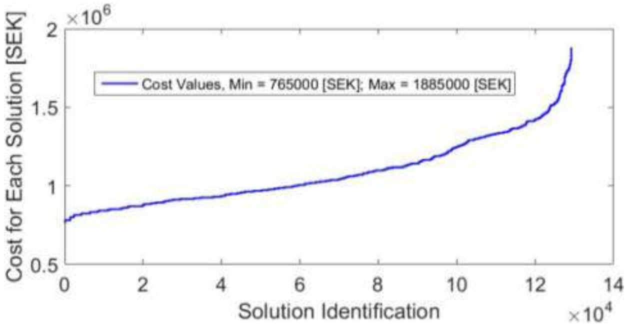


Fig. 13 Termination times for CM, PM, POM and POS for each applicable solution

Table 5 shows the termination times for alternative group E, associated with the maximum cost of *1,850,000 SEK*.

It is of interest to compare the solutions with one another with regard to cost, i.e. to compare the solutions within the controlled scenario with one another and with the non-controlled scenario. The results of such a comparison show that, in comparison with the non-controlled scenario, there is a 56% saving when an alternative within alternative group C (the alternatives with the highest cost) is selected and an 83% saving when alternatives within alternative group B (the alternatives with the lowest cost) are selected; the termination times are given in Table 2.

The alternatives within alternative group D and E give savings of 62% and 60%, respectively, and provide the added value of shutting down the repair shop facilities within a time period of six months (Table 6).

3 Discussions

Identifying the plethora of repair termination alternatives is a central and vital part of the PBSP programme. This also includes identifying a set of termination times for the parts received due to the PM, CM, POM and POS, to determine individual termination alternatives. This provides a foundation for further necessary measures to be taken and tasks to be performed within the retirement period, such as terminating maintenance contracts, discarding internal

Table 4 Termination times for CM, PM, POM and POS for the alternatives within alternative group D

	Alternatives														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Termination times—group D															
CM action	34	34	34	34	35	35	35	35	35	36	36	36	36	36	36
PM action	37	37	37	37	37	37	37	37	37	37	37	37	37	37	37
POM action	37	38	39	40	37	38	39	40	41	37	38	39	40	41	42
POS action	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43

Table 5 Termination times for CM, PM, POM and POS for the alternatives within alternative group E

	Alternatives		
	1	2	3
Termination times—group D			
CM action	34	35	36
PM action	38	38	38
POM action	38	38	38
POS action	38	38	38

maintenance capabilities, reviewing stocks, cutting back on administrative processes (e.g. spares procurement and obsolescence monitoring), etc.

In the study presented in this paper, the dynamics of spares flow and the associated decision nodes within PBSP have been modelled. A set of computational models have been proposed to estimate the stock level for both the non-controlled and the controlled scenario.

For the controlled scenario, the flows of spares to the repair shops and the stock are controlled through decisions to stop the CM, PM, POM and POS. A computational model is proposed to estimate the stock level for any possible repair termination alternative. A search algorithm is proposed to apply the initial and boundary conditions to identify the applicable solutions. The search algorithm is an effective method which starts from an initial state and initial input to describe a computation which, when executed, proceeds through a finite number of well-defined successive states and produces a result at a final end state. More important, the algorithm we develop is very robust and easy to implement since it is a pruning version of a naïve brute-force search algorithm. A brute-force algorithm is usually straightforward to use but it may suffer a huge computation burden. The robustness of our algorithm is also a consequence of the brute-force searching strategy. By adding the rules for pruning at each iteration, the overall structure of the algorithm after pruning is still easy to understand and use but its computational efficiency is improved significantly. In addition, a cost function has been developed to identify the cost-effective solutions among the applicable ones.

The non-controlled scenario involves a continuous parting-out of spares and continuous repair activities until the end of the retirement period. The results obtained for the non-controlled scenario within the case study show that there will be 69 cooling turbines in stock at the end of the termination period and the total cost of this scenario is estimated to be 4.6 MSEK.

Within the controlled scenario, the flows of spares to the repair shop and storage are controlled through the PBSP decision gates, CM, PM, POM and POS. Using the proposed search algorithm and the defined computational model, the successive states and applicable alternatives fulfilling the boundary conditions have been identified. The studied case shows that there is a set of 129,212 applicable solutions for combinations of repair termination alternatives, all of which fulfil the defined conditions. The highest cost for a solution within the controlled scenario is 1,888,500 SEK, which, in comparison with the cost for the non-controlled scenario, represents a large saving of 2,711,500 SEK. Which follows from the strategy founded in the controlled/non-controlled scenarios and the presented cost model, by implementing the PBSP approach and using the proposed algorithm to find suitable solutions for stopping CM, PM, POM and POS.

Comparing the results obtained for the non-controlled scenario with those obtained for the alternatives with the lowest cost in the controlled scenario (alternative group B),

Table 6 Alternatives within the controlled and non-controlled scenarios

Alternative			Number of solutions	Cost (SEK)	Saving %
Non-controlled scenario	A		1	4,600,000	–
Controlled scenario	Group B	Minimum cost	36	765,000	~ 83
	Group C	Maximum cost	3	1,888,500	~ 59
	Group D	Minimum cost	15	1,750,000	~ 62
	Group E	Maximum cost	3	1,850,000	~ 60

one can expect a saving of 3,835,000 SEK for the cooling turbine, for the whole retirement period, if one uses one of the alternatives in group B. Considering that an aircraft comprises approximately 200-300 repairable units, the PBSP programme approach provides the possibility of making substantial savings.

The results also show that, with regard to specific sub-costs, several solutions are economically very close, and that, consequently, there exists a margin of adaptability for terminating CM, PM, POM and POS, which provides an operational flexibility. In other words, it is not necessary to follow a set of termination times strictly and there are several similar applicable solutions in the same cost region.

In addition, as shown in this paper, the applicable solutions and their termination times for CM, PM, POM and POS are relatively scattered. Naturally, from the point of view of PBSP management, it would be desirable to terminate all the maintenance-related activities at about the same time, and simply continue to collect units from the reclamation process to fulfil future spares requirements. However, selecting a solution with early maintenance termination times entails an increased risk that it will be necessary to reinitiate the maintenance, which is associated with a high cost. If one waits longer to stop the maintenance, there is less risk that unforeseen events will occur which will affect the spares provisioning process, but this alternative does not provide the same possibility of making savings.

In a real-life context, the operator may have other preferences which may dictate that other solutions will be the most effective ones. For instance, the operator may prefer to keep a certain contract longer for strategic reasons, or to keep the option open of delaying the retirement significantly due to operational requirements. Furthermore; the methodology proposed can easily be adapted to civil aviation and other industrial areas with technically complex fleets of vehicles (e.g. trains, boats, dumpers, etc.), for a provisioning planning during the retirement period which will provide the possibility of making large cost savings.

4 Conclusion remark

In this paper, we present the mathematical model for spares provisioning strategy for the unit replacement in fleet management. We propose an efficient algorithm to search the admissible solutions and establish the corresponding cost model. The proposed model is validated by a case study on the cooling turbine systems of Saab-105 Fleet.

With good planning, a well-structured approach, common goals shared by all the stakeholders and an implementation of the proposed PBSP framework, greater savings can be achieved. In addition, the implementation of a PBSP programme itself is not associated with any large overhead. The most vital part is the application of the proposed computational model and search algorithm, whose results provide transparency concerning the applicable repair termination alternatives and their associated costs. This represents the most important contribution of the PBSP programme.

Somewhat surprisingly, although the PBSP method is quite commonly applied within both the military and the civilian sector, there are very few publications on the subject. Indeed, very little research work has been published on any aspects of maintenance during the end-of-life period. One possible reason for this is that the methods are often applied by consultants, who may not have any incentives to publish their knowledge. Hence, further research within the area covered in this paper that would result in publications would be of great interest to both practitioners and the research community.

5 Future research

The proposed methodology can easily be adapted to civil aviation and other industrial areas with technically complex fleets of vehicles, such as trains, ships, dumpers, etc., and can provide provisioning planning during the retirement period, resulting in the possibility of making substantial savings. It should be noted that the proposed model has been developed for single-indenture stock systems. For organizations using a multi-indenture stock system, the model should be adapted considering the dynamics of spares flow in a multi-indenture stock system. Furthermore, the study has been performed based on a fixed retirement plan. However, there may be more cost-effective solutions if one uses different retirement periods. Hence, it would be beneficial to perform a further analysis to identify the optimum retirement period, using an iterative process.

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