Image Cover Sheet

CLASSIFICATION	SYSTEM NUMBER 517323
UNCLASSIFIED	

TITLE

A methodology to improve the cost-effectiveness of the maintenance process of the CF-18 engine, through a better management of its life lim

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to: DK

This page is left blank

This page is left blank

DEPARTMENT OF NATIONAL DEFENCE
CANADA

OPERATIONAL RESEARCH DIVISION

DIRECTORATE OF OPERATIONAL RESEARCH
(MARITIME, LAND & AIR)

ORD PROJECT REPORT PR 2002/02

A METHODOLOGY TO IMPROVE THE COST-EFFECTIVENESS OF THE MAINTENANCE PROCESS OF THE CF-18 ENGINE, THROUGH A BETTER MANAGEMENT OF ITS LIFE LIMITED COMPONENTS

by

LUMINITA STEMATE

JANUARY 2002

OTTAWA, CANADA

National Defence Défense nationale

OPERATIONAL RESEARCH DIVISION

CATEGORIES OF PUBLICATION

ORD Reports are the most authoritative and most carefully considered publications of the DGOR scientific community. They normally embody the results of major research activities or are significant works of lasting value or provide a comprehensive view on major defence research initiatives. ORD Reports are approved personally by DGOR, and are subject to peer review.

ORD Project Reports record the analysis and results of studies conducted for specific sponsors. This Category is the main vehicle to report completed research to the sponsors and may also describe a significant milestone in ongoing work. They are approved by DGOR and are subject to peer review. They are released initially to sponsors and may, with sponsor approval, be released to other agencies having an interest in the material.

Directorate Research Notes are issued by directorates. They are intended to outline, develop or document proposals, ideas, analysis or models which do not warrant more formal publication. They may record development work done in support of sponsored projects which could be applied elsewhere in the future. As such they help serve as the corporate scientific memory of the directorates.

ORD Journal Reprints provide readily available copies of articles published with DGOR approval, by OR researchers in learned journals, open technical publications, proceedings, etc.

ORD Contractor Reports document research done under contract of DGOR agencies by industrial concerns, universities, consultants, other government departments or agencies, etc. The scientific content is the responsibility of the originator but has been reviewed by the scientific authority for the contract and approved for release by DGOR.

DEPARTMENT OF NATIONAL DEFENCE

CANADA

OPERATIONAL RESEARCH DIVISION

DIRECTORATE OF OPERATIONAL RESEARCH
(MARITIME, LAND & AIR)

ORD PROJECT REPORT 2002/02

A METHODOLOGY TO IMPROVE THE COST-EFFECTIVENESS OF THE MAINTENANCE PROCESS OF THE CF-18 ENGINE, THROUGH A BETTER MANAGEMENT OF ITS LIFE LIMITED COMPONENTS

by

LUMINITA STEMATE

Recommended by: J. EVANS
DOR(MLA)

Approved by: A. BRADFIELD
DGOR

OTTAWA, ONTARIO

JANUARY 2002

ABSTRACT

The aim of this study is to provide a methodology to improve the cost-effectiveness of the maintenance process of the F404-GE-400 engines of the Canadian Forces CF-18 Fighter Aircraft, through a better management of the limited life components inside the engine. An effort was made to construct the present report as a sufficient, stand-alone source of documentation to be used for any future implementation of the proposed methodology.

RÉSUMÉ

Le but de cette étude est de fournir une méthodologie permettant l'amélioration de la rentabilité du processus de maintenance de moteurs F404-GE-400 des aéronefs CF-18, par une meilleure gestion des composantes de ce moteur ayant une vie limitée. Des efforts ont été entrepris pour faire de ce rapport une source de documentation autonome et suffisante pour tous les besoins d'une future implémentation de cette méthodologie.

EXECUTIVE SUMMARY

This study, requested by the Directorate of Aerospace Equipment Program Management, Fighters and Trainers (DAEPM(FT)), proposes a methodology that will allow a significant improvement in the cost-effectiveness of the maintenance process of the CF-18 engine, by means of a better management of its life-limited components. Besides improving the cost-effectiveness, the proposed system will also be easier to use and will provide faster and more reliable solutions than the system currently in place.

This report is intended primarily for the analyst/programmer that will implement the methodology proposed. It aims to provide a comprehensive source of documentation on most issues related to the life-limited modules inside the CF-18 engine. The first part of the document is dedicated to a summary description of the background aspects of the maintenance process of the CF-18 engines, with a focus on those maintenance concepts and practices that are related to the limited life components. The second part of the document is dedicated to the methodology itself. An algorithm in four steps is presented in a structured form that is ready for translation into programming code. In an effort to produce an easy to understand document, which is a key element for a successful implementation of the methodology, numerical examples are inserted throughout the document.

Specifically, the problem that was solved in this study is how to optimize and automate the process of selection of the various life-limited components of a CF-18 engine, such that, when assembled, the engine obtained is "the best", according to two (conflicting) objectives:

a) *the number of hours the engine can fly maximized* (i.e., the number of hours between two consecutive visits at the Repair Facility for a Part Life Change Out (PLCO)[1] should be as high as possible); and

[1] Part Life Change Out (PLCO) = the operation of changing a life-limited component that has no more life remaining with one that has a suitable amount of life remaining.

b) *the number of hours that are lost minimized* on those lifed[2] components in the engine that are changed before exhausting their lives.

The two objectives are conflicting in the sense that, often, producing a better engine with respect to one of the objectives can only be done at the expense of the other objective.

In that sense, one of the main findings of this study is a formal criterion that can be used to compare two engines characterized by different amounts of hours remaining until the next visit to the Repair Facility *and* different amounts of hours lost due to those lifed components that are changed before their lives were exhausted. This criterion is the answer to one of the major problems of the existing system: the impossibility (up until now) of making sensible tradeoffs between the two conflicting objectives. For example, consider two different engines that could be built based on a given set of spare parts. One that is characterized by 800 flying hours remaining until the next PLCO and 300 hours lost on lifed components. The second is characterized by 700 flying hours remaining until the next PLCO and 50 hours lost on lifed components. The first engine is better than the second with respect to the first criterion. On the other hand, the second one is better than the first with respect to the second criterion. Until now, deciding which of the two engines is really the best, given that both criteria are important, would have been very difficult, if not impossible. However, using the criterion proposed in this study, the answer to this problem is as simple as calculating a *costing ratio* for each of the engines and finding the minimum between the two ratios (see pages 48-49).

Based on the analysis conducted for this study, a number of observations were made, regarding possible ways to further improve the system. Given that the CF-18 fleet is subject to a Life Extension Program that is meant to extend the life of the CF-18 aircraft until 2017, all the avenues recommended in this study are well worth being explored, because they can all result in important savings for the department, and even more so when the savings can be realized over such a long period of time. The

[2] Lifed components = Life-limited components; more information on this subject can be found on page 8.

recommendations issued from this study are provided in the followings paragraphs. Note that the order in which they are presented does not necessarily represent their ranking in terms of importance (or impact).

It is recommended that the concept of *fallout window*[3] be re-visited. Different discarding thresholds[4] should be employed for components that have different monetary values (i.e., different costs by flying hour), rather than employing the same value of 400 hours, regardless of the criticality of the component. Establishing a sound methodology to compute discarding thresholds specific to each type of component can be a source for significant additional savings.

It is also recommended that *all* costs involved in the maintenance process be tracked. In particular, the costs labelled as "unknown wastage costs" should be tracked. This will permit a more intimate comprehension of the costs involved in the maintenance process, conducive to a better control over these costs and therefore to additional potential savings.

Finally, it is recommended that the possibility of re-organizing the process of distribution of spare parts between the two Repair Facilities in Cold Lake and Bagotville, and the central pool situated in Toronto be explored, in order to achieve a better match between the supply and the demand of spare parts. Inventory management principles should also be examined and applied to further improve the matching between supply and demand.

---

[3] According to this concept, when an engine is inducted to the repair shop for the replacement of an expired component, any other lifed components in that engine that have less than 400 hours remaining until they expire themselves, will be replaced at the same time.

[4] The "discarding threshold" is a value that establishes the minimum amount of life remaining on a component so that the component is worth keeping in stock to be reinstalled in another engine. If a component has a life remaining below this threshold, it can be discarded.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AFH = Airframe Hours;

AHR = Airframe Hours Remaining (in the case of a single engine) *or* Average Hours Remaining (in the case of multiple engines);

CC = Combustor Case,

DAEPM(FT)= Directorate of Aerospace Equipment Program Management (Fighters and Trainers);

FDS = Fan Drive Shaft;

HPT = High Pressure Turbine;

LCF = Low Cycle Fatigue;

LPT = Low Pressure Turbine;

LUI = Life Used Index;

PLCO = Part Life Change Out;

RFI = Ready for Installation;

SAC = Serviceability Assurance Check;

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to thank Maj. Andrew Fitzgerald (formerly DAEPMFT 2-3-4) for all his efforts to introduce me to the world of engines' maintenance, including the facilitation of my visit to Bagotville, to meet some of the end users of this project. Also, many thanks to Mr. Randy Cook (DAEPMFT 2-3-9) for providing the data required for this study. Lastly, I would like to thank all the maintenance personnel in Bagotville for their enthusiasm in receiving this project and for their eagerness to help in any way they could. It was very much appreciated.

A METHODOLOGY TO IMPROVE THE COST-EFFECTIVENESS OF THE MAINTENANCE PROCESS OF THE CF-18 ENGINES, THROUGH A BETTER MANAGEMENT OF ITS LIFE-LIMITED COMPONENTS

INTRODUCTION

1. The present study, requested by the Directorate of Aerospace Equipment Program Management, Fighters and Trainers (DAEPM(FT)), proposes a methodology that can be used to improve the cost-effectiveness of the maintenance process of the CF-18 engines, by means of a better management of its life-limited components.

2. The author's objective during this project was not only to propose a methodology serving the purpose mentioned above, but also to provide a methodology that is ready for implementation. For this reason, the report was conceived as a stand-alone source of documentation, containing two main parts. The first part is dedicated to a comprehensive overview of the maintenance process of the CF-18 engines, with a focus on those maintenance concepts and practices that are related to the life-limited components. The second part is dedicated to the methodology itself, which is exposed in a manner that was considered by the author to be the most suitable for an easy understanding and translation of the algorithms into programming code.

PART I: BACKGROUND INFORMATION

The F 404-GE-400 Engine

3. The F 404-GE-400 engine is built in a modular fashion. Four of its modules are life-limited because some of their components have a pre-defined life limit. Annex A provides the logical configuration of each of these four modules, highlighting their lifed components. Each module contains several sub-assemblies, some of them life limited, some not. For the purpose of this study, not all lifed sub-components will be considered separately, because some of them arrive at the Repair Facility already pre-assembled. All pre-assembled lifed components are considered as one (lifed) entity.

4. Since the scope of the present study considers solely the lifed components of the engine, the schema in Figure 1 is proposed as a useful working tool. This schema illustrates, in a simplified manner, only the lifed modules/components, respecting their physical positioning in the engine as closely as possible.

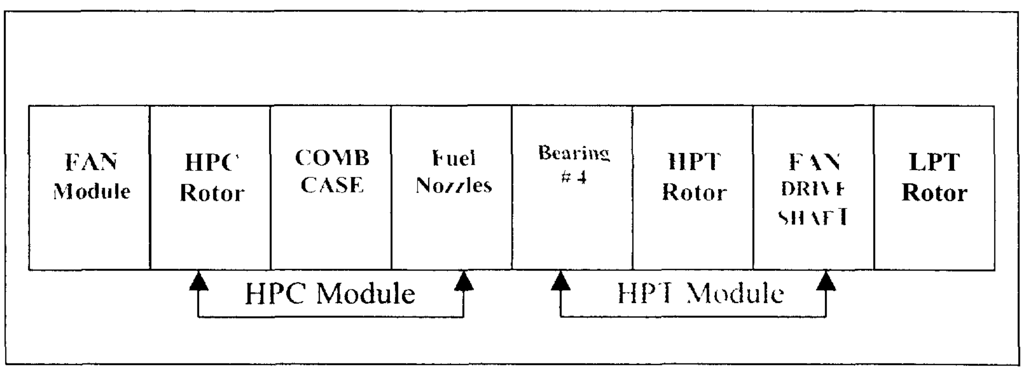

Figure 1. Lifed Modules/Components of the F 404-GE-400 Engine

5. The eight components in Figure 1 constitute the main "building blocks" of this study, along with the various costs involved. Each module was depicted in a different colour. It can be seen that two of the modules were de-composed into three different

components, each having different life limits and are relatively independent of one another, in the sense that they can be replaced without necessarily replacing the other components of the same module. Therefore, for the purpose of this study, eight life-limited components will be considered (instead of the four lifed modules).

6. **The "driver":** Figure 2 helps define the relationships between the eight life limited components composing an engine, with respect to the amount of life remaining on each of them at the time the engine is brought to the repair shop for a Part Life Change Out (PLCO)[5]. The component that actually brings (drives) the engine to the shop because its life has expired (i.e., it has zero hours remaining) is called the **driver**.

FAN Module	HPC Rotor	COMB CASE	Fuel Nozzles	Bearing #4	HPT Rotor	FAN DRIVE SHAFT	LPT Rotor
2100 hr	270 hr	5600 hr	2200 hr	320 hr	0 hr	6000 hr	150 hr
INDEP.	DEP	INDEP	INDEP	DEP	↑ DRIVER	INDEP	DEP.

Figure 2. Relationships between the various modules of an engine, from a life remaining perspective

7. **The "dependent modules":** Modules (or components) that have less than 400 hours remaining at the time of the PLCO of the driver will be changed in the same time as the driver, according to the "fallout window" policy (see para. 18). To convey the idea that the time of their changing depends on the driver (since, otherwise, they would still have some life remaining), these modules are called **dependent** (on the driver).

8. **The "independent modules":** Similarly, those modules that have more than 400 hours remaining at the time of the PLCO of the driver are called **independent**, i.e., they do not depend on the driver.

---

[5] PLCO = the operation of changing a life-limited component that has no more life remaining with one that has a suitable amount o life remaining.

Maintenance Concept of the F 404-GE-400 Engine

9. The maintenance process of the F404-GE-400 engine is very complex, reflecting on one side the complexity of the engine itself and on the other side the criticality of the potential consequences of the maintenance activities. The successfulness of a maintenance strategy could be estimated using the following parameters:

a) *airworthiness*: the engines should be maintained such that compliance with the regulations prescribed by the competent authority certifying their fitness for flight is achieved;
b) *operational capability*: the maintenance should be conducted in such a way as to ensure that the engines are able to function at maximum performances;
c) *availability*: engines' downtime due to maintenance activities should be reasonable, so that the impact of these activities on the availability of engines is kept to a minimum;
d) *cost-effectiveness*: such maintenance practices should be established to ensure that a), b) and c) can be achieved in a cost-effective manner.

This study focuses exclusively on subpara d).

10. There are three levels of maintenance performed on the F404-GE-400 engine (see Ref 1,2):

a) First Line Maintenance: This is performed at the operational unit level (Squadron's level) and consists of minor repairs, replacements or adjustments of accessible external components, done on a daily basis. Periodic Maintenance Inspections as well as some Modifications and Special Inspections are also performed at this level.

b) Second Line Maintenance: This is performed at the Wing Engine Repair Facility. Basically, engines are brought in second line maintenance for either snags[6] or replacements of life-limited components whose life has expired. At this level,

[6] Snag = Minor malfunction of the engine.

engines are disassembled, inspected, and reassembled after repairs or replacements have been done There is also a testing facility where the newly built engines are tested prior to being declared Ready for Installation (RFI). First line repairs, Periodic Maintenance Inspections as well as Modifications and Special Inspections can also be done at this level. Maintenance is normally done at the module level, with modules being removed from an engine and sent to the appropriate module shop for repair.

c) Third Line Maintenance: This is performed at an overhaul/repair contractor and consists of repairs of sub-components of the engine. If required, Modifications and Special Inspections can also be completed here.

11. The second line maintenance uses a significant part of the total budget allocated for the maintenance of the CF-18's engines. At the same time, because of the nature and quantity of work that is performed at this level, it also offers the most potential for improving the cost-effectiveness, through careful re-organization of the activities. For these reasons, special efforts have been dedicated during the last few years to improve the maintenance activities at the second level. The present study is part of this initiative, concentrating on improving the cost-effectiveness at the second line maintenance, through a better management of the life-limited components. Given the scope of this report, a detailed description of the second line maintenance activities was considered necessary. It is provided in the next paragraphs.

12. Presently, the maintenance concept at the second level is "On-Condition" maintenance (as opposed to regular intervals maintenance). More precisely, the engine is inducted into second line maintenance only if one of the following two conditions occurs:

a) the engine is due for a Parts Life Change Out (PLCO), because one of the life-limited components has exhausted its life and has to be replaced, or
b) the engine is snagged and the snag could not have been repaired at the first line maintenance level.

13 There are four types of inspections that are conducted at the second line:

a) *Induction Inspection* – This inspection is an external visual inspection of the engine. It is performed whenever an engine is inducted into the Engine Repair Facility for a PLCO. The role of this inspection is to identify any damaged or worn external components and attaching hardware. The identified items will be repaired or replaced while the engine is in the Repair Facility.

b) *Serviceability Assurance Check No. 1 (SAC 1)* – This inspection is performed on engines that were brought to the workshop for other reasons than the PLCO of the High Pressure Turbine (HPT) module. All the modules that are removed, either for PLCO or to gain access to another module, are subject to this type of inspection. The modules are not disassembled. Worn or damaged external components and attaching hardware are identified and repaired or replaced. Engines may be reassembled using the same modules or other modules that are ready for installation in the Engine Bay and which are not yet committed to other engines.

c) *Serviceability Assurance Check No. 2 (SAC 2)* – This inspection is performed on engines that were brought to the workshop because the HPT Rotor Assembly is due for PLCO. In order to remove the HPT rotor, the engine has to be completely disassembled into its six modules. It is therefore a good opportunity to perform a thorough verification of the serviceability of each of the modules. This type of inspection may involve some disassembly that could be added to a comprehensive visual inspection, to the functional testing of actuators and linkage systems, and completed by wear and clearance checks.

d) *Serviceability Assurance Check No. 3 (SAC 3)* – This type of inspection is performed on a module that is removed for its own rotor assembly PLCO (excluding the HPT, which is covered under SAC 2 and the Combustor and Afterburner modules, which do not have any life-limited components). The module is disassembled and the life expired components replaced. Following a detailed inspection and repair of the module, the engine is reassembled using this module or another module ready for installation and available in the repair shop.

14. Note that SAC1, SAC2 and SAC3 are mutually exclusive when performed on the same module. Table I illustrates, in a concise form, the maintenance philosophy presently in place with respect to the process of replacement of modules/components that have exhausted their life.

TABLE I

INSPECTIONS PERFORMED WHEN AN ENGINE IS BROUGHT TO THE REPAIR FACILITY FOR A PARTS LIFE CHANGE OUT (PLCO)

Engine is brought to the Repair Facility for PLCO of:	Inspections Performed
HPT Rotor	SAC2 on FAN Module SAC2 on HPC Module SAC2 on Combustor SAC2 on HPT Module SAC2 on LPT Module
FAN Module	SAC3 on FAN Module
HPC Module	SAC3 on HPC Module SAC1 on FAN Module SAC1 on Combustor SAC1 on HPT Module SAC1 on LPT Module
Combustor	SAC1 on FAN Module SAC1 on HPT Module SAC1 on LPT Module
LPT Module	SAC3 on LPT Module SAC1 on FAN Module

15. In addition to an engine being brought to the Repair Facility for the replacement of a life expired module, the engine can also be brought to the workshop for the repair of a snag (that cannot be repaired in first line maintenance). In this case, normally only the maintenance required to rectify the snag will be performed on the engine. However, in

case some lifed items have less than 100 hours remaining, the engine will also undergo all the procedures prescribed for the respective PLCO. Additionally, if the snag occurred less than 100 hours before the next Periodic Inspection (usually performed in first line maintenance), the Periodic Inspection will be carried out as well. The repair of the snag plus any other procedures that may have been needed are followed by the testing of the engine in the Test Cell.

16. In the present system, the Repair Facilities in Cold Lake and Bagotville have only a limited quantity of spare parts, the rest of them being held in a central pool situated in Toronto. Analyzing the appropriateness of such a system was beyond the scope of this study. However, it is the author's opinion that the possibility of re-organizing the process of distribution of spare parts should be thoroughly explored. A lot depends on what spare parts are available at a given location to be assembled into an engine, and therefore, special attention should be given to the process of allocation of the various spare parts between the two Repair Facilities. Inventory management principles should also be explored and applied to further improve the matching between the supply and the demand of spare parts.

Life-limited Components

17. Some of the engine's components have a pre-defined life limit. The manufacturer provides the lifespan of each life-limited item, as a value expressed in number of cycles. The speed at which the life of a given component is used-up is dependent not only on the time the engine is functioning, but also on the type of missions flown. Life Used Indices (LUI) are used to monitor the amount of life remaining for each of the lifed components, taking into account the type of missions flown. Speed cycles, pressure cycles and temperature are among the parameters that are continually monitored on all life-limited components inside an engine. Based on the values observed, average values for LUIs are calculated. It should be noted that these values are only valid for the Canadian Forces, since they are directly dependent on the mission profiles. The average values for LUIs are used to change the measurement unit of each component's life from number of cycles

(LCF, Low Cycle Fatigue) into a more manageable unit such as airframe hours (AFH). The formula used is the following:

$$\textit{Estimated AFH Life (hours)} = \frac{\textit{Life Limit (LCF)}}{LUI} \quad (1)$$

The measure used throughout this report is AFH in hours

18. Because of the costs involved, it is important to avoid a high shop visit rate for the engines. For this reason, the concept of *Fallout Window* is used in the current maintenance procedures. According to this concept, when an engine is inducted to the shop for the replacement of an expired component, any other modules in that engine that have less than 400 hours remaining until they expire themselves, will be replaced at the same time.

19. It should be noted that, although the "400 hours" figure is the one most extensively used, variations may occur to account for spare parts shortages, third line repair turnaround times, etc. Several considerations led to this figure. Among them are the following:

a) The periodic inspections are also scheduled at each 400 hours and there is some monetary savings in having a PLCO and a periodic inspection done at the same time;

b) It has been established that an engine just coming out of the repair shop should be able to fly at least for another 400 hours, mainly because of the additional, non-necessary costs[7] that would be incurred in case the engine would be brought to the shop in less than 400 hours.

---

[7] Examples of costs generated by an induction of an engine into the repair shop, that are not directly related to the fixing of the problems for which the engine was initially brought into the Repair Facility, are the costs related to the removal/mounting of the engine from/on the aircraft, fuel costs incurred due to the testing of the engine in the Test Cell of the Repair Facility, costs incurred by the requirement that a test flight by a pilot should be done on each "new" engine, costs related to the parts that break down inevitably each time an engine is dismantled

PART II: METHODOLOGY

Introduction

20. The issue addressed in this section is how to improve the cost-effectiveness of the current maintenance strategy of the F 404-GE-400 engine, through a better management of its life-limited components. Several major concepts and definitions were introduced in Part I. Because of their importance in ensuring a good comprehension of the rest of the document, the section will be started by a brief re-iteration of these concepts/definitions. Following that, some informal definitions of the costs involved in the maintenance process of the CF-18 engine will be introduced. Specifically, the costs related to the life-limited parts of this engine will be discussed. The definitions will be followed by a more in-depth analysis of these costs, because a good understanding of the costing issues is key in developing a methodology intended to enable monetary savings. Next, the system presently in place will be briefly described, followed by a detailed description of the system proposed, complete with numerical examples, which will conclude the section.

Major Concepts/Definitions Used in the Study – A Brief Summary of Part I

- The F 404-GE-400 engine is built in a modular fashion. Four of the modules are life-limited, since they contain life-limited parts.
- For the purpose of this study, eight life-limited components are considered.
- The *driver* is that component of the engine that brings (drives) the engine to the repair shop because its life has expired (it has zero hours remaining).
- A *dependent module* is a module (or component) that has less than 400 hours remaining at the time of the PLCO of the driver. Such a module will be replaced in the same time as the driver.
- An *independent module* is a module (or component) that has more than 400 hours remaining at the time of the PLCO of the driver. The replacement of such a module does not depend on the driver.

Informal Definitions of the Costs Involved

21 There are several costs involved in a PLCO process. They could be classified in any number of ways (such as "fixed costs" vs. "variable costs", etc.) For this study however, a classification considered by the author more natural and easier to grasp by readers without an economic background was preferred. As such, four cost categories are considered, each of them containing several sub-categories:

Type a) Engine Removal and Transportation Costs

Specifically, there are four types of costs included in this category:

i. costs associated with the removal of the engine from the aircraft;
ii. costs associated with the installation of the engine (after it has been repaired) into the aircraft;
iii. costs associated with the test flight that is conducted every time a newly assembled engine is installed in an aircraft;
iv. transportation costs (two ways: from the aircraft to the workshop and back).

Type b) Workshop Costs

Specifically, the costs included in this category are the following:

i. cost of disassembling the engine, in order to replace the driver and any other modules that are approaching the end of their life;
ii. cost of reassembling the engine, after all the required replacements are made;
iii. cost associated with the testing that is done in the workshop to any newly assembled engine.

Type c) Known "Wasted Life" Costs

These are the costs associated with the modules that are replaced while they still have some life remaining. The "wasted life" on these modules has a cost associated with it that depends on the number of hours that are lost and also on the cost per flying hour associated with the particular module. These costs are labelled "known", because when an engine is assembled, it is known which module will be the next driver and also which other components (the "dependent" ones) will be replaced in the same time as the driver.

Type d) Unknown Wastage Costs

When a PLCO is performed, besides the driver and the dependent modules, there may be (and usually are) other parts that are exchanged. There are basically two reasons for this. The first one is that some parts may simply break in the dismantling process of the engine and therefore have to be exchanged. The second reason is that, during the visual inspection that accompanies any dismantling process, some parts are discovered not to look "good enough" and usually a decision is made to change them. This often results in over-maintaining the engines. These costs are labelled "unknown", because unlike the costs of Type c), they cannot be known beforehand – they are only apparent after an engine has been disassembled and inspected.

More About Costs

22. The author did not have direct access to any databases containing costing information. The values used in this study were provided by the study's sponsor (DAEPM(FT)). For the most part, they constitute rounded average values. Acknowledging that this level of precision is not the best, it is to be noted that it is nevertheless considered satisfactory for the present study. The purpose of this study is to provide a methodology, which would remain the same whether the costs involved are accurate or not. As such, the actual figures serve mainly for orientation purposes. However, in the implementation stage, it becomes critical to have as accurate costing information as possible. In the next paragraphs, details on the way the costs are handled in the present study are provided.

23. Costs of Type a), associated with the engine's removal and transportation, are considered fixed for the purpose of this study. The operations of removal and installation of an engine are the same for every engine and therefore the cost associated with these operations must be the same as well. Similarly, the test flight that is conducted for any newly installed engine is standard (and fixed) for every engine. Transportation costs may vary slightly, but they are minor. It was therefore decided that it would not be worthwhile considering these costs variable. It is suggested that the value to be used for this cost should be the average value for the fleet. The value supplied by the sponsor was $2,500.

24. Costs of Type b), the workshop costs, are considered variable. Depending on the amount of work that is required, which in turn depends on which and how many of the modules are to be replaced, this cost will be different for every engine. The replacement of some modules requires the removal of one or more of the neighbouring modules (or components), to gain access to the module to be replaced. As such, the manpower costs can be different for the replacement of different modules.

25. In order for the model to be able to calculate the costs of Type b) for each engine, the following information is required:

a) cost to remove /inspect / reinstall every module;
b) for each module, it is necessary to know which parts need to be removed in order to gain access to that particular module; and
c) which inspections or test procedures are associated with the removal of each item.

26. The information required at a) and b) is provided in Table II, containing data supplied by the sponsor. The information required at c) is partly provided in Table I (page 7). In addition to the data included in Table I, it was indicated by the sponsor that, regardless of the type of work that was done on the engine, the same testing is performed on the engine, and that the approximate cost of a test cell run, including fuel and labour, is $3,000.

TABLE II

INFORMATION REQUIRED TO COMPUTE THE "WORKSHOP COSTS"

Item Name	Cost to remove /inspect /reinstall the item itself ($)	Modules that need to be removed to gain access to the item
FAN	500	None
HPC	1,500	FAN, CC, HPT, LPT
Combustor Case (CC)	300	HPT, LPT
HPT	2,000	LPT
LPT	1,200	None

27. Costs of Type c) are also variable costs. They concern the amount of life that is "wasted" on the modules that are exchanged in the same time as the driver, while they still have some amount of hours remaining. Two special cases can be identified: when the module is composed of a sole life-limited component, and when the module is composed of several life-limited components. The costs of Type c) will be calculated using a different formula for each case.

28. When a module is composed of a single life-limited component, the costs of Type c) (wastage costs) can be calculated using the following formula:

$$Wastage\ costs = x \times Cost\ per\ flying\ hour\ corresponding\ to\ the\ module \quad (2)$$

where x is the amount of hours wasted on the given module and the *Cost per flying hour corresponding to the module* takes a value that can be calculated from the costing data available in the existent databases.

29. When a module is composed of several life-limited components, the life of a module is determined by the component that has the shortest life. Therefore, when such a module is removed before reaching the end of its life, it means at least that its shortest lifed component will be discarded. However, other lifed components within the module may be discarded as well, because the same principles concerning the management of

life-limited components that apply at the engine level also apply at the module level[8]. As such, the total wastage cost related to the removal of a module before its time will be calculated in this case as the sum of two different costs:

a) the cost associated with the amount of life wasted on the shortest lifed component of the module, and
b) the cost associated with the amount of life that is wasted (eventually)[9] on other lifed components of that module.

The following formula can therefore be used:

$$Wastage\ costs = Wastage\ Costs\_type\ a) + Wastage\ Costs\_type\ b) \qquad (3)$$

30. To clarify this issue, let us develop a generic example, illustrated by the diagram in Figure 3. Suppose an engine is composed of eight modules: *Module 1, Module 2, ..., Module 8*, and that *Module 7* is the driver for this engine, while *Module 2* is the only module that is dependent on the driver (i.e., it has to be changed in the same time as the driver). *Module 2* is composed of several sub-components, four of which are life-limited. Let us call them *Comp 1*, *Comp 2*, *Comp 3* and *Comp 4*. Finally, suppose that the driver (i.e., the sub-component that has the shortest life remaining) within *Module 2* is *Comp 1*, while the only dependent component in *Module 2* is *Comp 2* (i.e., *Comp 2* would have to be changed in the same time as *Comp 1*, assuming that *Comp 1* actually reaches the end of its life).

31. Now, let us look at the wastage costs associate to this case. Suppose x is the amount of hours remaining on *Module 2* when the engine's driver has zero hours remaining. Because the life remaining on *Module 2* is actually the life remaining on the

[8] The same concepts of dependence and independence with respect to the driver of an engine apply in the case of a module, with respect to the driver of the module More precisely, when disassembling a module to remove and discard its shortest lifed component, other life-limited components may be discarded as well, if their life remaining is not long enough to make it worthwhile to keep these components longer in the module.

[9] "Eventually", because it may happen that in that particular module only the driver of the module (the component with the shortest life) is discarded

driver of the *Module 2*, it means that x is actually the amount of hours remaining on *Comp 1*. Therefore, the wastage costs of type a) cost can be calculated as follows:

$$\textit{Wastage Costs\_type a)} = x \times \textit{Cost per flying hour corresponding to Comp 1} \qquad (4)$$

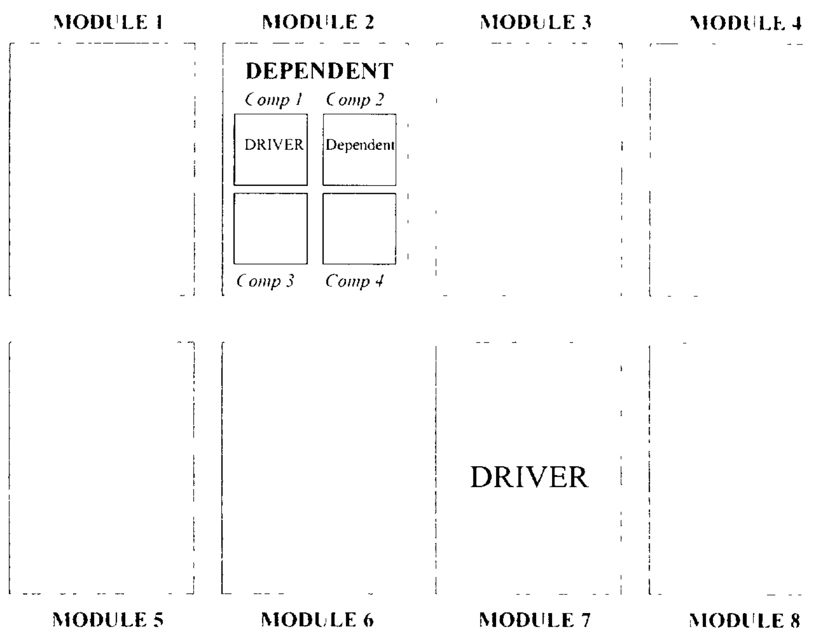

Figure 3. Wastage Costs – A Generic Example

32. *Comp 2*, being dependent on *Comp 1*, has a life remaining equal to ($x + \Delta$), where Δ is a value that is under the pre-established "discarding threshold"[10] for *Comp 2*. Depending on the value of x, two situations may occur: (a) the value ($x + \Delta$) remains small enough such that *Comp 2* has to be discarded, or (b) the value ($x + \Delta$) becomes big enough so that *Comp 2* does not have to be discarded. Depending on the situation, the costs of type b) will be:

[10] The "discarding threshold" is a value that establishes the minimum amount of life remaining on a component so that the component is worth keeping in stock to be reinstalled in another engine. If a component has a life remaining below this threshold, it can be discarded

Situation (a):

$$\textit{Wastage costs\_type b)} = (x + \Delta) \times \textit{Cost per flying hour corresponding to Comp 2} \qquad (5)$$

Situation (b):

$$\textit{Wastage costs\_type b)} = 0 \qquad (6)$$

33 The example provided is a simple one, in which the engine has only one module that is dependent on the driver (Module 2) and this module has also only one sub-component that is dependent on its driver (i.e., the module's driver, *Comp 1*). Generalizing the formula to apply to an engine with several dependent modules, with these modules also having multiple dependent sub-components is, however, a straightforward process. Unfortunately, in spite of this fact, the notation for the general case would make the formula look very heavy and not so easy to grasp anymore. For this reason, the author chose not to include the general formula here.

34. Finally, to be able to apply this formula in a real context, there are two things that have to be available:

a) **the costs per flying hour**, for every one of the lifed sub-components of an engine;
b) **the "discarding threshold" values**, for every one of the lifed sub-components of an engine.

35. To the author's knowledge, while the costs per flying hour do exist for each lifed component, values for the discarding thresholds corresponding to each component do not. Up until now, the only value that was used by the CF is the value of 400 hrs (the *fallout window* concept). However, given that the costs per flying hour for the various sub-components can vary anywhere from \$0.69/hour to \$32.03/hour, it is suggested that *various* discarding thresholds should be computed and operated for various components. Some suggestions on the approach that could be taken to tackle this issue are provided next. However, lacking intimate knowledge of engine maintenance issues, the author is

not in a position to provide a full answer to this problem for the time being. It is suggested that this topic is considered for future study.

36. A simplistic approach in deriving these thresholds, based on purely monetary arguments, could be to first agree on a maximum amount of money that is acceptable to lose on a single component and than divide this amount by the cost per flying hour of that component, as in the formula below:

$$Discarding\ threshold_{Component\ j}\ [hours] = \frac{Max\ acceptable\ "loseable"\ amount\ [\$]}{Cost\ per\ flying\ hour_{Component\ j}\ [\$\ hrs]} \quad (7)$$

37. However, this approach appears to be too simplistic. To become applicable in a real life situation, this approach should be further refined. One suggestion could be to base the calculation of the discarding thresholds on other issues, such as the cost to remove and install a certain component. As an example, if a component is very difficult to access (which translates into high removal/installation costs), the discarding threshold should be calculated based on the trade-off between the wastage costs and the removal/installation costs. The idea of the trade-off is actually very simple: "We should always gain more than we lose." As an example, a decision to re-use a given component should be taken only if the amount that is gained on the "non-wasted" hours is bigger than the amount required to reinstall this component on a different engine.

38. For practical purposes, the methodology proposed here can always make use of the concept of the fallout window, i.e., to use the same discarding threshold of 400 hours regardless of the type of component. However, there is definitely value in a more in-depth study of the issue of different discarding thresholds, as another area where savings could be made.

39. Costs of Type d), "unknown wastage costs", are the last category of costs that is considered in this study. As it was mentioned earlier, these costs are related to any part (not necessarily a lifed part) that breaks during the dismantling process or that does not look good enough at the inspection process. Unfortunately, these costs are not currently tracked. The ideal way to handle these costs would be to attempt to establish a

relationship between them and the time since the last inspection. This idea is based on the assumption that the number of parts that do not look "good enough" at an inspection would probably be higher in a case where the engine had not been inspected since 1500 hours, compared to a case where the engine had not been inspected since 500 hours. However, given that these costs are not tracked at all, it is very difficult to establish any kind of relationship, even a very approximate one. Therefore, it was decided, for the purpose of this study, to consider these costs fixed (constant).

Two Conflicting Objectives

40. From the cost considerations presented earlier, two issues appear particularly desirable in order to maintain the maintenance operations cost-effective:

a) An engine should be brought to the Repair Facility as seldom as possible; and

b) the lifed parts in an engine should be matched as well as possible, according to two criteria:

  i. As many parts as possible should be "PLCO ready" when an engine is brought to the Repair Facility for the PLCO of its driver.

  ii. The number of hours lost on the "PLCO ready" items (i.e., items that are replaced before their lives are exhausted) should be as low as possible.

41. These are the two objectives that are currently being pursued by the maintenance teams in their effort towards reducing the costs associated with the maintenance process. It is important to note that the two objectives may be conflicting.

42. Let us clarify this issue by means of an example. Suppose eight modules are the first set of candidates to be assembled together into an engine. In an effort to pursue the first objective, the maintenance technician will try a number of different combinations, changing one module at a time to end up with an engine (engine A) that is satisfactory, according to the first objective. However, the technician observes that, with respect to

the second objective, engine A is not ideal He then attempts to make other module exchanges, in order to improve the engine with respect to the second objective. This results in engine B, which looks good with respect to the second objective but is not that satisfactory with respect to the first one. The conclusion being that the two objectives are actually conflicting and the technician is left with an option to improve one of them but only at the expense of the other.

The Existing System

43 The existing system[11] succeeded in improving the maintenance process for the CF-18's engines in more ways than one. It improved the availability of engines, allowed a reduction of the maintenance costs and offered better control over the maintenance issues in general. Acknowledging all these good points, it is also true that the present system has its limitations and it is precisely to correct some of these limitations that the present study was initiated.

44. The existing system, based on a scoring system, assists with the process of "building" an engine from a number of modules. The system is actually a computer program that allows the user to manually choose a driver from a list of available modules, for the engine he wants to re-build. As such, the user fixes at the outset the date of the next visit of the engine to the repair shop. Once the driver is selected, the user has the option of manually selecting various combinations for the rest of the modules to be assembled in the same engine. The idea is to obtain a good matching between the modules of the engine, mainly in the sense that as many modules as possible should be changed at the same time, without wasting too many "hours remaining" on the modules that are changed before their lives are exhausted. The user is assisted in this process by the software, which automatically assigns a number of points (positive or negative) to each selection, according to some pre-defined rules.

45. The present system is not optimal. In fact, very little is done with regard to the first objective, and, although somewhat more is done with respect to the second objective,

[11] The system that is referred to as "the existing system" is a software package that assists (to a certain extent) the staff in the process building "new" engines.

the benefits are limited, due to the fact that the user has to *manually* select different options (which limits severely the number of options that may be tested in order to find the best one).

The Proposed System

46. The system proposed in this study should be seen as an addition to the current system. Most of the features of the existing system are necessary and should be preserved, however, the main limitations should be corrected by new features. The role of this new system continues to be that of assisting maintenance staff in building "new" engines from a selection of modules. However, the level of assistance offered is significantly higher than that of its predecessor, as is the potential for monetary savings. In the proposed system, three options are to be available to the user

Option 1: Manual building of the engines

47. This is basically the option that is offered by the system in place. It is important that this option is kept because it may arrive that an engine has to be built in a certain way, regardless of the costs involved. However, since there is nothing new to be added, this option will not be discussed in this report.

Option 2: Partly automatic building of engines

48. This option consists of offering the user the possibility to select the driver(s) for the future engine(s). The system will respond by automatically building the best engine (or best set of engines) around the given driver(s).

49. This option is required because it might happen that an engine having a given number of hours remaining (which is set by the driver) is needed. Such an engine may be needed, for instance, for the purpose of adjusting the workload in the repair shop, to make it as regular (or constant) as possible.

50. Note that this option is a special case of Option 3, which will be discussed next. As such, Option 2 will not be tackled at great length in this report. It suffices to mention that implementing Option 2 is equivalent to implementing Steps 3 and 4 of Option 3.

Option 3: Completely automatic building of engines

51. This option does not involve any input from the user, other than the number of engines that he would like to build at the same time (i.e., using the same set of available modules). The system selects the driver (or the set of drivers), as well as the matching modules for that driver and provides the user with the final selection of all modules composing an engine. Option 3 brings the most financial gains and should be used on a regular basis. Options 1 and 2 should only be used in exceptional circumstances.

Algorithm for Automating the Building of Engines (Option 3)

52. The reader is reminded that two (conflicting) objectives were identified. The first one is to maximize the number of hours between two consecutive visits of an engine to the repair shop. In case several engines are built at the same time, the objective becomes to maximize the *average* number of hours remaining until the next visit to the shop.

53. The second objective is to produce engines that have well matched components. The "well matching" of the components is judged by the success of attaining two "desired" characteristics of an engine. The first desired feature of an engine is that it should contain as many modules as possible that are ready for PLCO at roughly the same time. The idea being, when an engine is brought to the repair shop for PLCO of its driver, the occasion should be exploited to conduct PLCO work on as many parts as possible. The second desired feature is that the number of hours lost by replacing parts, while they still have some amount of life remaining, should be as low as possible. A more concise form of expressing the second objective could be: maximize the number of dependent modules in the engine and minimize the wastage (the number of hours lost) on the dependent modules (i.e., the modules that are exchanged before their life has expired).

54. Note that both objectives have the same underlying idea, which is to reduce costs. One way to blend the two objectives into a single one and erase the conflict between the two objectives, would be to express everything in terms of costs and establish a new objective which would be to minimize the overall cost. However, such an approach was differed to a later date by the military sponsors of this study, who preferred, for the time being, a solution that would build upon the present system, rather than changing it completely

55. In compliance with the preference expressed by the sponsors of the study, the proposed algorithm aims to find the best engine (or the best set of engines) that can be built from a given set of modules, according to the two objectives stated earlier.

56. The main idea of the algorithm is to first find the optimum (or near optimum) solutions according to the first objective, and then perform a search among this set of solutions to find those that are optimal according to the second objective. The result of this double optimization process will be a solution (an engine or a set of engines) that satisfies best the two conflicting objectives.[12]

57. Note that the order in which the two optimization processes are done is not done at random, nor is it meaningless. It actually means that more weight is given to the first objective, compared to the second one. The reason for this is that the number of hours between two consecutive visits to the shop has a more significant impact on the overall cost, compared to the impact that the number of wasted hours has on the same cost. This aspect will become more obvious later in this report. For now, it will only be said that this also reflects the general opinion of the maintenance staff[13].

[12] Note that the solution may be sub-optimal with respect to each of the objectives

[13] It may be of some significance to note that, when knowledgeable staff were asked which objective is, in their opinion, more important, practically everybody answered "We don't know, they are both important" However, when provided with numeric examples and asked to select which engine they would choose to build, everybody selected the engine with a higher number of hours remaining until the next PLCO That proves, that, although lacking a formal way of choosing between the two, their experience concerning the readiness levels required, and their knowledge of the costs involved told them that the first objective is actually more important than the second

Input Data for Automatic Engine Building (Option 3)

58. The only input data that is requested from the user is the number of engines (k) that are to be built at the same time (i.e., using the same set of available modules). The minimum value of k is 1 and the maximum value was set to 5. This upper limit was selected because it is extremely unlikely that more than 5 engines need to be assembled at any one time. In practice, the usual values for k are 1, 2 or 3.

59. In addition, the algorithm makes use of a certain number of databases: costing databases, as well as the databases containing the modules available to be installed in an engine. However, since an implementation of the algorithm is beyond the scope of the present study, no further details regarding these databases will be provided here.

The algorithm in 4 steps

60. Note that, to simplify the wording of the algorithm, it is always considered that a set of engines are to be built at the same time, as opposed to presenting in parallel the case of one single engine and the case of multiple engines. The case of a single engine ($k = 1$) is clearly a sub-case of the case of multiple engines ($k > 1$).

61. The algorithm presented here is suitable for building engines "from scratch". However, this does not mean that any engine brought to the Repair Facility for a PLCO will be completely dismantled and then rebuilt For certain, the driver and the dependent modules will be removed. As for the independent modules, the most economic solution would be to "keep an open mind" and consider whether it would make more sense (financially) to keep them in the current engine or to replace them with more appropriate items, rather than taking for granted that it is more economical to keep them where they are One way to do that is to declare the independent modules of an engine being rebuilt after a PLCO as "available spares" with special properties:

- The cost of installing such a module in the engine in construction is nil (since the module is already installed).

- The cost of installing such a module in another engine is equal to the cost to install the item plus the cost to remove it from its current location
- The cost of replacing an such an independent module with a more appropriate one from the list of spare parts is equal to the installation cost of the new item plus the cost to remove the independent module (as opposed to the case when a new item replaces a dependent module and when the installation cost associated is just the cost to install the new item, since the dependent module had to be removed anyway).

With these remarks, it can now be seen that the best approach when rebuilding engines is to consider their building from scratch, while taking into account the three observations above. For this reason, the algorithm proposed here is considered suitable for all cases of rebuilding of engines.

62. Each step of the algorithm will be described in detail in the following paragraphs. However, because the explanations provided at some of the steps of the algorithm are rather lengthy, it is possible that the reader may experience some difficulties in seeing the continuity of the information flow from one step to the next. For this reason, a succinct form of the algorithm is provided here, to illustrate the purpose of each step and how the four steps are interconnected:

Step 1: Identification of a set of modules that maximizes the Average number of Hours Remaining (AHR);
Step 2: Identification of all sets of feasible drivers that are situated in the neighbourhood of AHR maximum;
Step 3: Identification of the best set of engines corresponding to each of the sets of drivers identified at Step 2;
Step 4: Identification of the *overall best* set of engines from all those determined at Step 3

Step 1

63 Purpose: The purpose of this first step is to determine a set of modules that, when assigned the role of drivers for future engines, will provide the maximum average number of hours remaining until the next visit to the shop of these engines (i.e., *maximize* AHR[14]).

64 Databases involved. The databases involved at this step are the ones containing the lists of spare modules of each type. Since there are eight life-limited modules in an engine, there should be eight lists of spare modules of each type to select from.

65. Operations to be done:

Operation 1: Order each one of the eight lists of spare modules in decreasing order, with respect to the number of hours remaining on each module.

Operation 2: Select the first *k* elements of seven of the eight sorted lists (the list containing Bearing # 4 module is eliminated because Bearing # 4 cannot be a driver[15]) and create a new list with these elements.

Operation 3: Order the newly created list in increasing order (again, with respect to the number of hours remaining on each module).

Operation 4: Select the first *k* elements of this list. They constitute the set of drivers that maximizes the average number of hours remaining.

66. To help clarify this algorithm, a numerical example will be provided further, based on the data sample that was provided by the military sponsor. This data set is composed of eight lists of ten items (spare parts), for each of the eight life-limited

[14] AHR = Note that this notation is used for both "Airframe Hours Remaining" (in the case of a single engine) and for "Average Hours Remaining" (in the case of multiple engines) Since the sense is exactly the same, it was not considered worthwhile to complicate the presentation by using two different notations for the two cases

[15] Bearing # 4 is situated in a very difficult to access area and is of a very low monetary value For these reasons, it is not acceptable that an engine should come to the repair shop and incur all the costs associated with a PLCO process, for the PLCO of Bearing # 4 As such, it was decided that Bearing # 4 can never be a driver

modules composing an engine (one list for each module). Each item from the list of available spare parts has a certain number of hours remaining associated with it (For the comprehensive set of data, complete with serial numbers, see Annex B). For the purpose of this example, a modified set of data was used in which the items were attributed item numbers from 1 to 10, for ease of reference. The modified set of data is provided in Table III. The lists contained in this table are ordered in decreasing order of the number of hours remaining. As such, Table III represents the result obtained after Operation 1 of Step 1 of the algorithm is executed.

TABLE III

MODIFIED DATA SAMPLE SET

Item #	Number of hours remaining on each item of each type (hrs.)							
	FAN Module	HPC Module	COMB Case	Fuel Nozzles	Bearing # 4	HPT Module	FAN Dr.Sh.	LPT Module
1	4456	1715	7357	2249	2103	1091	6797	1350
2	4148	1676	7272	2213	2103	1006	6595	1326
3	4069	1654	7241	2170	2103	896	6140	1268
4	3716	1542	6808	1861	1862	648	4648	1191
5	3440	1400	6582	1284	1753	578	4409	1136
6	895	1247	6453	1140	1588	473	4197	997
7	761	1247	6450	1081	1539	461	4065	994
8	472	878	6291	620	1346	415	3835	868
9	327	381	5238	531	1188	345	3656	727
10	202	209	2617	239	511	202	2973	292

67. As an example, suppose the user needs to build three engines at the same time (i.e., from the same set of spare parts), using the set of spare parts given in Table III. The purpose of the algorithm in Step 1 is to find 3 items from the lists in Table III that can be drivers for the 3 engines to be built, such that the average[16] number of hours remaining until the next visit to the shop will be maximum, i.e., any other set of three drivers chosen from the list in Table III will have an average of hours remaining smaller than the set of 3 items identified through this algorithm.

[16] The term "average" is used in this case for the arithmetic mean (for the 3 engines) of the number of hours remaining on each engine until its next visit to the Repair Facility

68. Since three engines are to be built, this means that three items of each of the eight modules are needed. Because our purpose is to maximize the average number of hours remaining, it follows that the best three items (in terms of number of hours remaining) of each of the eight categories should be the ones to select as candidates for the set of three drivers.

69. The items contained in the "best 3" list (i.e., the results of Operation 2 of the algorithm) are given in Table IV. Note that elements from the "Bearing # 4" category were not included in the "best 3" list, since this is the list that will be used to select the set of drivers from, and it was decided that Bearing # 4 can never be a driver.

TABLE IV

ITEMS INCLUDED IN THE "BEST 3" LIST

Type of Module	Number of hours remaining
FAN	4456
FAN	4148
FAN	4069
HPC	1715
HPC	1676
HPC	1654
COMB Case	7357
COMB Case	7272
COMB Case	7241
Fuel Nozzles	2249
Fuel Nozzles	2213
Fuel Nozzles	2170
HPT	1091
HPT	1006
HPT	896
FAN Drive Shaft	6797
FAN Drive Shaft	6595
FAN Drive Shaft	6140
LPT	1350
LPT	1326
LPT	1268

70. Operation 3 of the algorithm consists of ordering the "best 3" list in increasing order of the number of hours remaining on each module. Table V provides the result obtained after this operation is executed (i.e., the ordered "best 3" list).

71. According to the algorithm proposed, the first three elements of the list ordered at Operation 3, highlighted in red, constitute the set of three drivers maximizing the average number of hours remaining until the next visit to the repair shop.

TABLE V

ORDERED "BEST 3" LIST

Type of Module	Number of hours remaining
HPT	896
HPT	1006
HPT	1091
LPT	1268
LPT	1326
LPT	1350
HPC	1654
HPC	1676
HPC	1715
Fuel Nozzzles	2170
Fuel Nozzzles	2213
Fuel Nozzzles	2249
FAN	4069
FAN	4148
FAN	4456
FAN Drive Shaft	6140
FAN Drive Shaft	6595
FAN Drive Shaft	6797
Comb Case	7241
Comb Case	7272
Comb Case	7357

Step 2

72. Purpose: The purpose of Step 2 is to determine all feasible sets of k drivers and to identify those that have an AHR in the neighbourhood of the maximum AHR. A set of drivers is considered *feasible* if for each driver included in the set there is at least one module of each type that is available and has a number of hours remaining higher than the driver itself. In other words, a set of drivers is feasible if there are enough spare modules such that an engine can be constructed around each of the drivers in the set.

73. Databases involved: The databases involved at this step are the ones containing the lists of spare modules of each type, with the exception of the "Bearing # 4" list. These include the complete list illustrated in Table III.

74. Operations to be done:

Operation 1: Create the list of all spare modules that can be drivers.
Suppose the list has $n \geq k$ elements. The underlying observation here is that some of the spare modules available cannot be drivers. Thus, eliminating from the total number of spare modules those modules that cannot be drivers creates the list of potential drivers. Two conditions are used in the process:

a) Bearing # 4 cannot be a driver, and
b) the definition of a driver (i.e.: For a module "*A*" to be a driver, there has to be at least one module of each type (other than the type of the module "*A*", the "candidate driver") that has a number of hours remaining higher than the number of hours remaining on the module "*A*").

Operation 2: Enumerate all combinations of n elements (of the list of potential drivers) taken k at a time and evaluate the feasibility and AHR corresponding to each set of drivers.

75. A C-program implementing an algorithm that can be used to enumerate all combinations of n elements taken k at a time is provided in Ref 3, which is actually reproduced entirely in Annex C, for convenience.

76. The number of such combinations can "explode" very rapidly, according to the formula:

$$C_n^k = \frac{n!}{k!(n-k)!} \tag{8}$$

However, for the type of numbers (k and n) typically involved in a real life maintenance scenario, and given the computing power of today's computers, this does not present a problem

77. In parallel with the enumeration process, two other things are done. The first one is to determine whether the identified set of drivers is feasible or not. Then, for each feasible set, a calculation of its corresponding AHR is performed.

78. <u>Operation 3:</u> Compare the AHR value corresponding to each feasible set to the maximum AHR, as it was determined at Step 1. Retain only those sets that have an AHR within a certain percentage (M %) from maximum AHR.

79. The idea is that the engine that will ultimately be declared "the best" will have to ensure a good compromise between the two parameters of interest – AHR and the number of wasted hours. For this reason, it is reasonable to think that engines that are far away from maximum AHR are unlikely to be good candidates for this "best engine contest". Therefore, in order to avoid unnecessary and time consuming calculations, the search for the best engine should be conducted only among the engines with an AHR that is in the neighbourhood of the maximum AHR.

80. Now, the question is, how big should this neighbourhood be? How big should M be? At present, with the costing information available, it is not possible to estimate the

value of *M*. A value such as 25 % may appear reasonable, but it would hardly be defendable, because it cannot be proved with certainty that the best engine can always be found within 25% of the maximum AHR, nor can it be proved that the amount of calculations performed in such a case is not higher than necessary.

81. The solution proposed to this problem is a self-adjusting algorithm that, in time, will be able to determine the value of *M* by itself. More precisely, such an algorithm will use as an initial value of *M*, a value that is big enough to ensure that there is no chance that the "best engine" is outside the neighbourhood defined by *M*. A value of 50% is suggested. Then, every time the algorithm is employed to find a solution (i.e., the "best engine"), it will accumulate evidence on how far from the maximum AHR the solution is situated. As such, it will be possible, after a large enough number of solutions are found, to adjust the value of *M* accordingly. For instance, if, after ten solutions it is discovered that they are all within 15% from the maximum AHR, than the algorithm will self-adjust the value of *M* to 15.

82. The numeric example given was very simple. It is likely that the real life results will not be as neat as that. However, depending on the type of results that will be obtained, the basic idea of self-adjustment could be "enhanced" in a variety of ways, such as decreasing the initial value of *M* gradually (in steps), using "security cushions" (for instance, if, after ten solutions, they are all found to be within 15% from the AHR maximum, *M* will be decreased not to 15, but to 20 (i.e., 15 + a security cushion of 5%), to give the algorithm more time to accumulate evidence that indeed 15 is the best value, or, alternatively, to change this value for another that seems more appropriate). The result of such a self-adjustment is a significant reduction of the computational effort, associated with an increased confidence that the best engine will actually be found within the neighbourhood selected for the search.

83. At the end of step 2, a list of all sets of feasible drivers that constitute good candidates for the "best engine" search is created.

Step 3

84. The purpose of this step is to build for each set of drivers determined at Step 2, the best set of engines with respect to the second objective, i.e., maximize the number of dependent modules and minimize the number of hours lost on the dependent modules (i.e., those modules that are replaced before their lives had expired).

85. More precisely, at this step, the sets of drivers identified at the previous step will be considered one at a time, and the best engine will be built around each of the drivers in the set For each set, the initial pool of available modules consists of all available modules, except for the ones that are already the drivers for that particular set of engines.

86. The process of building an engine around a given driver could be visualized as a big box (the engine) that is divided into eight smaller boxes (corresponding to the eight life-limited modules in an engine). One of the eight boxes is already filled (because the driver is given), while the other seven boxes are still empty. Building an engine is equivalent to filling the empty boxes. The empty boxes will eventually be filled with dependent and independent modules, according to several selection criteria.

87. The most important selection criterion is that modules have to be assigned to engines in such a way that the average number of hours lost (for the *k* engines that are built in the same time) is minimum, while still using the maximum number of dependent modules for each engine in the set. Other criteria, corresponding to various other objectives that are desirable (but not compulsory) are equally used, and they will be discussed in the following paragraphs.

88. The databases involved at this step are the ones containing the lists of spare modules of each type (similar to the sample data in Table III).

89. Operations to be done:

Operation 1: For each set of drivers determined at Step 2, select the **dependent** modules that will be assigned to each of the *k* engines to be built.

The selection of dependent modules in an engine will be based on the following two principles.

Principle a) Maximize the number of dependent modules in an engine.

In other words, if, for a given empty box, there is a choice of modules that could fill that box, and, if chosen, some of them would become dependent modules (i.e., within 400 hours from the driver), while others would become independent modules, then one of the dependent modules will be selected. This is in accordance to the desire to have as many dependent modules as possible in any engine. This "desire" can be justified in several ways. The most obvious one would probably be the sense of efficiency that one has when performing several exchanges of modules at the same time, rather than having the engine brought back several times to perform one PLCO at a time. A second justification could be obtained by looking at the impact that a *non*-observance of such practices could have. If, at any time, an independent module would be preferred to a dependent one, than the result would be that the inventory of parts having low amounts of life remaining will continuously grow, while the inventory of parts having medium or high amounts of life remaining will continuously decrease, with the result that, from some point on, the lapse of time between two consecutive visits of an engine to the shop will become smaller and smaller (because only the parts having the lowest amounts of life remaining are left to choose from), with grave consequences on both the availability of engines for flying and the maintenance related costs.

Principle b) Minimize the average number of hours lost on the set of engines in construction.

Principles a) and b) are actually *objectives* and it may occur that they are conflicting. Note that in such a case, objective b) will take precedence over objective a).

Operation 2: For each set of drivers determined at Step 2, select the **independent** modules to be assigned to each of the k engines to be built. Note that this operation is done *after* the selection of the dependent modules for the set was performed.

90. The selection of the independent modules will be based on the following principles:

a) **The independent modules should be as well matched between them as possible.** The advantage of having the independent modules in a given engine well matched between them is basically that this ensures that well matched modules of different types will be available in the same time, so that they can eventually be used together at a later time.

b) **All other things being equal, one should select as independent modules those modules characterized by the least probability of being required in the near future.** Note that, despite its "mathematical" formulation, this principle is basically a qualitative principle, in the sense that no rigorous calculation of the "least probability of being required in the near future" is performed (nor it is possible to perform). For the practical application of this principle, two main ideas are suggested:

- Select modules that have a number of hours remaining that is really high, or
- Select modules that are situated in a range of hours remaining that is particularly well populated.

The advantage offered by the observance of this principle is that it makes it possible to avoid a situation in which using a particular module does not bring any advantage to the engine being constructed, but which may be really advantageous for a future engine, when unfortunately the module will no longer be available. Using modules that have little chances to become really interesting in the near future can also be viewed as a very basic attempt to perform some inventory management.

c) **All other things being equal, in the process of selection of independent modules that are situated relatively close[17] to the driver, one should give priority to the modules situated farther away (rather than closer) to the driver.** This third principle is based on the observation that those independent modules that are relatively close to the driver stand very good chances of becoming drivers themselves in the very near future (i.e., just after the engine they are presently in is brought to the Repair Facility for the PLCO of its present driver). As such, and given that it is definitely desirable to have drivers having as high a number of hours remaining as possible, modules situated farther away (rather than closer) to the driver should be given priority in the selection process. For example, all other things being equal, if there is choice between selecting a module having 600 hours remaining more than the present driver and one having 800 hours remaining more than the present driver, then the 800 hours module should be selected (because it is preferable to have a driver of 800 hours rather than a driver of 600 hours). This principle can also be viewed as a primitive way to perform some inventory management, in the sense that it attempts to limit the number of spare parts situated in the low ranges of hours remaining.

91. Note that, while the selection of the dependent modules is performed in an exact manner (which is quite natural given the precise objectives of minimizing the number of hours lost and of maximizing the number of dependent modules), the selection of the independent modules is very qualitative and also very subjective. Its subjectivity is a consequence of the fact that it is quite difficult even to rank the three principles stated under Operation 2.

92. It cannot be proven that having independent modules well matched between them is more important (in the sense of leading to more savings for the department) than attempting to do some inventory management of the spare parts. The implementation

[17] In terms of life remaining (hours)

(coding) of this part should be done only after consultation with the users, whom may have very strong intuitions in one sense or the other. However, this being said, it may be that the best way to implement Operation 2 is to give alternatively priority (i.e., higher significance) to each of the criteria (of course, only in those situations when they cannot be all satisfied at the same time). Such an approach will basically minimize the errors that might otherwise appear if one of the criteria is wrongly considered to be more important than the others.

An example for Step 3

93. To clarify these concepts, the procedure described above (Operations 1 and 2 of Step 3) will be illustrated with a numeric example that is based on the sample data in Table III (page 27) Specifically, it will be shown how the principles exposed earlier can be applied to construct "the best" set of engines, for a particular set of drivers identified at Step 2, say the set characterized by the maximum AHR. This set of drivers contains the following elements: an HPT Rotor having 896 hours remaining, a second HPT Rotor having 1006 hours remaining and a third HPT Rotor that has 1091 hours remaining (see Table V).

94. Before starting Step 3, one module (the driver) in each of the engines contained in any of the sets has been identified (at Step 2). The rest of the modules in each engine are to be selected during Step 3.

95. The following notation convention will be used in an engine description:

- as long as an element of an engine was not definitively selected (i.e., still an "empty box"), that element is marked by its generic name (such as "FAN", or "HPT", for instance);
- when a decision is made to assign a certain module to a particular engine, the generic name of that module in the engine to which it was assigned will be replaced by the number of hours remaining corresponding to the component assigned.

96. According to this convention, at the beginning of Step 3, for the set of drivers characterized by the maximum AHR, the three engines are described as follows:

Engine 1 = [FAN, HPC, CC, FN, B#4, 896, FDS, LPT]
Engine 2 = [FAN, HPC, CC, FN, B#4, 1006, FDS, LPT]
Engine 3 = [FAN, HPC, CC, FN, B#4, 1091, FDS, LPT]

97. Building "the best" set of engines around a given set of drivers is equivalent to assigning the most appropriate modules from the selection available, to each of the engines in the set.

98. Operation 1: Let us begin this assignment process for the FAN module. From Table III, it can be seen that the FAN modules that are available are characterized by the following amounts of hours remaining (in increasing order): 202, 327, 472, 761, 895, 3440, 3716, 4069, 4148, 4456. One of these will have to be selected for assignment to each of the three engines. A list of possible candidates has to be created for each engine. The only rule for creating such a list is that all FAN candidates for a particular engine must have a number of hours remaining that is greater or equal to the number of hours remaining of that engine's driver. Note that, according to this rule, the three lists of candidates for the FAN module are identical and contain the modules characterized by the following amounts of hours remaining: 3440, 3716, 4069, 4148, 4456. It can be observed that any of these candidates will become an independent module, whichever the engine it will be assigned to. As such, no assignment will be done as yet, because it was decided that the assignment of *dependent* modules takes precedence over the assignment of *independent* modules.

99. The assignment process continues with the next module in an engine, which is the HPC Rotor. The three candidate lists are again identical for the three engines, as it can be seen from Table VI.

TABLE VI

CANDIDATE LISTS FOR THE "HPC Module"

Engine 1 (driver: 896 hrs.)		**Engine 2 (driver: 1006 hrs.)**		**Engine 3 (driver: 1091 hrs.)**	
HPC candidates [hrs remaining]	**Distance from the driver** [hrs.]	**HPC candidates** [hrs remaining]	**Distance from the driver** [hrs.]	**HPC candidates** [hrs remaining]	**Distance from the driver** [hrs.]
1247	351	1247	241	1247	156
1247	351	1247	241	1247	156
1400	504	1400	394	1400	309
1542	646	1542	536	1542	451
1654	758	1654	648	1654	563
1676	780	1676	670	1676	585
1715	819	1715	709	1715	624

100. The reader is reminded that, when assigning a module to an engine, two principles are important: to maximize the number of dependent modules in an engine and to minimize the average number of hours lost corresponding to the set of engines. As it was stated earlier (Principle b)), when the two objectives are conflicting, the second one takes precedence. For practical purposes, this translates into the following rule: the first candidates to be "tried" for assignments should be the first ones on the lists ordered in increasing order. For this example, the assignment marked in red (i.e., one of the 1247 modules to be assigned to Engine 2 and the other 1247 module to be assigned to Engine 3) minimizes the total number of hours that are lost due to the HPC modules, which is equal to 397 (i.e., 241 + 156) hours. However, if these two components are assigned to Engines 2 and 3, it means that they are no longer available for Engine 1 and therefore Engine 1 will have an independent HPC module (to be assigned later in the process) rather than a dependent one. The assignment marked in blue maximizes the number of dependent modules (because in this case all the engines have dependent HPC modules). However, for the blue assignment, the total number of hours lost due to the HPC module would be 901 hours, much higher than for the red assignment. According to Principle b), the red assignment will be preferred.

101. This process allowed the assignment of two more modules, that are known to be the most appropriate according to the objectives stated. The process of "building" the engines has progressed to the following state, where the new additions are marked in red:

Engine 1 = [FAN, HPC, CC, FN, B#4, 896, FDS, LPT]
Engine 2 = [FAN, 1247, CC, FN, B#4, 1006, FDS, LPT]
Engine 3 = [FAN, 1247, CC, FN, B#4, 1091, FDS, LPT]

102. The next module considered in the assignment process is the Comb Case (CC). As in the previous cases, a candidate list will be constructed for each of the three engines. The three lists are once again identical, containing the following elements: 2617, 5238, 6291, 6450, 6453, 6582, 6808, 7241, 7272, 7357. It can be seen that there is no element on this list that is appropriate as a dependent module for any of the engines. Therefore, the assignment of the CC modules will be postponed until the process of assignment of independent modules begins (i.e., until the process of assignment of dependent modules is finished).

103. The next item considered is Fuel Nozzles. The three candidate lists for this component are given in Table VII.

TABLE VII

CANDIDATE LISTS FOR THE "Fuel Nozzles" MODULE

Engine 1 (driver: 896 hrs.)		**Engine 2 (driver: 1006 hrs.)**		**Engine 3 (driver: 1091 hrs.)**	
Fuel Nozzles Candidates [hrs remaining]	**Distance from the driver** [hrs.]	**Fuel Nozzles Candidates** [hrs remaining]	**Distance from the driver** [hrs.]	**Fuel Nozzles candidates** [hrs remaining]	**Distance from the driver** [hrs.]
1081	185	1081	75	1140	49
1140	244	1140	134	1284	193
1284	388	1284	278	1861	770
1861	965	1861	855	2170	1079
2170	1274	2170	1164	2213	1122
2213	1317	2213	1207	2249	1158
2249	1353	2249	1243		

104. The rules for the selection of modules are the same as in the previous cases and therefore they will not be discussed again in great detail. Note, however, that whether the assignment marked in red will be chosen or the one marked in blue will be chosen, the total number of hours lost due to the Fuel Nozzles component is the same. Specifically, the number of hours lost for the red assignment is: 388 + 75 + 49 = 512, while the number of hours lost for the blue assignment is: 185 + 134 + 193 = 512. Therefore, the two assignments are equivalent, because they both result in three dependent modules and the same number of hours lost. Note also that the two assignments identified so far are not the only ones. However, any assignment involving these three elements will yield the same results, both in terms of the number of dependent modules and in terms of the number of hours lost. This is because the measure of performance used is a global one, over the *set* of engines, rather than for each individual engine. As such, the total number of hours lost over the set of three engines, when the same three elements are selected, can also be calculated as: (1081 + 1140 + 1284) – (896 + 1006 + 1091) = 512, showing that regardless of the way each of the three components is assigned to one engine or other, the total number of hours lost will always be the same. In this case, the red assignment was selected.

Engine 1 = [FAN, HPC, CC, 1284, B#4, 896, FDS, LPT]
Engine 2 = [FAN, 1247, CC, 1081, B#4, 1006, FDS, LPT]
Engine 3 = [FAN, 1247, CC, 1140, B#4, 1091, FDS, LPT]

105. The process continues in a similar manner for the next item, Bearing # 4. The three candidate lists are provided in Table VIII. Using the same principles as above, it was possible to select two other items to assign to our engines. Note that the red and blue assignments are equivalent. Note also that the selection of the Bearing # 4 component for Engine 1 will be done later, in the process of assignment of independent modules. Selecting the red assignment for Bearing # 4, the following description of engines is obtained:

Engine 1 = [FAN, HPC, CC, 1284, B#4, 896, FDS, LPT]
Engine 2 = [FAN, 1247, CC, 1081, 1346, 1006, FDS, LPT]
Engine 3 = [FAN, 1247, CC, 1140, 1188, 1091, FDS, LPT]

TABLE VIII

CANDIDATE LISTS FOR THE "Bearing # 4" COMPONENT

Engine 1 (driver: 896 hrs.)		**Engine 2 (driver: 1006 hrs.)**		**Engine 3 (driver: 1091 hrs.)**	
Bearing # 4 Candidates [hrs remaining]	**Distance from the driver** [hrs.]	**Bearing # 4 Candidates** [hrs remaining]	**Distance from the driver** [hrs.]	**Bearing # 4 Candidates** [hrs remaining]	**Distance from the driver** [hrs.]
1188	292	1188	182	1188	97
1346	450	1346	340	1346	255
1539	643	1539	533	1539	448
1588	692	1588	582	1588	497
1753	857	1753	857	1753	662
1862	966	1862	966	1862	771
2103	1207	2103	1097	2103	1012
2103	1207	2103	1097	2103	1012
2103	1207	2103	1097	2103	1012

106. Continuing the process for the "Fan Drive Shaft" component, it is observed that, once again, the three candidate lists are identical, containing the following elements: 2973, 3656, 3835, 4065, 4197, 4409, 4648, 6140, 6595, 6797. It can be seen from that list that the Fan Drive Shaft component will be an independent component for any of the three engines, and, as such, it will be selected later, in the process of assignment of independent modules.

107. Finally, the last component to be considered is the LPT module. The three candidate lists for the LPT module are provided in Table IX. The selection of the red assignment will result in the following description of the engines:

Engine 1 = [FAN, HPC, CC, 1284, B#4, 896, FDS, 994]
Engine 2 = [FAN, 1247, CC, 1081, 1346, 1006, FDS, 1191]
Engine 3 = [FAN, 1247, CC, 1140, 1188, 1091, FDS, 1136]

At this point, all the dependent modules have been selected.

TABLE IX

CANDIDATE LISTS FOR THE "LPT Module"

Engine 1 (driver: 896 hrs.)		**Engine 2 (driver: 1006 hrs.)**		**Engine 3 (driver: 1091 hrs.)**	
LPT candidates [hrs remaining]	**Distance from the driver** [hrs.]	**LPT candidates** [hrs remaining]	**Distance from the driver** [hrs.]	**LPT candidates** [hrs remaining]	**Distance from the driver** [hrs.]
994	98	1136	130	1136	45
997	101	1191	185	1191	100
1136	240	1268	262	1268	177
1191	295	1326	320	1326	235
1268	372	1350	344	1350	259
1326	430				
1350	454				

108. Operation 2: The selection of the independent modules will be performed according to the principles stated earlier, when Operation 2 was described. At the beginning of this process, the engines have all the dependent modules already selected. In the following description of engines, a green colour will be introduced to distinguish the dependent modules. The driver modules are in black.

Engine 1 = [FAN, HPC, CC, 1284, B#4, 896, FDS, 994]

Engine 2 = [FAN, 1247, CC, 1081, 1346, 1006, FDS, 1191]

Engine 3 = [FAN, 1247, CC, 1140, 1188, 1091, FDS, 1136]

109. Table X provides an overview of the spare parts of each type that are still available at this point in the process.

110. Given the qualitative aspect of the principles suggested for the selection of the independent modules, it is obvious that the solution will not be unique, nor can it be proved the best. It is important to understand that once an engine is brought to the shop for a PLCO, basically anything can happen: besides the PLCOs, other parts may be

changed as well, if there is a reason to do so, or else they may be kept in the same engine. The only certainty that exists regards the driver and the dependent modules. That is why selection of the dependent modules should be done with the greatest care. On the other hand, the future employment of the independent modules is quite uncertain. A random assignment of those modules is not recommended though, for the simple reason that there are better ways to handle this assignment. However, only a reasonable amount of effort should be spent in the assignment of the independent modules. It is the author's opinion that employing the three principles described under "Operation 2" represents a good balance between the amount of effort required and the potential advantages obtained.

TABLE X

COMPONENTS THAT ARE STILL AVAILABLE FOR THE SELECTION OF INDEPENDENT MODULES

Number of hours remaining on each available item of each type (hrs.)				
FAN	**HPC**	**CC**	**B # 4**	**FDS**
3440	1400	2617	1539	2973
3716	1542	5238	1588	3656
4069	1654	6291	1753	3835
4148	1676	6450	1862	4065
4456	1715	6453	2103	4197
		6582	2103	4409
		6808	2103	4648
		7241		6140
		7272		6595
		7357		6797

111. From Table X, a number of observations can be made. One of them is that the HPC module having 1542 hours remaining and the Bearing # 4 having 1539 hours remaining are very closely matched. According to the first principle, these two components should be excellent candidates for Engine 1. However, at a closer look, it can be seen that, at the time of the next visit (due to the PLCO of its driver) of this engine to the workshop, if these two items were selected, Bearing # 4 will still have 643 (i.e., 1539 – 896) hours remaining, which, given the very low cost per flying hour of this component, makes it almost worthless, and the HPC module will have 646 (i.e., 1542 – 896) hours remaining, which gives this component a high probability of becoming a

driver. Another option for HPC, suggested by the third principle, would be to assign to Engine 1 the HPC module that has 1715 hours remaining. By the time of the first visit of this engine to the repair shop, it will still have 819 hours remaining, which gives this component a high probability of becoming a driver, as well. Since it is preferable to have a driver of 819 hours rather than one that has 646 hours remaining, and since good matching with the Bearing # 4 brings very little advantages, the second option (for the HPC module) will be selected.

112. In the case of Bearing # 4, applying the second principle seems the most appropriate. According to this principle, the component that seems the most appropriate to assign to Engine 1 is the one that has 2103 hours remaining (being therefore in a range that is well populated). This brings the selection process in the following state, where the latest additions are marked in red, as always.

Engine 1 = [FAN, 1715, CC, 1284, 2103, 896, FDS, 994]
Engine 2 = [FAN, 1247, CC, 1081, 1346, 1006, FDS, 1191]
Engine 3 = [FAN, 1247, CC, 1140, 1188, 1091, FDS, 1136]

113. Three more independent modules still have to be selected for each of the three engines: FAN, CC and FDS. It can be observed that the FAN and FDS components can be very well matched. Good matchings can also be obtained between CC and FDS. Matching the CC having 6582 hours remaining to the FDS having 6595 hours remaining seems like a very good solution, since it responds simultaneously to the first two principles: the two components are very well matched, and they are also very unlikely to be required in the near future. Another very good match is between the FAN having 4069 hours remaining and the FDS having 4065 hours remaining. Also, between the FAN having 4456 hours and the FDS having 4409 hours. A possible assignment of these components to the engines can be the following:

Engine 1 = [4069, 1715, CC, 1284, 2103, 896, 4065, 994]
Engine 2 = [4456, 1247, CC, 1081, 1346, 1006, 4409, 1191]
Engine 3 = [FAN, 1247, 6582, 1140, 1188, 1091, 6595, 1136]

114. In the engines' description above, the red elements are the latest additions, the green ones represent the dependent modules and the pink ones represent the independent modules that were assigned previously.

115. Three more elements are yet to be assigned: the CC component for Engines 1 and 2 and the FAN component for Engine 3. No good matching between the available components and the independent ones that are already assigned to an engine can be found. Also, all available components are sufficiently far away[18] from the driver to make the third principle not applicable for this situation. Therefore, the selection of these modules will be done according to the second principle, which offers actually a significant amount of flexibility. One of the multiple solutions that satisfy this second criterion (principle) could be to assign a CC of 7357 hours remaining to Engine 1, a CC of 7272 hours remaining to Engine 2 and a FAN of 4148 hours remaining to Engine 3.

116. Following these assignments, the final solution will be obtained in the form of:

Engine 1 = [4069, 1715, 7357, 1284, 2103, 896, 4065, 994]
Engine 2 = [4456, 1247, 7272, 1081, 1346, 1006, 4409, 1191]
Engine 3 = [4148, 1247, 6582, 1140, 1188, 1091, 6595, 1136]

117. This set of engines is deemed to be the best that can be constructed around the given set of drivers (896, 1006, 1091) that corresponds to the highest AHR remaining. Again, "the best" is defined in terms of total number of hours lost due to premature PLCOs (i.e., due to the dependent modules), and in terms of the number of dependent modules in each engine. More precisely, the best solution will have a minimum total number of hours lost and a maximum number of dependent modules that can be put into an engine (without compromising on the first objective of minimizing the total number of hours lost).

[18] In terms of life remaining

118. The numerical example above illustrated the manner in which the best set of engines corresponding to the set of drivers maximizing AHR was constructed. At Step 3, the same procedure is applied several times, so that the best set of engines is identified for *all* sets of drivers that are situated in the neighbourhood of AHR maximum. As such, at the end of Step 3, a whole set of "best engines" are identified. Each of them is "best" with respect to the particular set of drivers to which it is associated. Together, they form a pool of "reasonably good" sets of engines from which the *overall best* set will be finally selected, in Step 4.

Step 4

119. Purpose: The purpose of this step is to detect the best set of engines among all those constructed at Step 3. At Step 3, a multitude of sets of engines that are reasonably good were determined. At Step 4, the best one of them will be determined, and it will be presented to the user as THE SOLUTION.

120. Databases involved: The database involved in Step 4 is the one containing the costs by flying hour corresponding to each type of life-limited components inside an engine

121. Operations to be done: The criterion that will be used to compare two engines characterized by different amounts of hours remaining until the next visit to the Repair Facility *and* different amounts of hours lost due to the dependent modules is the following:

The best set of k engines is the one that minimizes the ratio: Cost_{total} / AHR (which will be called *costing ratio*), where:

$$\text{Cost}_{total} = \sum_{i=1}^{k} (\text{Cost}^{i}_{removal\ transp} + \text{Cost}^{i}_{workshop} + \text{Cost}^{i}_{known\ wastage} + \text{Cost}^{i}_{unknown\ wastage}) \quad (9)$$

and the average number of hours remaining (AHR) for the set of engines is the arithmetic mean of the number of hours remaining (HR) for each of the engines in the set:

$$\text{AHR} = \frac{\sum_{i=1}^{k} HR_i}{k} \quad (10)$$

122. Therefore, at this step, the costing ratio has to be calculated for each of the sets of engines built at the previous step. The set minimizing this ratio is selected and presented to the user as the final solution.

123. This ratio provides a way to make tradeoffs between the two conflicting objectives: maximizing AHR on one hand and minimizing the wastage due to the premature retirement of some of the engines' components The idea of the costing ratio is that it enables one to compare, from a cost perspective, two different kinds of advantages: the ones offered by a high AHR and the ones offered by a low number of hours lost.

124. The reasons for which it is interesting to have a high AHR are that the fixed costs associated with the removal/transportation of the engine, as well as some of the workshop costs (such as the costs due to the testing of the newly built engine) and the costs covered by the category "unknown wastage costs" are incurred less often. The more time between two consecutive visits of an engine to the workshop, the better the "amortization" of the fixed costs. On the other hand, the better the matching of the components in an engine (conducive to a small number of hours lost), the better the savings. Hence, the idea of blending in a meaningful way the two performance measures into one, through the ratio Cost_{total} /AHR. This allows the characterization of an engine

by only one parameter (the costing ratio), instead of two parameters (AHR and number of hours lost), while still capturing all the information contained by the two parameters.

125. When $k = 1$ (i.e., the set of engines contains only one engine), this ratio provides a mathematical way of comparing two different engines. For instance, answering the question "Between two engines, one characterized by 800 hours remaining and 300 hours lost and one characterized by 700 hours remaining and 50 hours lost, which one is better?" was a very difficult job until now, because the user did not have any consistent quantitative way to perform such a comparison. Using the criterion proposed above, the answer can now be easily determined by the computer.

126. To clarify the procedure, let us consider the example of the two engines described above and let us assume some (imaginary) values for the costs involved, as given in Table XI.

TABLE XI

COSTS INVOLVED IN THE NUMERICAL EXAMPLE

	Engine 1	**Engine 2**
$\mathbf{Cost}_{\text{removal/transp}}$	\$2,500	\$2,500
$\mathbf{Cost}_{\text{workshop}}$	\$6,000	\$5,500
$\mathbf{Cost}_{\text{known wastage}}$	\$25 / hour lost	\$30 / hour lost
$\mathbf{Cost}_{\text{unknown wastage}}$	\$1,000	\$1,000

Then, the costing ratio $Cost_{total}$ / AHR will assume the following values, for the two engines:

$$\text{Costing Ratio for Engine 1} = \frac{\$2500 + \$6000 + (300 \times \$25) + \$1000}{800} = 21.25$$

$$\text{Costing Ratio for Engine 2} = \frac{\$2500 + \$5500 + (50 \times \$30) + \$1000}{700} = 15$$

Selecting which engine is better (cost wise) is as simple as finding the minimum of the two ratios. Hence, the final solution in this example would be Engine 2.

CONCLUSIONS AND RECOMMENDATIONS

127. The present study provides a ready-to-implement methodology that will allow a significant improvement of the cost-effectiveness of the maintenance process of the CF-18 engines, through a better management of its life-limited components. Besides improving the cost-effectiveness, the system proposed will also be easier to use and will provide faster and more reliable solutions than the system currently in place.

128. The focus of the present study was the development of the methodology itself, with special efforts directed towards providing algorithms that are ready for a relatively straightforward translation into programming code. However, besides the development of the methodology, the analysis conducted for this study also permitted the identification of several problem areas that should be tackled in the future. As such, the following recommendations are made.

129. It is recommended that the concept of "fallout window" be re-visited. Different discarding thresholds should be employed for components that have different monetary values (i.e., different costs per flying hour), rather than employing the same value of 400 hours, regardless of the type of component. Establishing a sound methodology to compute discarding thresholds specific to each type of component can be a source for significant additional savings.

130. It is also recommended that *all* costs involved in the maintenance process be tracked. In particular, the costs labelled in this study as "unknown wastage costs" should be tracked. This will permit gaining a more intimate comprehension of the costs involved in the maintenance process, conducive to a better control over these costs and therefore to additional potential savings.

131. Finally, it is recommended to explore the possibility of re-organizing the process of distribution of spare parts between the two Repair Facilities in Cold Lake and

respectively, Bagotville, and the central pool situated in Toronto, in order to achieve a better match between the supply and the demand of spare parts. Inventory management principles should also be explored and applied, to further improve the match between supply and demand.

132. Given that the CF-18 fleet is subject to a Life Extension Program that is meant to extend the life of the CF-18 aircraft until 2017, all the avenues recommended above are well worth being explored, because they can all result in important savings for the department, and even more so when the savings can be realized over such a long period of time.

133. To conclude, the system proposed here, although offering significant advantages when compared to the current system, can still be improved. To begin with, it could be improved by such refinements as using different discarding thresholds for different types of components, however, a major improvement that can only be done after more costing information is gathered (i.e., after *all* costs are tracked for a sufficient period of time), will consist of a reformulation of the problem in terms of costs only. More precisely, instead of trying to deal with two conflicting objectives, one should go to the root of the problem by reformulating it into one objective: *minimize total cost.*

LIST OF REFERENCES

1. Meetings, Capt. A. Fizgerald/Mr. Cook/Ms. L.Stemate, February – May 2001

2. Meetings, Mr. R.Cook/Ms. L. Stemate, June – August 2001

3 Joe Sawada, C Program for Generation of Combinations in Lexicographic Order, Combinatorial Object Server, www.forum.swarthmore.edu/library/topics

ANNEX A
ORD PROJECT REPORT PR 2002/02
JANUARY 2002

LOGICAL CONFIGURATION OF THE LIFE-LIMITED MODULES OF THE F 404-GE-400 ENGINE

The F 404-GE-400 engine contains four modules that have a finite life. Figures A1 to A4 highlight the lifed components within each of these modules.

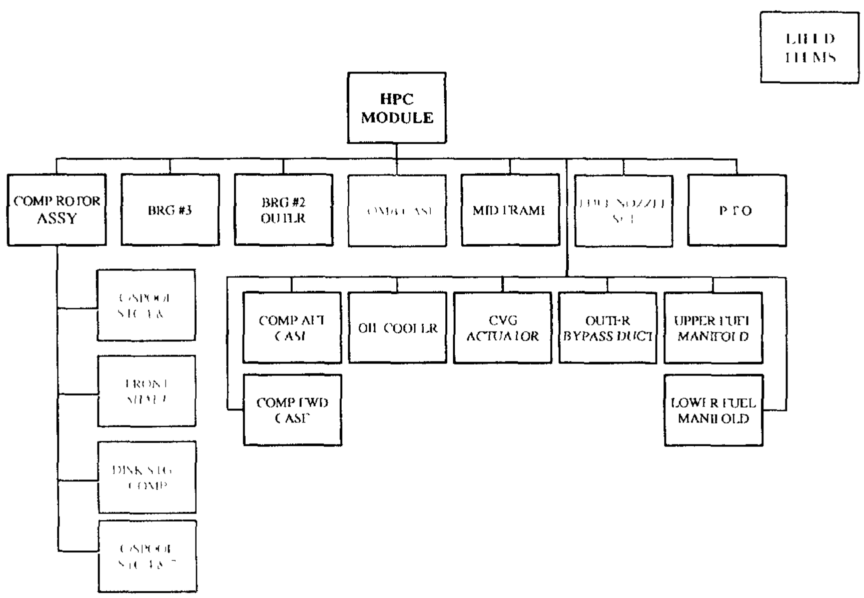

Figure A 1. Logical Configuration of the High Pressure Compressor (HPC) Module

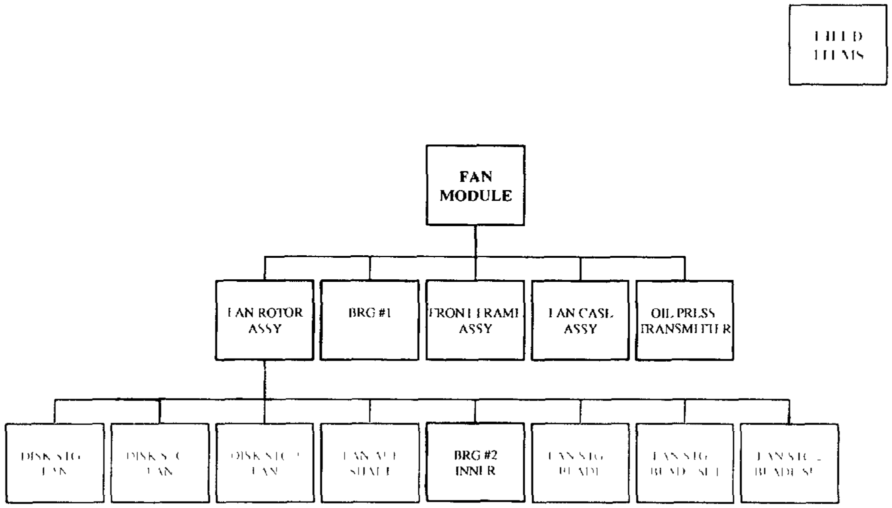

Figure A 2. Logical Configuration of the Fan Module

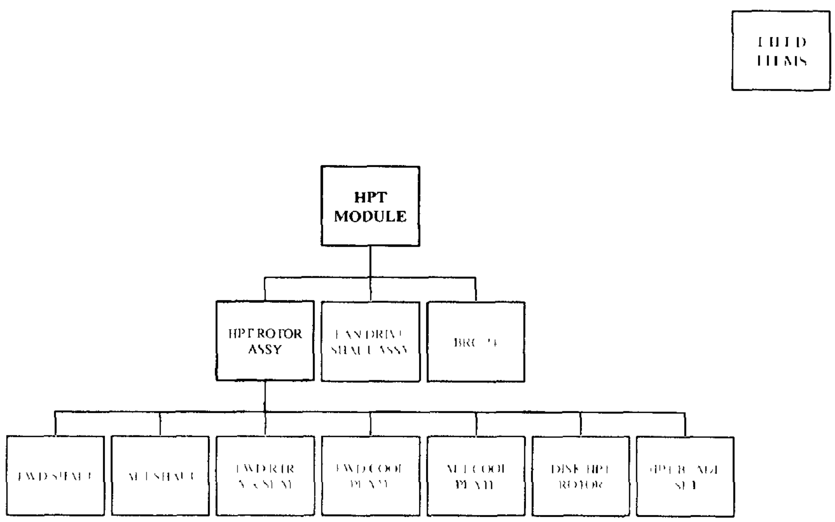

Figure A 3. Logical Configuration of the High Pressure Turbine (HPT) Module

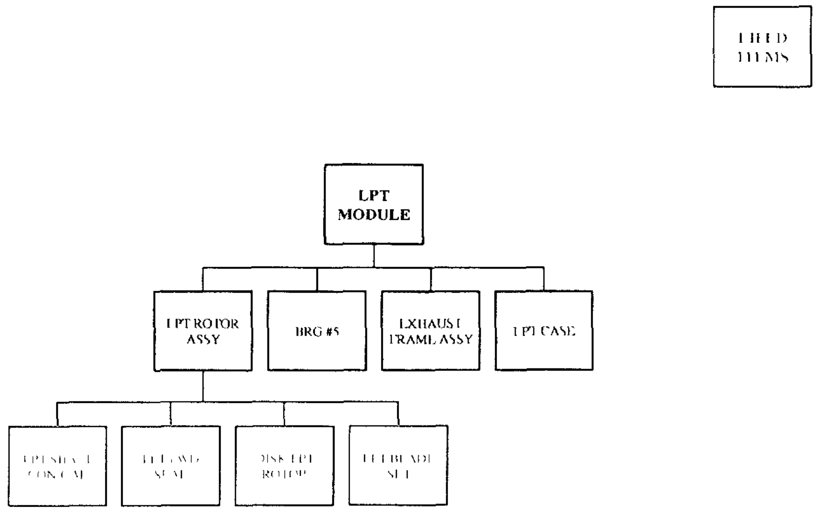

Figure A 4. Logical Configuration of the Low Pressure Turbine (LPT) Module

ANNEX B
ORD PROJECT REPORT PR 2002/02
JANUARY 2002

SET OF SAMPLE DATA

Fan Module/NH SN	Fan Item SN	Fan AFH Remaining
MF37921600	GLAA211600	202
MF37913500	GLA7965400	327
CFFR010100	GLAC843400	472
MF37905600	GAT6467M00	761
MF37907500	GAT3742U00	895
MF37911400	GEE0504700	3440
MF37903300	GEE0337100	3716
MF37913300	GEE0671500	4069
CFFR024700	GEE0815600	4148
CFFR030200	GEE0610700	4456
HPC Module/NH SN	**HPC Item SN**	**HPC AFH Remaining**
GACC159100	GATJN27000	209
MC37712000	GATKW54900	381
MC37725800	GATKW53500	878
MC37707700	GATT302300	1247
MC37723900	GATEW87900	1247
MC37702500	GWNE038700	1400
MC37721000	GWNE159100	1542
MC37703900	GATAG84200	1654
MC37721200	GWNB154800	1676
GGAC050000	GWNE024400	1715
Comb Case/NH SN	**Comb Case SN**	**Comb Case AFH Remaining**
MC37707400	GJP0058900	2617
MC37711500	GJP0075000	5238
MC37723900	GJP0200400	6291
MC37707700	GJP0053300	6450
MC37728200	GJP0190400	6453
MC37712100	GJP0076300	6582
MC37723800	GJP0163800	6808
MC37719500	GJP0124700	7241
MC37721600	GJP0147000	7272
MC37701100	GJP0179300	7357
Fuel Nozzle Set/NH SN	**Fuel Nozzle Set SN**	**Fuel Nozzle Set Remaining**
MC37702100	NZOEL57500	239
MC37705000	NZOEL25200	531
MC37705600	NZOEL51200	620
MC37712100	NZOEL04200	1081
MC37714400	NZOEL00700	1140
MC37711800	NZOEL04600	1284
MC37700800	NZOEL09500	1861
MC37707400	NZOEL14900	2170

MC37710600	NZOEL11400	2213
MC37705300	NZOEL10700	2249
HPT Module/NH SN	**HPT Item SN**	**HPT AFH Remaining**
MH38105700	GATY440800	202
MH38126700	GWNV065800	345
MH38123600	GATW9436A2	415
GACH089900	GACH0899D1	461
MH38117700	GATS5035A1	473
MH38106200	GWNV064100	578
MH38126100	GATFV54300	648
MH38108300	GATP189900	896
MH38123800	GWNKG85600	1006
MH38110800	GATCG29600	1091
Fan Drive Shaft/NH SN	**Fan Drive Shaft SN**	**Fan Drive Shaft AFH Remaining**
MH38102700	GATV353500	2973
MH38116900	GATCN32800	3656
MH38118900	GATER40400	3835
MH38105700	GATW126700	4065
MH38116800	GATAP57700	4197
MH38106200	GATHW59800	4409
MH38129800	GATNV54600	4648
MH38126700	GATAF99600	6140
MH38101700	GEE0685000	6595
MH38123300	GEE142LV00	6797
No 4 Bearing/NH SN	**No 4 Bearing SN**	**No 4 Bearing Remaining**
MH38118200	MABF483000	511
MH38126100	MABN386500	1188
MH38114000	SBBOB55100	1346
MH76551200	SBBOB58400	1539
MH38127200	SBBOB52400	1588
MH38101600	MABS028400	1753
MH38118100	SBB4G17800	1862
MH38108300	SBBOH73000	2103
MH38110900	SBBOH76500	2103
MH38124800	SBB0H77000	2103
LPT Module/NH SN	**LPT Item SN**	**LPT AFH Remaining**
ML38207900	GATAF90700	292
GGAL023300	GATV050100	727
ML38220500	GATAE90600	868
ML38211000	GATDU77700	994
ML38202500	GATJH57800	997
ML38220800	GATNW29500	1136
GGAL026200	GATV017300	1191
ML38209800	GATT986000	1268
GACL165400	GATKT67900	1326
GACL124800	GATLA64300	1350

AN ALGORITHM THAT CAN BE USED TO ENUMERATE COMBINATIONS OF "*N*" ELEMENTS TAKEN "*K*" AT A TIME

```
/*==============================================================*/
/* C program for distribution from the Combinatorial Object Server.        */
/* Generate combinations in lexicographic order. This is the same version used in  */
/* book "Combinatorial Generation". The program can be modified, translated to   */
/* other languages, etc., so long as proper acknowledgement is given (author and  */
/* source).                                                                */
/* Programmer: Joe Sawada, 1997                                           */
/* The latest version of this program may be found at the site             */
/* http://sue.uvic.ca/~cos/inf/comb/CombinationsInfo.html                   */
/*============================================================== */

int n,k;
int a[100];     /* The string */

void PrintIt()
{
        int i;
        for (i=1; i <= n; i++)  printf( "%d", a[i]);
        printf("\n");
}

void Comb(int j, int m)
{
        if (j > n) PrintIt();
        else
        {
                if (k-m < n-j+1)
                {
                        a[j] = 0;
                        Comb(j+1, m);
                }
                if (m < k)
                {
                        a[j] = 1;
                        Comb(j+1, m+1);
                }
        }
}
```

```
void main ()
{
        printf( "Enter n, k: ");
        scanf( "%d %d", &n, &k);
        if (n <= 0) exit(1);
        printf( "\n" );
        Comb(1, 0);
        printf( "\n"),
}
```

UNCLASSIFIED
SECURITY CLASSIFICATION OF FORM
(highest classification of Title, Abstract, Keywords)

DOCUMENT CONTROL DATA
(Security classification of title body of abstract and indexing annotation must be entered when the overall document is classified)

1 ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared e g Establishment Sponsoring a contractor's report, or tasking agency, are entered in Section 8) OPERATIONAL RESEARCH DIVISION DEPARTMENT OF NATIONAL DEFENCE OTTAWA, ONTARIO K1A 0K2	2 SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable) UNCLASSIFIED

3 TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title)
A METHODOLOGY TO IMPROVE THE COST-EFFECTIVENESS OF THE MAINTENANCE PROCESS OF THE CF-18 ENGINE, THROUGH A BETTER MANAGEMENT OF ITS LIFE LIMITED COMPONENTS

4 AUTHORS (last name, first name, middle initial)

STEMATE, LUMINITA C

5 DATE OF PUBLICATION (month Year of Publication of document) JANUARY 2002	6a NO OF PAGES (total containing information. Include Annexes, Appendices, etc) 67	6b NO OF REFS (total cited in document) 3

7 DESCRIPTIVE NOTES (the category of document, e g technical report, technical note or memorandum. If appropriate, enter the type of report e g interim, progress summary, annual or final. Give the inclusive dates when a specific reporting period is covered)

PROJECT REPORT

8 SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address)

CHIEF OF THE AIR STAFF

9a PROJECT OR GRANT NO (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)	9b CONTRACT NO (if appropriate, the applicable number under which the document was written)
10a ORIGINATOR's document number (the official document number by which the document is identified by the originating activity. This number must be unique to this document) ORD PROJECT REPORT PR 2002/02	10b OTHER DOCUMENT NOS (Any other numbers which may be assigned this document either by the originator or by the sponsor)

11 DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)
(X) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors, further distribution only as approved
( ) Distribution limited to government departments and agencies, further distribution only as approved
( ) Distribution limited to defence departments, further distribution only as approved
( ) Other (please specify)

12 DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected)

UNCLASSIFIED
SECURITY CLASSIFICATION OF FORM

UNCLASSIFIED
SECURITY CLASSIFICATION OF FORM

13 ABSTRACT (a brief and factual summary of the document It may also appear elsewhere in the body of the document itself It is highly desirable that the abstract of classified documents be unclassified Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), or (U) It is not necessary to include here abstracts in both official languages unless the text is bilingual)

The aim of this study is to provide a methodology to improve the cost-effectiveness of the maintenance process of the F404-GE-400 engines of the Canadian Forces CF-18 Fighter Aircraft, through a better management of the limited life components inside the engine. An effort was made to construct the present report as a sufficient, stand-alone source of documentation to be used for any future implementation of the proposed methodology.

14 KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document They should be selected so that no security classification is required Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included If possible keywords should be selected from a published thesaurus e g Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified If it is not possible to select indexing terms which are Unclassified the classification of each should be indicated as with the title)

CF-18
CF-18 ENGINE
F404-GE-400
LIFED COMPONENTS
LIFE LMITED COMPONENTS
METHODOLOGY
COST-EFFECTIVENESS
ENGINE MAINTENANCE
CF-18 MAINTENANCE

Canada