An Economic Evaluation for CP-140 Aircraft Replacement

A. Sokri
Materiel Group Operational Research

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Materiel Group Operational Research
Assistant Deputy Minister (Materiel)

National Defence Défense nationale

Canada

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Author
Original signed by

A. Sokri

Approved by
Original signed by

Charles Morrisey
DRDC CORA Acting S/H (Joint & Common)

Approved for release by
Original signed by

D. Reding
DRDC CORA Chief Scientist

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Abstract

The purpose of this report is to identify the optimal replacement strategy for the Canadian Forces (CF) Long-Range Patrol CP-140 fleet. The adopted mathematical formulation is a fusion between an intergenerational model and an approach which uses the notion of operational availability of aircraft. In this resulting model, operating and maintenance costs per available year are estimated as a function of aircraft age during its life cycle. After determining the optimal age of replacement, a sensitivity analysis was carried out to assess the impact of some key model parameters on the result. This repair or replace model has the huge advantage of being applicable to any kind of heavy equipment. For example, it may be used to determine, in the same manner, the optimal age of replacing several types of fleets such as helicopters, ships, tanks, trucks, etc.

Résumé

Ce travail fournit un modèle intergénérationnel hybride permettant l'identification de la stratégie optimale de remplacement de la flotte des aéronefs militaires de surveillance territoriale CP-140. La formulation mathématique adoptée est un croisement entre un modèle intergénérationnel qui cherche à minimiser le coût de l'appareil durant son cycle de vie, et une approche qui tient compte de la disponibilité opérationnelle des aéronefs. Après avoir déterminé l'âge optimal de retraite de la flotte, une analyse de sensibilité a été accomplie afin d'estimer l'impact d'une variation dans les paramètres du modèle sur le résultat. Ce modèle présente l'énorme avantage d'être applicable à toute sorte d'équipement lourd. Il peut servir, en effet, à déterminer d'une manière similaire l'âge optimal de remplacement de plusieurs flottes comme les hélicoptères les navires, les chars, les camions ou autres.

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Executive summary

The CP-140 fleet of long-range patrol aircraft includes the two maritime surveillance aircraft Aurora (CP-140) and Arcturus (CP-140A). The fleet is aging and requires increasing operating and maintenance (O&M) costs. In 2005, for example, operating an Aurora aircraft cost $11,758 per flying hour, compared to $5,087 in 1996 [1]. Replacing the fleet would involve an investment of billions of dollars accrued over the operational life. Therefore, a central question arises: Is it more economical to replace the fleet or continue its maintenance?

While the question of replacing or repairing equipment is a classic case of dynamic optimization, few papers deal with the optimal age to replace military aircraft. The reason behind this rarity is that the sevices generated by the equipment are not quantifiable and therefore not easily treated using conventional cost-benefit analysis.

This paper complements the few existing papers on this subject by providing an intergenerational hybrid model to identify the optimal strategy for replacing the fleet of CP-140 aircraft. The adopted mathematical framework is a fusion between the Greenfield and Persselin intergenerational model ([2, 3]), which seeks to minimize the total cost of the aircraft during its life cycle, and the Keating and Dixon approach which takes into account the Operational Availability (Ao) of the fleet ([4, 5]). These two models were prepared by The RAND Corporation for the United States Air Force under Project Air Force ([3, 5]).

To determine the optimal replacement age (ORA) of the aircraft, it is assumed, as in references ([2, 3]), that each generation of aircraft will be replaced by a similar generation in terms of constant dollar cost. A cyclic model of the fleet's life cycle is employed.

The model would gain in reliability if the data used were exhaustive and covered the whole lifetime of each aircraft. For want of better data, only 13 average annual observations were taken from the Cost Factors Manual [1] for costs, and the Director General Aerospace Equipment Program Management (DGAEPM) PERFORMA database for Ao [6].

The adopted approach consists of estimating the growth rate of O&M costs for each available year and using this information to trace the curve of the total cost. A sensitivity analysis was performed to assess the impact of some key model factors on the result and to evaluate the robustness of the model.

The ORA is 15 years for the Aurora and 13 years for the Arcturus. Each additional year produces an added cost due to the rise in O&M costs. This cost is relatively low for the first years, but it becomes exponential if the replacement is delayed too long. If the Arcturus is to be retired in 2009 (which corresponds to an age of 16 years), the loss is approximately $1.7M per aircraft. If the Aurora is to be retired in 2015 (which corresponds to an age of 35 years), the loss is approximately $63M per aircraft.

A. Sokri; 2009; An Economic Evaluation for CP-140 Aircraft Replacement; DRDC CORA TM 2009-027; DRDC – Centre for Operational Research and Analysis.

Sommaire

La flotte canadienne d'avions militaires CP-140 regroupe les deux aéronefs de surveillance territoriale Aurora (CP-140) et Arcturus (CP-140A) .

Âgée en moyenne de plus de 25 ans en septembre 2007, cette flotte, requiert des frais croissant de fonctionnement et de maintenance. En 2005, par exemple, le fonctionnement d'un aéronef Aurora a coûté $11,758 par heure de vol, soit une augmentation de 131.14% par rapport à l'année précédente [1]. Remplacer cet appareil nécessiterait un investissement de plusieurs millions de dollars. Dès lors une question centrale se pose : Est-t-il économiquement plus efficient de remplacer cette flotte ou de continuer sa maintenance ? L'objectif de ce rapport est justement de répondre à cette grande question.

Le remplacement ou la réparation d'une machine est un sujet classique en optimisation dynamique. Cependant peu de papier ont traité de l'âge optimal de remplacement d'un avion militaire. La raison derrière cette rareté est que cet appareil ne génère pas de profits quantifiables et ne s'apprête donc pas aisément aux analyses coûts-avantages classiques.

Ce travail complète les quelques écrits existants en fournissant un modèle intergénérationnel hybride permettant l'identification de la stratégie optimale de remplacement de la flotte des avions militaires CP-140. La formulation mathématique adoptée est un croisement entre le modèle intergénérationnel de Greenfield et Persselin ([2, 3]), qui cherche à minimiser le coût total de l'aéronef durant son cycle de vie, et l'approche de Keating et Dixon ([4, 5]) qui tient compte de la Disponibilité Opérationnelle des appareils.

Pour pouvoir déterminer l'âge optimal de remplacement de la flotte, nous supposons comme dans les références ([2, 3]) que chaque génération d'avions sera remplacée par une génération qui lui est semblable en termes de coût. Notre objectif étant de minimiser le coût de l'appareil durant son cycle de vie. La prise en considération d'une infinité de générations dans ce modèle n'est qu'un moyen mathématique pour déterminer l'âge optimal de retraite de la génération courante.

Ce modèle gagnerait en qualité si les données utilisées étaient désagrégées et portaient sur la durée de vie de chaque aéronef. Mais faute de mieux, on s'est contenté de 13 observations annuelles moyennes en provenance du Manuel des Coûts Standard [1] pour ce qui est des coûts. La Disponibilité Opérationnelle des aéronefs est fournie, quant à elle, par la base de donnée PERFORMA [6] de la Direction Générale - Gestion du Programme d'Équipement Aérospatial (DGGPEA).

Notre approche consiste d'abord à estimer le taux de croissance des frais de fonctionnement et de maintenance par année de disponibilité en fonction de l'âge de l'appareil. Ensuite, cette information est exploitée pour tracer la courbe du coût total. Une analyse de sensibilité est effectuée afin de détecter l'impact des fluctuations dans les paramètres sur le résultat et de juger par la même de la robustesse du modèle.

L'âge optimal de remplacement est de 15 ans pour Aurora et de 13 pour Arcturus. Après cet âge optimal, chaque année additionnelle engendrerait un coût supplémentaire dû à l’augmentation des frais d’opération et de maintenance. Le coût est relativement faible durant les toutes premières années, mais il deviendra exponentiel si le remplacement est différé pour une longue durée. Si l’aéronef Arcturus devait être substitué en 2009 (ce qui correspond à un âge de 16 ans), la perte marginale serait de l’ordre de $1.7M par appareil. Si l’aéronef Aurora devait être renouvelé en 2015 (ce qui coïncide avec un âge de 35 ans), cette perte unitaire est d’environ $63M.

A. Sokri; 2009; An Economic Evaluation for CP-140 Aircraft Replacement; DRDC CORA TM 2009-027; RDDC – Centre pour la recherche et l’analyse opérationnelles.

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1 Introduction

1.1 Background

The longer equipment stays in service, the higher are its maintenance costs, and the lower are its productivity. When equipment reaches a certain age, it may be more economical to replace it rather than continue its operation. The problem thus reduces to determining the most economical age for replacement [7].

With the department faced with aging equipment and increasing maintenance costs, the Defence Planning Board asked the Assistant Deputy Minister (Materiel), ADM(Mat), "... to present an analysis that outlines the point at which it becomes disadvantageous to maintain a specific fleet." [8]. The fleet chosen for this analysis was the CP-140 long-range maritime patrol aircraft (Figure 1).

Figure 1: *CP-140A Arcturus*

The strategic maritime surveillance fleet, consisting of 18 Aurora (CP-140) and 3 Arcturus (CP-140A) [1] aircraft is aging and experiencing increasing O&M costs. In 2007, for example, operating one CP-140 aircraft cost on average approximately \$4.98M, compared to \$2.84M in 1998 [1]. Several indicators illustrate a certain degradation in the fleet. One observes in particular that:

1. For the Aurora portion of the fleet, annual O&M costs have increased between 1997 and 2007 by about 84%, in terms of current dollars and by about 51%, in terms of 1989 constant dollar. These ratios are respectively 98% and 56% for the Arcturus [2]. The year 2007 has a special status since the data of the two types of aircraft were aggregated in this year.
2. The average On-Aircraft Workload Ratio has increased approximately by 137.5% between 1985 and 2007 [9]. The Workload Ratio measures the number of Maintenance

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[1] The Arcturus presents the same characteristics as the Aurora except that it is not equipped for anti-submarine warfare

[2] The Defence Specific Inflation Index was used to obtain costs in constant dollar

Person-Hours (MPHRs) per flying hour. It provides an indication of the unit maintenance effort required by an aircraft. As shown in Figure 2, the On-Aircraft Workload Ratio is increasing quite rapidly but what is most telling is that as the fleet has aged the variance in the ratio has also increased considerably. The average age varies over time. It changes when a new aircraft is acquired.

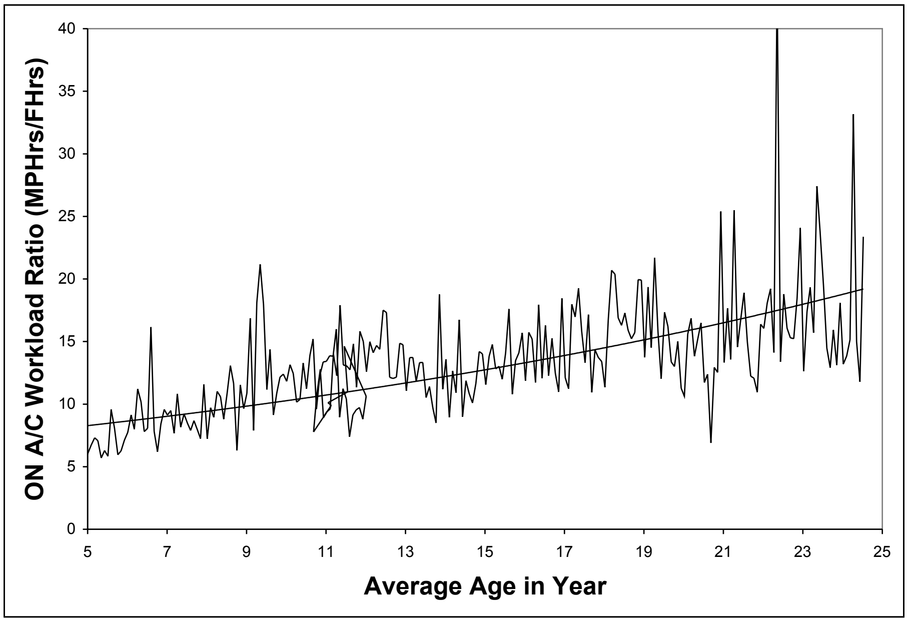

***Figure 2:** Evolution of On Aircraft Workload Ratio*

Replacing the fleet would involve an investment of billions of dollars accrued over the operational life. Therefore, a decision whether to repair or replace should not be taken lightly.

Replacing or repairing heavy equipment is a classic case of dynamic optimization, however, few papers have dealt with the optimal age to replace an aircraft. The reason being is that equipment of this nature provide services that are not directly quantifiable and therefore cannot easily be treated using conventional cost-benefit analysis.

Among the studies that have treated limited aspects of this question are: Greenfield and Persselin ([2, 3]) where the authors developed an intergenerational framework to identify the optimal replacement strategy that recognizes cost trade-offs and incorporates age effects; using an availability-oriented approach, Keating and Dixon ([4, 5]) developed a methodology to decide when to replace an aging system; Lincoln and Melliere [10] provided a procedure to determine the economic life for military aircraft; Chickermane and Gea [11] also present a methodology that generates optimal mechanical repairs for aging aircraft; Schwartz et al. [12] presented a dynamic program to determine optimal repair and replacement policies for an aircraft; and, more recently, Castro and Sanjuán [13] determined an optimal repair policy for a system with a limited number of repairs. For a review of literature related to the effect of aircraft age on maintenance costs see Dixon (2005) [14].

1.2 Scope

The objective of this study is to provide an answer to the following central question: "Is it economically efficient to replace the CP-140 fleet or continue its maintenance?"

Taking acquisition, O&M costs, and operational availability (Ao) into account, a procedure is developed to determine the optimal replacement age (ORA) for the fleet. This work complements the existing literature by providing a hybrid intergenerational model to identify the optimal replacement strategy for the CP-140 fleet. The adopted mathematical formulation is a fusion between the Greenfield and Persselin ([2, 3]) intergenerational model and the Keating and Dixon ([4, 5]) approach where Ao of the fleet is taken into consideration. In this model, O&M costs of one aircraft is estimated during its life cycle. The resulting curve is a convex parabola where the minimum coincides with the optimal age of replacement.

This report is organized into six sections. Following the introduction, section 2 describes the CP-140 fleet profile and presents the data used in the analysis.

Section 3 sets up the two used mathematical models and describes their derivations. It describes the complete derivation of the Greenfield and Persselin intergenerational model which seeks to minimize the total cost of the aircraft during its life cycle. It also describes the optimality condition of Keating and Dixon based on the Ao of the fleet.

Section 4 contains the full estimation of the model. It provides the ORA of the fleet and shows the marginal loss incurred by deferring the replacement beyond the ORA.

Section 5 demonstrates the impact of certain structural or institutional factors - such as the number of aircraft maintainers, the Aurora Incremental Modernization Project (AIMP) and the Ao of the fleet - on the optimal retirement age. More importantly, a sensitivity analysis is performed in this section to assess the impact of some key model parameters on the results and to evaluate the robustness of the model.

The report concludes in section 6 with a summary of the results concerning the optimal replacement strategy for the CP-140 fleet.

2 Data

2.1 Data Structure

The CP-140 fleet of aircraft includes 18 Aurora and 3 Arcturus[3]. The Aurora was acquired in 1980 with a unit acquisition cost of approximately \$37M [15] and an Estimated Life Expectancy of 30 years. It has the ability to fly more than 9000 km without refueling; and its 9266 km range and 7-hour endurance make it a multi-purpose aircraft ideal for performing a multitude of missions [16]. The Arcturus was accepted into service in 1993 with a unit cost of \$79.6\$M [15] [4] and an Estimated Life Expectancy of 13 years. It presents the same characteristics as the Aurora except that it is not equipped for anti-submarine warfare, making it a lighter and more fuel-efficient aircraft [16].

Table 1: *The CP-140 fleet*

	Aurora	Arcturus
Average age	27 years (1980)	14 years (1993)
Acquisition cost	37.3 \$M	79.6 \$M or 47.48 \$M in 1980 dollars
Quantity	18	3
Estimated Life Expectancy	30 years (2010)	13 years (2006)
Possible extension	2016	2009
Current Net Book value per A/C	7.35 \$M	0

In order to estimate the optimal retirement age of the fleet, the following information is required:

2.1.1 Average Age of the Fleet

Since aircraft do not all enter service at the same time, the age of each fleet will be represented by an average. As of September 2007, the CP-140 fleet (as a whole) has reached an average age of approximately 25 years. However, this average conceals a large difference between the two types of aircraft. The average age of the Aurora fleet, acquired in 1980, is 27 years[5], whereas that of the Arcturus fleet, acquired in 1991 and accepted into service in 1993, is only 14 years[6].

2.1.2 Average Acquisition Cost of One Aircraft

Analyzing the Aurora and Arcturus according to their acquisition costs shows that the two aircraft respectively cost \$37.3M and \$79.7M each when they were accepted into service. The acquisition costs include the purchase price itself and the various improvements on each

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[3] From hereon we use the designation CP-140 to refer to the entire fleet (common usage), although we acknowledge that it more accurately refers to the Aurora portion of the 21 aircraft fleet.

[4] Using a discount rate of 4.4%, 79.6\$M in 1993, has a value of 47.48\$M in 1980

[5] The first/last Auroras entered service May 1980/July 1981

[6] The first/last Arcturus entered service Dec. 1992/Apr. 1993.

aircraft. These improvements represent approximately 6% (or $2.18M) of the acquisition cost for the Aurora and 0.32% (or $.25M) for the Arcturus. When dealing with the entire fleet, a weighted average price was used.

2.1.3 The Trend in Operational Availability

According to the Director General Aerospace Equipment Program Management (DGAEPM) PERFORMA database [6], Ao is defined as the proportion of observed time that a group of aircraft is in an operable state (not undergoing maintenance) in relation to the total operational time available during a stated period. For the whole fleet, Ao has substantially deteriorated during the last decade, reaching its lowest level in 2005 (17.30%), over 6 percentage points less than the previous year (23.51%). Analyzing O&M costs of an aircraft will be more significant if the Ao is taken into account as it corrects the annual costs to obtain costs per available year. For example, expending $5M to operate an aircraft that is continuously available is not the same as spending $5M to operate an aircraft that is ready only half the time. It is this argument which justifies, in our view, the use of Ao to correct the deficiencies of the Greenfield and Persselin model ([2, 3]).

2.1.4 The Evolution of O&M Costs

The costs used in this study were drawn from Chapter 3 of the Cost Factors Manual (Aircraft Costs) [1]. Chapter 3 presents the national average cost per flying hour of every aircraft used by the Canadian Forces (CF). O&M costs considered in this study include:

- Petroleum, oil and lubricants;
- Engineering services;
- Repairs and overhaul; and
- Spares.

The total of these costs without Ao is used by the Department of National Defence (DND) to determine the costs to be recovered from other governmental departments. It can therefore be seen as an economic opportunity cost for aircraft [1].

Totaling about $5.20M in 2007, the yearly cost of operating and maintaining the fleet shows an annual increase of 7.87% since 1998. The year 2005 is clearly distinguishable from the others, since at the end of this year, yearly operating costs were valued at $6.42M, registering an increase of over 26.13% compared to the previous year.

Due to its young age, the Arcturus costs far less to operate and maintain. In 2006, for example, O&M costs totaled only $3.5M per Arcturus compared to $5.24M per Aurora. The year 2007 has a special status since it coincides with data aggregation of the two types of aircraft. During this year, the cost of operating and maintaining the whole fleet reached $5.20M per aircraft, largely due to the cost of operating the Aurora.

Table 2: *CP-140 O&M Costs per Aircraft (in current dollars)*

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Avg. Age (in year)	15	16	17	18	19	20	21	22	23	24
Aurora										
OM/FH ($\$10^3$)	5.09	7.03	7.93	10.12	10.96	11.32	11.55	13.43	11.76	12.02
Annual FH	792	669	552	480	483	463	463	500	446	433
Annual OM Cost ($\$10^6$)	4.03	4.70	4.38	4.86	5.29	5.24	5.35	6.72	5.24	5.20
Arcturus										
OM/FHs ($\$ 10^3$)	3.51	4.78	5.32	6.78	7.77	6.19	6.32	8.40	7.13	12.02
Annual FH	750	634	523	454	434	557	557	557	492	433
Annual OM Cost ($\$10^6$)	2.63	3.03	2.78	3.08	3.37	3.45	3.52	4.68	3.51	5.20
Average										
Annual OM (1)	3.83	4.46	4.15	4.60	5.02	4.98	5.09	6.42	5.00	5.20
Availability (in %) (2)	47.53	40.59	40.90	37.99	38.08	32.51	23.51	17.30	19.82	21.92
M=(1)/(2)	8.06	10.99	10.15	12.11	13.18	15.33	21.64	37.13	25.21	23.74

Figure 3 presents the evolution of the average annual O&M costs per aircraft as tabulated in bottom of Table 2. The average cost considered here is the weighted average incurred by the two types of aircraft. The average O&M cost per available year is obtained by dividing the average operating cost of each year by the corresponding Ao of the fleet.

2.1.5 O&M Costs at Acquisition and Their Growth Rate

In order to estimate the model, we need an estimate of O&M costs when the aircraft age was zero. An estimate of the growth rate of these costs is also required. These two parameters will be econometrically estimated using the two variables "O&M Costs" and "Age".

2.1.6 Discounting

Discounting is the process of finding the present value of an amount of cash at some future date and the discount rate expresses the opportunity cost of capital. For a department like DND, a good approximation for this rate would be the risk-free rate which could be the percentage of return generated by investing in long-term government bonds (4.40%). This rate was provided by the Bank Of Canada [17].

2.2 Data and Model Assumptions

The following assumptions are inherent in the data and the model:

1. Given that the objective of this study is to determine the ORA of the CP-140 fleet, Aircraft technology, operational requirements, and other environmental factors are assumed to be constant over time in the basic model.
2. All calculations are performed at age zero through a discounting process with a discount rate (assumed to be 4.4%) which provides the present value of an amount of cash at

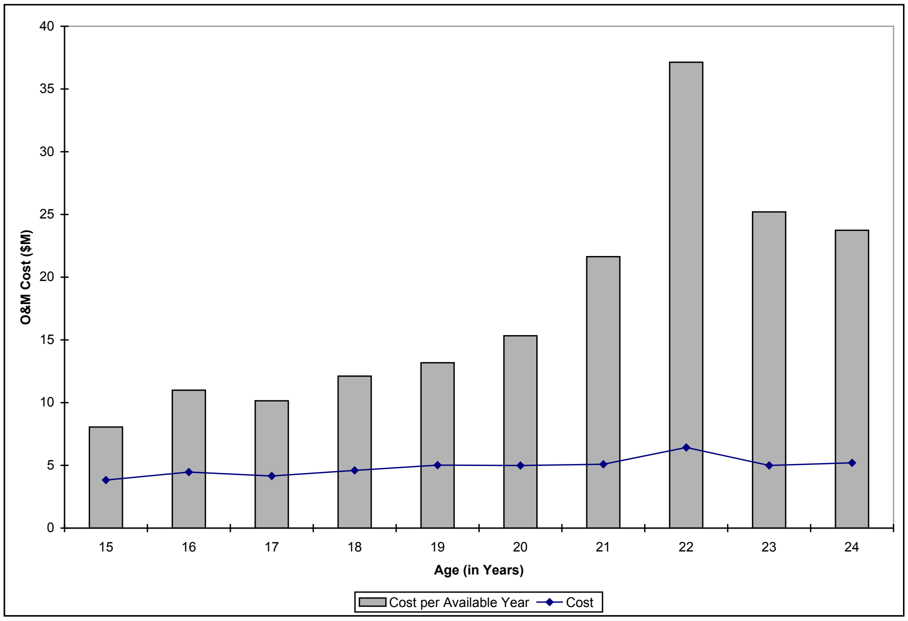

Figure 3: *O&M Cost Per Aircraft*

some future date. The value chosen corresponds to a risk-free rate akin to return on long-term government bonds [17].

3. Costs do not include salaries, personnel support and amortization. The costs related to personnel and to squadron support are independent of the age of the aircraft and will be disbursed regardless of the aircraft state (old or new). Amortization, for its part, is considered only for accounting purposes. It corresponds to the reduction of the value of aircraft. It does not correspond to any release of money.

4. Moreover, based on available information, O&M costs, Ao and ages considered in this analysis are all annual national averages.

3 The Model

Given the objective of this study and the nature of available data, a modified version of the Greenfield and Persselin economic model ([2, 3]) was used which takes into account the Ao of aircraft as presented by the Keating and Dixon model model ([4, 5]). For its implementation, the model used in this study requires a preliminary statistical analysis to estimate the evolution of operating costs with respect to aircraft age. For simplicity, the two models are presented separately in the following subsections.

3.1 The Economic Model

It is assumed that the CF initially acquires an aircraft at price p and disburses O&M costs, m, until the aircraft is withdrawn from service. Taking operational availability, A, into account the O&M cost per available year is given by

$$M = \frac{m}{A}$$

It is also assumed that O&M costs per available year, M, depend on aircraft age, a, through an increasing continuous function, i.e., $M'(a) > 0$. In the adopted framework age is defined broadly to include other related factors affecting the O&M costs per available year, such as engine cycles, sorties and flying hours. The objective is to minimize the total cost of acquiring, operating, and maintaining the aircraft during its life cycle. To determine the optimal age of replacement, we assume, as in references [2] and [3] that each generation of aircraft will be replaced by a new generation presenting the same costs in terms of constant dollars. With these conditions, the lifecycle cost of a given generation can be presented by:

$$p + \int_0^s e^{-ra} M(a)\, da\,, \tag{1}$$

where r is the discount rate and s is the replacement interval. In this expression, the cost has two components:

(a) the initial acquisition cost p which includes the purchase price and all improvements (Betterments) made initially on the aircraft; and

(b) the cost equation:

$$\int_0^s e^{-ra} M(a)\, da\,, \tag{2}$$

which is the sum of all expenses generated by operating and maintaining the aircraft since its acquisition until its retirement at age s.

The integral assumes a continuous time scale, which is a reasonable approximation to the discrete fiscal year based methods. Indexing each replacement by i, the total cost of n replacements is simply given by:

$$c(s) = \sum_{i=0}^{n} \left(p + \int_0^s e^{-ra} M(a)\, da \right) e^{-rsi}\,. \tag{3}$$

This expression is the sum of the first n terms of a geometric series where the first term is $p + \int_0^s e^{-ra} m(a)\, da$ and the ratio is e^{-rs}. Using the well-known formula for the sum of an infinite geometric series, this is equivalent to

$$c(s) = \left(p + \int_0^s e^{-ra} M(a)\, da \right) \frac{1 - e^{-rs(n+1)}}{1 - e^{-rs}}\,. \tag{4}$$

Since $e^{-rs} < 1$ and $r > 0$,

$$\lim_{n \longrightarrow \infty} e^{-rs(n+1)} = 0\,, \tag{5}$$

and one can rewrite the total present value of acquiring, operating and maintaining all generations of the fleet as[7]

$$c\left(s\right) = \frac{p + \int_0^s e^{-ra} M\left(a\right) da}{1 - e^{-rs}}\,. \tag{6}$$

Considering an infinite series of replacements is a mathematical way of determining the optimal age of retirement for the current generation. This procedure is necessary to determine the optimal age of the fleet. This model draws heavily from Preinreich's framework [18] which is an extension of Faustmann's model on forest management [19].

After dividing a yearly cost by the availability percentage, the cost per availability is obtained. Even if this change may seem minor, its impact on the results can be very important.

The derivative of function (6) with respect to s is given by

$$c'\left(s\right) = \frac{e^{-rs}}{\left(1 - e^{-rs}\right)^2}\left(M\left(s\right) - M\left(s\right)e^{-rs} - pr - r\int_0^s e^{-ar} m\left(a\right) da\right)\,. \tag{7}$$

Equating this derivative to zero, one obtains the following optimality condition:

$$M\left(s^*\right) = r\frac{p + \int_0^{s^*} e^{-ra} M\left(a\right) da}{1 - e^{-rs^*}}\,. \tag{8}$$

Assuming an interior solution, equation (8) provides the first order condition of the problem, where s^* is the ORA. This condition establishes equality between the marginal cost of further retention - on the left-hand side, and the corresponding marginal benefit - on the right-hand side. The benefit appears as a present value savings for an additional period. If the O&M costs evolve exponentially over time, namely

$$M\left(a\right) = be^{\alpha a}\,, \tag{9}$$

then Equation (6) becomes

$$c\left(s\right) = \frac{p + \frac{b\left(1 - e^{-(r-\alpha)s}\right)}{r-\alpha}}{1 - e^{-rs}}\,, \tag{10}$$

and the first order condition will be

$$M\left(s^*\right) = r\frac{p + b\int_0^{s^*} e^{(\alpha-r)a} da}{1 - e^{-rs^*}} = r\frac{p + \frac{b}{\alpha-r}\left(e^{(\alpha-r)s^*} - 1\right)}{1 - e^{-rs^*}}\,. \tag{11}$$

Note that the parameter b coincides with O&M costs when $a = 0$, (i.e. $M(0) = b$). Furthermore, noticing that

$$\ln\left(M\left(a\right)\right) = \ln\left(b\right) + \alpha a\,, \tag{12}$$

we conclude also that

$$\frac{M'\left(a\right)}{M\left(a\right)} = \frac{dM/da}{M} = \alpha\,, \tag{13}$$

which implies that the parameter α is nothing more than the growth rate of the O&M costs. This could directly be seen from (9).

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[7] The sum $a + ar + ar^2 + \ldots$ converges to $\frac{a}{1-r}$, when $|r| < 1$

The two parameters (α and b) are estimated by applying an Ordinary Least Squares (OLS) regression to Equation (14) below, where the dependent variable is $\ln(m)$, the independent variable is the aircraft age a, and ε is the error term.

$$\ln(M) = \alpha a + \ln(b) + \varepsilon\,. \tag{14}$$

3.2 The Availability Model

By assuming a Keating and Dixon ([4, 5]) approach, we consider that the CF have an existing aircraft, *I*, and envision having in the foreseeable future a replacement aircraft, *R*. Following the notation of [4, 5], the replacement aircraft would have a discrete series of discounted future expenses

$$x = \sum_{t=1}^{\infty} \frac{\text{Expend}_{R_t}}{(\text{1+Discount})^{t-1}}\,, \tag{15}$$

and would provide the following expression as the future availability sum

$$y = \sum_{t=1}^{\infty} \frac{\text{Availability}_{R_t}}{(\text{1+Discount})^{t-1}}\,. \tag{16}$$

Not sure it makes sense to discount availability as it is not monetary in nature. That is why all we have adopted from this model is only the idea of cost per available year. If the existing aircraft is kept only one more year, the discounted infinite sum of expenditures would be

$$\text{Expend}_{I_1} + \frac{x}{\text{1+Discount}}\,, \tag{17}$$

and the sum of availability would be

$$\text{Availability}_{I_1} + \frac{y}{\text{1+Discount}}\,. \tag{18}$$

If the CF's objective is to minimize the expenditures, then it would keep the existing aircraft one more year if and only if

$$\text{Expend}_{I_1} + \frac{x}{\text{1+Discount}} \leq x\,. \tag{19}$$

If Ao is taken into account, retaining the aging aircraft for one more year results in an average cost per availability of

$$\frac{\text{Expend}_{I_1} + \frac{x}{\text{1+Discount}}}{\text{Availability}_{I_1} + \frac{y}{\text{1+Discount}}}\,. \tag{20}$$

Thus, the CF should repair, rather than replace, a current aircraft for one more year if and only if

$$\frac{\text{Expend}_{I_1} + \frac{x}{\text{1+Discount}}}{\text{Availability}_{I_1} + \frac{y}{\text{1+Discount}}} \leq \frac{x}{y}\,, \tag{21}$$

or after simplification

$$\frac{\text{Expend}_{I_1}}{\text{Availability}_{I_1}} \leq \frac{x}{y}\,. \tag{22}$$

Controlling for aircraft availability levels, this rule explains that it would be optimal to continue to repair an aircraft if the annual cost of doing so is less than the annualized total cost of a new aircraft. For application purposes, this optimality condition should be used prospectively several years before the optimal retirement year.

3.3 The Hybrid Model

The hybrid model is a fusion between the Greenfield and Persselin intergenerational model ([2, 3]), which seeks to minimize the total cost of the aircraft during its life cycle, and the Keating and Dixon approach which takes into account the Operational Availability (Ao) of the fleet ([4, 5]). These two models were prepared by The RAND Corporation for the United States Air Force under Project Air Force ([3, 5]). The hybrid model is presented in section 3. It differs from that of Greenfield and Persselin ([2, 3]) by considering the O&M cost per available year is given by

$$M = \frac{m}{A}$$

instead of O&M costs, m. The adopted mathematical framework retains the full rigor of the first model while the main idea of the second model is incorporated to it. This change may seem simple, but its impact on the results can be significant.

4 The Optimal Retirement Calculation

In this section, all the estimation results are presented. A sensitivity analysis is carried out in the next section to assess the impact of some key model parameters and factors on the basic result.

4.1 Estimation

OLS regression is an explanatory method (i.e. It attempts to explain the evolution of the response (or dependent variable) using one or more explanatory variables (also regressors or independent variables)), which can serve as a predictive method. The goal is to measure in a linear form the relationship between the response variable $\ln(M)$ and the explanatory variable a. The following assumptions are generally accepted as standard for this type of analysis::

1. All errors are uncorrelated with constant variance and zero mean; and,

2. The error is assumed to be normally distributed [20, 21].

The O&M costs per available year are statistically estimated as a function of age. A linear regression equation was built giving the natural logarithm of O&M costs per year (dependent variable) as a function of aircraft age (independent variable). Applying an OLS regression on the data in Row 10 of Table 2 provides the following linear model for equation

(14), i.e.,

$$\begin{aligned} \ln(m) &= \alpha a + \ln(b) && (23) \\ &= 0.145a + 13.683\,, && (24) \end{aligned}$$

where the results show a strong linear correlation between the dependent variable (*ln (m)*) and the explanatory variable age, a, with coefficient of determination $R^2 = 0.826$; Ljung-Box test proves the absence of any autocorrelation between errors. These results show that the exponential specification between M and a provides an acceptable and reasonable fit. Equation (24) provides the value of the growth rate of operating costs per year, α, and the initial O&M cost per available year, b.

$$b = e^{13.683} = \$8.75893 \times 10^5. \tag{25}$$

Given that the total cost of an infinite series of replacements is provided by equation (10), replacing all the parameters by their respective values namely $p = 38.75$ (the average price), $b = 0.876$ (equation (25)), $\alpha = 0.145$ (equation (24)) and and $r = 4.40$ (the assumed discount rate), the following equation is obtained:

$$c(s) = \frac{1}{1 - e^{-0.044s}} \left(7.9636e^{0.11s} + 11.411\right). \tag{26}$$

The average unit price is calculated by weighting the unit purchase price of each type of aircraft by the corresponding number of aircraft after discounting the two prices to the same calculation year (1980).

Although the minimum of this expression can not easily be derived in closed form, a minimum can be established both graphically and numerically by plotting the total cost equation as a function of the replacement age.

4.2 Basic Result

Figure 4 shows the CP-140 fleet's ORA as replacement age that achieves the minimum total cost, where the marginal cost of further retention equals the marginal benefit from deferring the purchase of a replacement. The minimum of the plot is found to be at 15 years. Separating the fleet into the two classes of aircraft, it is found for the Aurora, that the initial O&M costs per year (b) passes from a fleet value of \$0.876M to \$0.954M; the ratio of the *acquisition cost/initial O&M costs*, p/b, decreases to 39.14; and the rate of increase of O&M costs (α) decreases from 14.5% to 13.8%. It is important to note that, with these new parameters, the ORA of the Aurora portion of the fleet remains at 15 years from inception, which corresponds to the year 1995.

For the case of the Arcturus, the initial O&M costs per year (b) increases to more than \$3.02M, the *p/b* ratio decreases to 26.40, and the rate of increase in O&M costs is approximately 14%. The combined effect of all these parameters decrease the ORA from 15 years, for the whole fleet, to 13 years from inception, which corresponds to the year 2006.

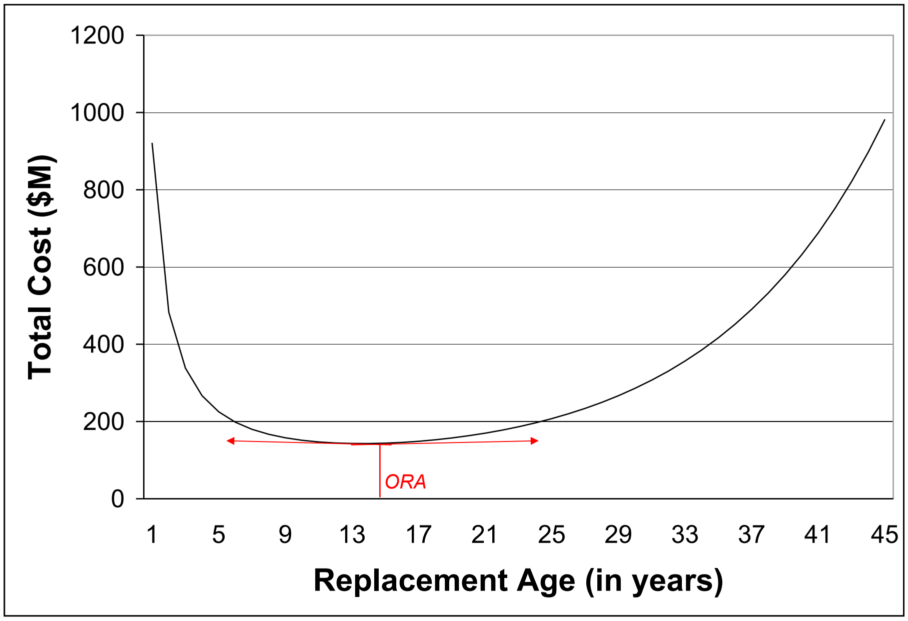

Figure 4: *ORA for the Average Fleet*

4.3 Deferment Costs

As stated, the ORA is 15 years for the Aurora and 13 years for the Arcturus. Each additional year produces an added cost due to the rise in O&M costs. Figure 5 shows the marginal loss incurred by deferring the replacement beyond the ORA. This cost is relatively low for the first few years, but it becomes exponential if the replacement is delayed too long. If the Arcturus is to be retired in 2009 (which corresponds to an age of 16 years), the loss is approximately $1.7M per aircraft. If the Aurora is to be retired in 2015 (which corresponds to an age of 35 years), the loss is about $63M per aircraft for a total loss of $1.14B for an 18 aircraft fleet.

5 Sensitivity Analysis

In the adopted framework, age is defined broadly to include other related factors affecting the O&M cost per year, such as engine cycles, sorties, and flying hours. Actually, even if chronological age can be considered as a rough proxy for engine cycles, sorties, and flying hours, other relevant factors, such as workforce reductions or modernization projects may account for higher O&M costs. These kinds of structural and institutional factors can affect the unit cost per available year and therefore the ORA. A complete discussion of these results will be given in the following subsections. We assess, in particular,

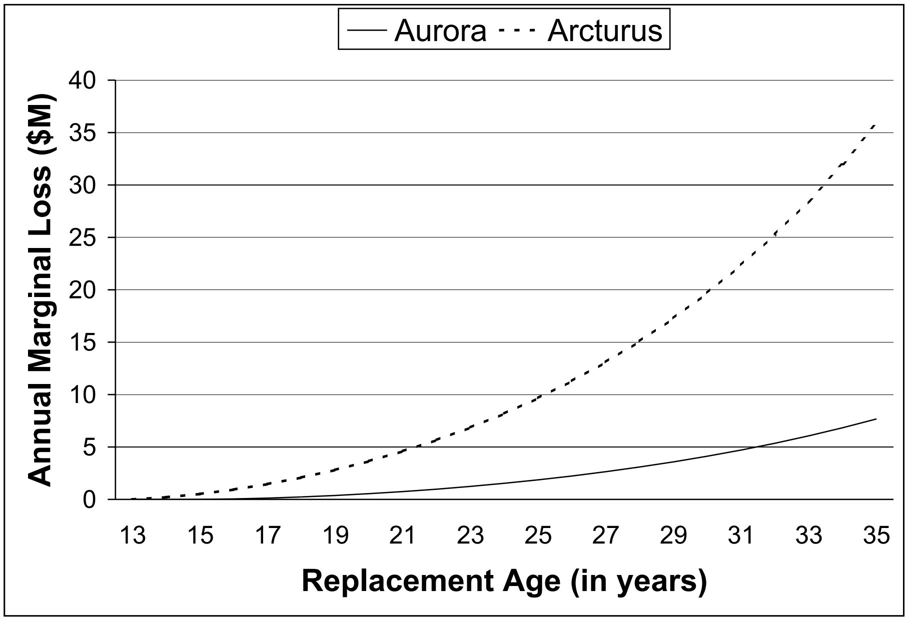

Figure 5: *Annual Additional Costs Beyond the ORA*

- the effect of the number of maintainers;
- the effect of the Aurora Incremental Modernization Project (AIMP);
- the effect of Ao; and
- the impact of the key model parameters on the result.

5.1 Effect of the Number of Maintainers

Workforce reductions may account for decreasing availability. Any decrease in the number of maintainers could expectedly push the fleet availability downward. A brief overview on the number of technicians reveals that it has decreased from 876 in 1997 to 647 in 2007 registering an average annual decrease rate of approximately 3% [22]. As shown in Figure 6, there is no understandable impact of the number of technicians on the decrease in the Arcturus Ao. For Aurora, the correlation was not sufficient to alter the ORA. This situation may have two main reasons:

1. Reduction in technicians is not strong enough to influence the Aurora Ao. To prove this

statement, consider the following regression model which accounts for lag effects:

$$Ao(t) = \beta_0 + \beta_1 \text{Techicians}(t-1) \ + \beta_2 \text{Age}(t) \tag{27}$$

As stated in table 3, the reduction of one technician reduces Ao by .006 percentage points which is statistically nil[8]

Table 3: *Effect of the Number of Maintainers on the Aurora Ao*

	Estimate	Std. Error	t	(95%) Confidence Interval
Techicians	.006	.023	.252	[-.051, .062]
Age	-3.945	.661	-5.973	[-5.562, -2.329]
Intercept	111.136	31.004	3.585	[35.271, 187.001]

2. Another reason could be due to "‘learning by doing"’ which could improve the technicians’ productivity. The idea behind the economic concept of learning by doing is simple: With experience, the employees acquire skills and abilities that improve their productivity.

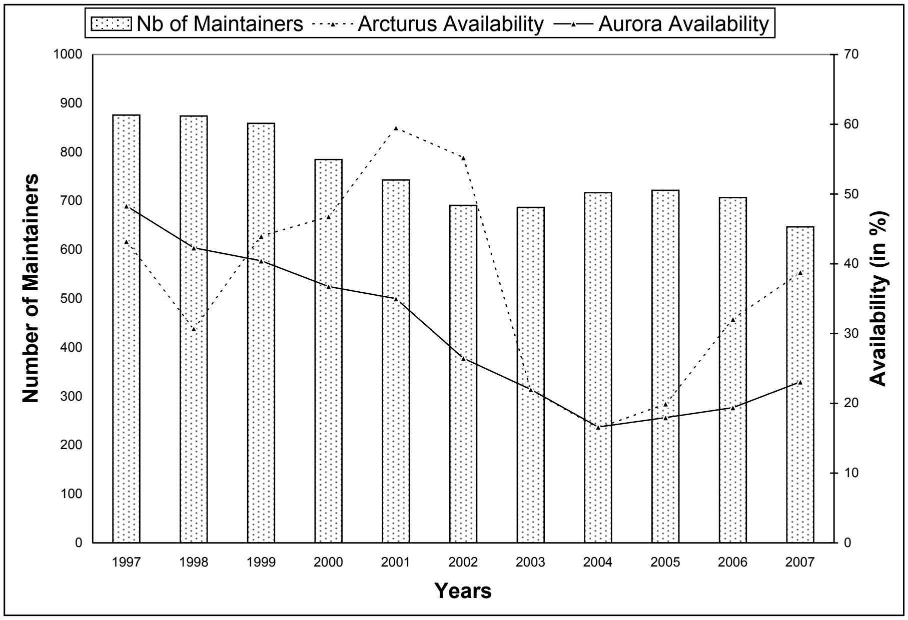

Figure 6: *Numbers of Maintainers and Fleet Availability*

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[8] Note that between 2005 and 2007, the number of technicians decreased from 722 to 647 (-10.39%), and Ao increased from 17.95% to 23.08% (+5.13%).

5.2 Effect of the Aurora Incremental Modernization Project

The AIMP was implemented in the late 1990's to restore the Aurora's operational capability ([23, 24]). Since the Aurora's systems are based on 1960's technology, the AIMP was indispensable to upgrade Canada's surveillance needs at home and abroad. In this subsection, this modernization is seen as a repair. This program should improve the Aurora flight safety, supportability and reliability of its tactical systems.

Analyzing the unit costs generated by this program, Figure 7 shows that they have increased from \$82.7K in 2000 to nearly \$8.9M in 2007, registering an average annual growth rate of approximately 95% [25]. The year 2005 is clearly distinguishable from all others, since in this year the average cost reached the peak of \$12.9M. Adding in these costs pushes O&M upward, but it does not significantly affect the Aurora ORA. It is as if the O&M costs had experienced a generalized increase, which does not affect, in a marked manner, the minimum on the total cost curve.

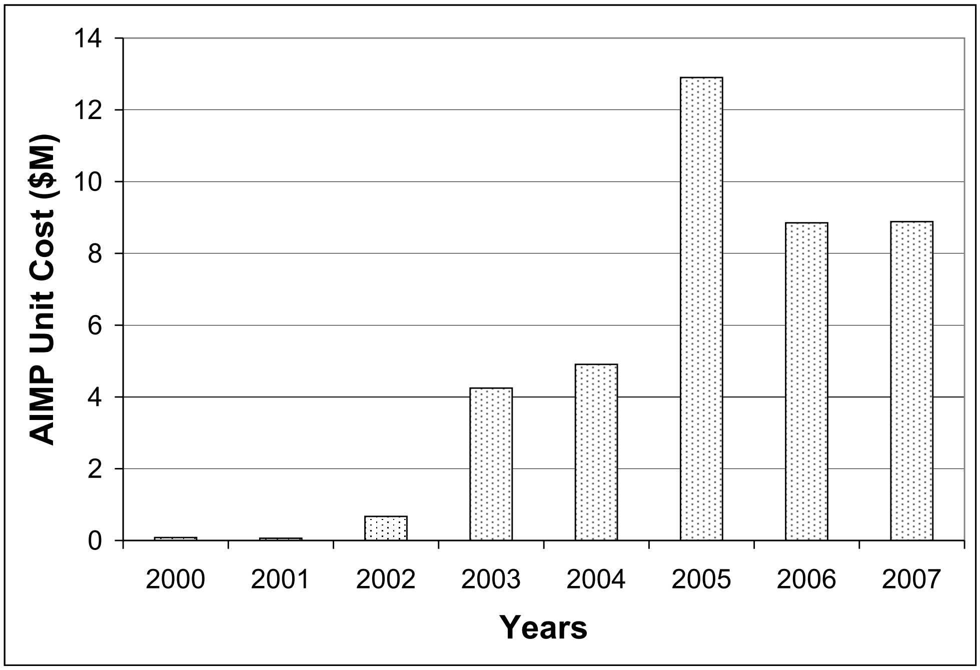

***Figure 7:** AIMP Unit Costs*

5.3 Effect of Operational Availability

Taking into account the Ao of aircraft as built into the model, the optimal policy would be to replace the fleet when it reached the age of 15 years. If Ao was omitted from the analysis,using data from Row 8 of table 2 rather than Row 10, the optimal age of retirement would be between 29 and 37 years (Figure 8). Indeed, the growth rate of operating costs, α, would fall to 3.7% and the initial value of such costs, b, would rise to \$2.32M. These two changes would have an opposite effect on the optimal age of replacement, but the decline in α, would prevail. The result is a combined effect that augments the ORA.

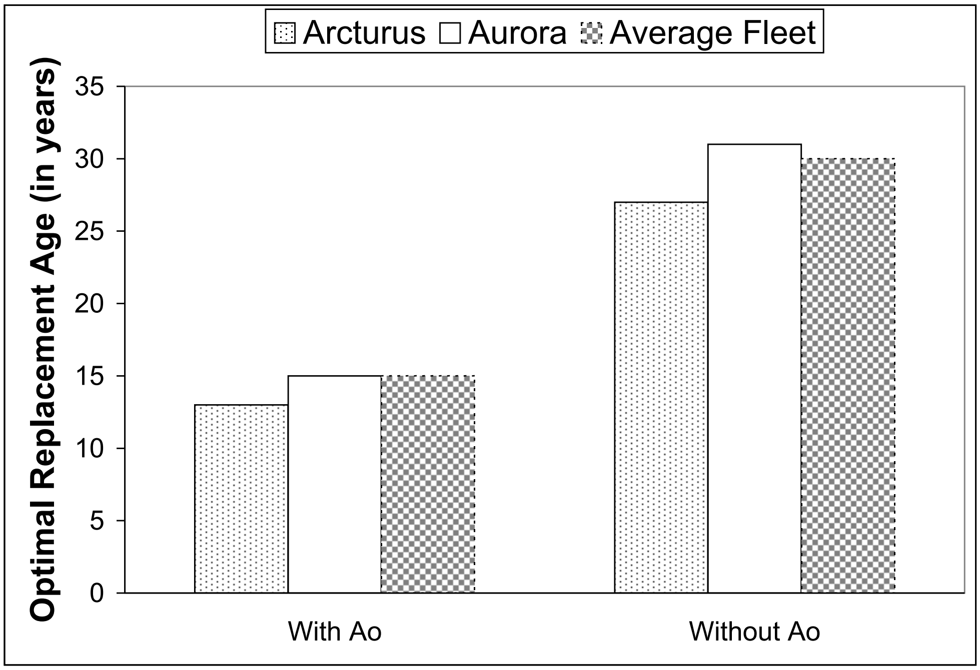

Figure 8: *Effect of Operational Availability*

5.4 Effect of Varying the Parameters

In order to test the model's robustness, a sensitivity analysis was done to detect the impact of varying the parameters on the ORA of the fleet. The model has four parameters, p

(acquisition cost), *b* (initial annual O&M cost), α (exponential growth rate of O&M costs) and *r* (discount rate). Table 4, in which the highlighted column provides the results of the baseline scenario, contains the results of the variations. This table mainly highlights the following key points:

Table 4: *Sensitivity Analysis*

Parameter	Value					Impact	Importance
p	20	30	**43.38**	60	80	+	Weak
Age	11	13	**15**	16	17		
b	0.40	0.6	**0.876**	0.90	1	-	Weak
Age	17.5	16	**15**	14	13.5		
α	5 %	10 %	**14.5%**	20 %	30 %	-	Strong
Age	34	19	**15**	11	8		
r	2 %	3 %	**4.40%**	6 %	10 %	+	Weak
Age	13.5	14	**15**	15	15.5		

1. The parameters *p* and *b* have opposite effects. Increasing *p* or decreasing *b* will have qualitatively the same impact on the optimal age of replacement but in different proportions. Proportional change in *p* will offset the impact of *b*. Because Equation (11) is linear in p and b, the ratio p/b can provide a good basis for quantitative analysis.

2. Table 4 shows also that the adopted model is very insensitive with respect to changes in the parameters *p*, *b* and *r*. A variation in any of these parameters did not significantly affect the results of the analysis. The model is, however, very sensitive to variations in the growth rate of O&M costs, α. As this rate increases, the ORA shortens. For example, as shown by the simulation (Table 4), an increase from 5% to 10% may reduce the ORA by 15 years (from 34 to 19 years). This observation leads to the main conclusion that controlling the ORA of any fleet must first pass through the O&M costs control. Figure 9 which uses the same data in Table 4 shows the effect of modifying each parameter on the ORA. The variation of age according to α highlights the importance of the negative impact that this parameter has on the solution.

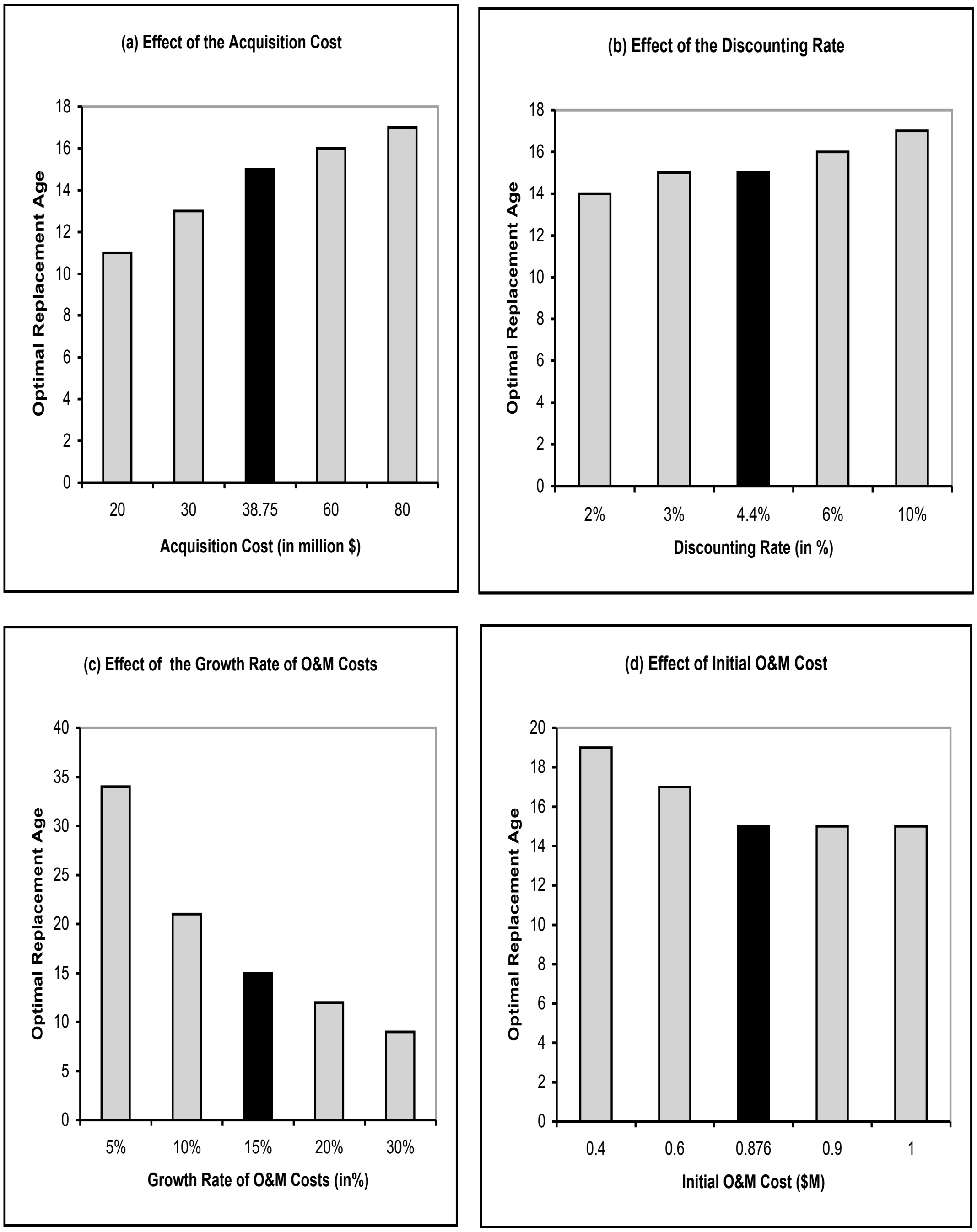

Figure 9: *Impact of Key Model Parameters on the ORA: (a) Effect of the Acquisition Cost. (b) Effect of the Discounting Rate. (c) Effect of the Growth Rate of O&M Costs. (d) Effect of Initial O&M Cost.*

6 Summary

The longer a fleet stays in service, the higher will be its O&M costs and the lower its operational availability, and hence its overall capability. For this reason, the CF would like to determine the ORA for their CP-140 fleet.

The CP140 fleet is over 25 years old and consists of 18 Aurora and 3 Arcturus aircraft, which require increasing O&M costs. For the Aurora, Annual O&M costs have increased between 1997 and 2007 by approximately 84%, in terms of current dollars and by approximately 51%, in terms of 1989 constant dollar. These ratios are respectively 98% and 56% for the Arcturus. The Workload Ratio, which measures the number of Maintenance Person-Hours (MPHRs) per flying hour, have increased by 137.5% between 1985 and 2007.

Analysis shows that factors, such as workforce reductions and the Aurora Incremental Modernization Project, may account for higher O&M costs but they are not strong enough to influence the ORA of the fleet.

A sensitivity analysis was carried out to assess the impact of key model parameters, such as the acquisition cost and the growth rate of O&M costs, on the result. The numerical simulation shows that the basic results are relatively insensitive to changes in the acquisition cost and the discount rate. The simulation emphasizes, however, that the key parameter in this model remains the exponential growth rate parameter of O&M costs. This result reveals that to control the optimal replacement interval of the fleet requires a serious control of the O&M costs trend.

6.1 Recommendations

This study provides a strategy for determining the ORA for this fleet. Taking Ao into account, results show that the ORA was 15 years for the Aurora which corresponds to the year 1995 and 13 years for the Arcturus, which corresponds to the year 2006. Each additional year beyond the ORA produces an added cost. This cost is relatively low for the first few years, but becomes very significant if the replacement is delayed too long.

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List of symbols/abbreviations/acronyms/initialisms

ADM(Mat)	Assistant Deputy Minister(Materiel)
Ao	Operational Availability
AIMP	Aurora Incremental Modernization Project
B	Billion
CF	Canadian Forces
DGAEPM	Director General Aerospace Equipment Program Management
FH	flying hour
K	Thousand
M	Million
MPHRs	Maintenance Person-Hours
OLS	Ordinary Least Squares
O&M	Operating and Maintenance
ORA	Optimal Replacement Age

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The purpose of this report is to identify the optimal replacement strategy for the Canadian Forces (CF) Long-Range Patrol CP-140 fleet. The adopted mathematical formulation is a fusion between an intergenerational model and an approach which uses the notion of operational availability of aircraft. In this resulting model, operating and maintenance costs per available year are estimated as a function of aircraft age during its life cycle. After determining the optimal age of replacement, a sensitivity analysis was carried out to assess the impact of some key model parameters on the result. This repair or replace model has the huge advantage of being applicable to any kind of heavy equipment. For example, it may be used to determine, in the same manner, the optimal age of replacing several types of fleets such as helicopters, ships, tanks, trucks, etc.

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