MORE RELIABLE AIRCAFT ENGINE MAINTENANCE OPTIMIZATION BY A CLASSIFICATION FRAMEWORK FOR ON-CONDITION PARTS

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Abstract: An aircraft engine is a complex and advanced system with high demands on safety and reliability. Maintenance and how it is performed is therefore of outmost importance. Each maintenance occasion must be as effective as possible and execute the maintenance needed without performing excessive maintenance. A previous research project has developed an optimization model to calculate the optimal balance between the remaining lives in engine components and the cost related to each maintenance occasion. A potential to further improve the optimization using the model has been identified if the life-length of all the components used can be estimated. Hence, the aim of this paper is to describe a research challenge on how to develop a framework for estimation of the remaining life in aircraft engine components and by that group the components in different life-length classes.

Keywords: Aircraft engine maintenance, maintenance optimization, on-conditions parts, estimation of remaining life, real world case study

1. INTRODUCTION

Maintenance of aircraft engines is one of GKN Aerospace Engine Systems (GKN) core business. Maintenance is also an expensive and time consuming operation and maintenance costs typically account for 10-20% of aircraft related operating cost according to (Maple 2001). That is why it is important to, at each maintenance occasion be as effective as possible and do as much maintenance as needed without performing excessive maintenance. To do this, an mathematical replacement model has been developed by (Almgren, Andréasson et al. 2008) to calculate the optimum balance between the remaining life in engine components and the fixed costs for each maintenance event, and the costs for components and the cost of exchanging them.

The main purpose with this paper is to present an area with potential for improvements were the existing working practise can be significantly improved using an improved optimization tool, to describe the research challenges that need to be addressed, to outline how the challenges will be attacked by describing the research process, and present how the research can change and improve how GKN will perform aircraft engine maintenance tomorrow.
The research area for aircraft engine maintenance has during the years focused on several aspects, mainly to map and develop methods and to lower the costs related to maintenance. Remaining useful life is one method that is addressed by (Xue, Bonissone et al. 2007) to develop engine maintenance. Multidisciplinary approaches that include design feed-back, if the design of a component is life-limiting, and methods to estimate how failure occur and affect life-lengths have also been studied by (Benac and Bryant 2002). To measure the effects of new methods and developments, Life Cycle Cost (LCC) approaches by (Seemann 2010) and (Iyer 1999), are used to estimate the economic perspective during the complete life cycle.

2. BACKGROUND

GKN is Original Equipment Manufacturer (OEM) for aircraft engine RM12 used in the Swedish Gripen fighter and almost all maintenance and module replacement for the engine is performed at depot level at GKN. Older engine types, like for example the RM8 in the Viggen fighter were maintained at certain fixed occasions. However the continuous price increase of new fighters and their engines, spare parts, maintenance and usage, in combination with development and applications of new maintenance concepts, have led to changes in how maintenance is performed as stated by (Siladic and Rasuo 2008). This is why RM12 and other newer engines are developed to be maintained when a component has reached its life limit or something indicates a fault in the engine.

Presently, the decisions regarding what to maintain in an engine at each maintenance occasion are made manually by an engine technician. The initial maintenance plan is based on engine information and data that is complemented with information from ocular inspections and use of optical instruments to inspect the inside of the engine. This information is then the basis for an initial plan specifying what modules and component to maintain. There are, however, a lot of different information to consider for the engine technician while creating the initial plan, e.g., the remaining life lengths of the components, engine data, costs related to maintenance,. While the engine is disassembled and its components are more closely inspected, it is not uncommon that more faults are discovered. Hence, the initial plan needs to be revised.

An engine consists of two types of components; life limited parts (LLP) and On-Condition parts (OC-parts). The former are safety critical and therefore have a fixed lifetime. This means that there are defined rules for how many "use" cycles that these components are allowed to consume before being replaced or maintained. The OC-parts are components that are not safety critical and therefore are exchanged first when there is a need for it. An OC-part is no longer approved for operation when fault modes as cracks, fretting, etc, are outside approved limits.

In 2012 a new system, Life Tracking System (LTS) described by (Andersson 2011), were taken into operation in order to calculate remaining life for LLPs. LTS calculates the fatigue life consumption for the LLPs in the engine based on actual flown missions were each mission is a usage cycle. Using LTS has made it possible to reduce the safety margins due to better calculation methods. The LLP components can thereby be used for a longer period of time. However the opportunity to use the LLPs longer has not only made it possible to save spare part costs, but it has also increased the variation in the remaining life of the engine components, which makes it more difficult to plan each maintenance occasion.

While the LTS gives very exact calculations of remaining life for the LLPs, there are no estimations of how much remaining life there is left in each one of the OC-parts in the present maintenance process. The OC-parts are instead inspected at each maintenance occasion and it is then determined if each component is approved for continued operation or not. Outside the maintenance process the life estimates of the OC-parts are mainly used to forecast spare parts demand. These life length estimates are mainly based on information from the fleet leading program, where some engines have extra flight time in order to learn more about component usage. This information is then used to introduce actions for the remaining fleet in due time.

Given the information above it can be concluded that the present maintenance planning process is a manual process where decisions are made without any decision support tool. Today there exist a lot of data and information about OC-parts kept by the maintenance personnel. The actual decisions made during their inspections could also be used as an input to an improved planning. The complicated situation today could however be improved by using a maintenance optimization tool and thereby secure that the decisions about what to maintain are made, optimal based on both economical and component status aspects.

In the existing optimization model, the LLPs are given a fixed life-length. The OC-parts are all given the same life-length. If the remaining life of each OC part could be estimated, the optimization model results could improve and become more reliable.

3. POTENTIAL FOR IMPROVEMENTS

The optimization model developed, see (Andréasson 2004), is designed to consider the cost for interrupted airplane use while minimizing the cost of maintenance. In practice this means, that the model will strive to create a maintenance plan with as infrequent maintenance occurrences as possible while maintaining a sound use of replacement parts, new as well as used components as described by (Almgren, Andréasson et al. 2008). With input data consisting of actual engine status, available new, used and repaired components in stock, plus all costs related to maintenance, it is possible for the replacement model to calculate which components that are most optimal to replace at this maintenance interval. LTS has already given the maintenance organization at GKN a new and improved approach on how to estimate the remaining life for the LLPs while the OC-parts at present do not have an individual quantified life limit. This project will therefore evaluate how to estimate the remaining life in OC-parts with a classification method making it possible to improve the input data to the mathematical replacement model. The improvements in more accurate remaining life data will make it possible to obtain more reliable optimization results, se Fig. 1.

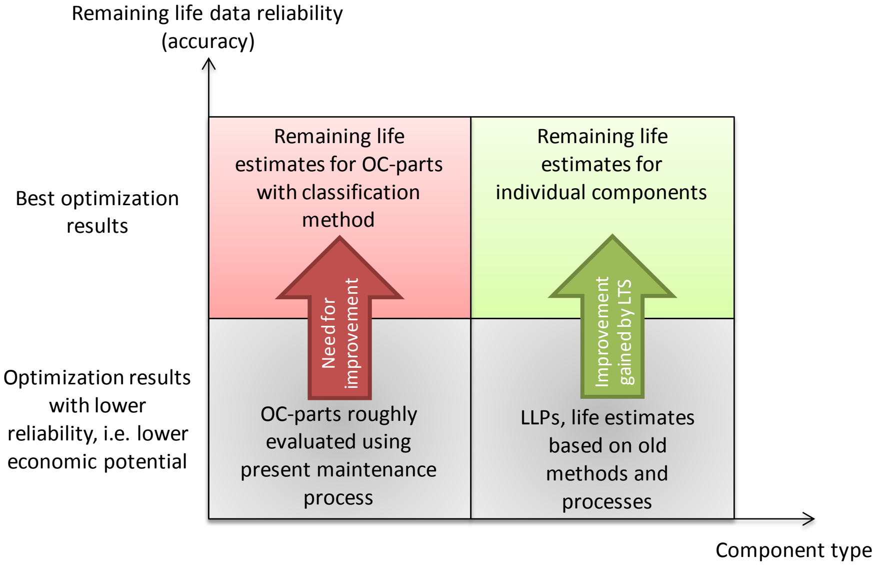

Fig. 1. Illustration indicating the desired improvements.

Implementation of a framework to estimate remaining life for the OC-parts will tentatively not provide an exact remaining life, but instead an interval (an estimated class) for how much longer each considered OC-part will be able to be kept in operation. Each interval will, however, be represented by a fixed value in the optimization model. Of course, large intervals could be handled by multiple runs of the model using various representations of the interval. Development of a framework to classify the remaining life of OC-parts would lead to a more standardize way of working with life estimations since the components today only are roughly evaluated by ocular inspection and through non destructive testing. No specific procedure are used to record compilation between detected fault modes at the OC-components and their consumed flight time in the present maintenance process. Instead the components are only evaluated against allowed boundaries for fault modes and evaluated regarding approval for continued operation. Summing up, there are no estimates made of how much longer an OC-part will be able to be kept in operation in present maintenance process, but this will be improved by this research project. The framework or work scheme on how to estimate remaining life in OC-components will when it is used, create better decisions about life estimates based on defined rules. This is a large difference from the existing situation where a large amount of experience is needed to be able to make these decisions. With a more standardized method, which this developed framework will provide, therefore will make this work easier to perform and less dependent on individual knowledge.

4. RESEARCH CHALLENGES

The idea presented in this paper is a framework on how to estimate remaining life in OC-parts to and thereby increase in the reliability of the maintenance planning and lower the total maintenance cost. In order to be able to end up in a developed framework the work has been divided into four research challenges that need to be addressed:

1. OC-parts selection
2. Classification resolution
3. How to perform the classification
4. Framework and method for classification of OC-parts

a. Research challenge 1: OC-part selection.

The first challenge aims to define rules deciding which components that should be incorporated in the replacement model. To do this, the existing parts in engine RM12 need to be analyzed to identify issues regarding which components that drive the need for maintenance and/or which ones that influence the extent of the maintenance. A definition of characteristics that influences whether a component should be included or not needs to be identified. In this part, existing heuristic methods will be examined in order to find a basis for different life-length groups. Other existing schemes will also be studied, and experience drawn will be evaluated and eventually used.

b. Research challenge 2: Classification resolution.

The second challenge will address and explore the importance of finding a balance between the derived estimates of remaining life and what is required to gain reliable plans from the optimization model. This means that there is a need to analyse how good remaining life estimates that can be obtained due to the uncertainties regarding the mechanical properties of the component in combination with uncertainties regarding future usage of the components. Next thing to consider is what a reasonable effort is (regarding lead-time, labour hours, resources etc.) to classify the OC-parts and estimate their remaining life. In this challenge is there are also a need to evaluate the robustness of the maintenance optimization model. This means that an analysis of the model will be done with intention to evaluate how sensitive the model is to deviations or “errors” in the estimations of remaining lives.

c. Research challenge 3: How to perform classification.

In the third challenge, the focus will be to study and learn more from available classification schemes and methods and to analyze which ones are the most relevant ones from an aircraft engine perspective. When this information is gathered, it will be possible to suggest which available classifications methods that can be used when and also describe the pros and cons. In this challenge will also developed methods on how to perform classifications for estimations of remaining life in OC-parts be evaluated. Questions, as if the classifications can be done based on ocular inspections and if currently available testing methods are enough, will be evaluated. Synchronously the need for new techniques to estimate remaining life in the OC-parts must be evaluated. Another interesting aspect to consider is if it is possible to use available usage history data and if data about predicted upcoming usage can be used to estimate remaining lives. Finally, this challenge will also address the aspect of to which extent it is possible to predict current status of an OC-part based on previous classification of reaming life from an earlier maintenance occasion.

d. Research challenge 4: Framework and method for classification of OC-parts.

The fourth and final research challenge will focus on the actual development of the framework for classifying OC-parts to get an estimation of remaining life for each component. In this research challenge, it will be necessary to explore how the classifications should be presented. Is it enough to have two classes there one is ok and the other not ok, or should they be expressed in a few possible values or should the output be a calculated number that continuously varies in a specified range? Another thing to evaluate is if subjective values, objective measures and other data can be combined together in an algorithm. This will probably vary from component to component, but it needs to be specified what method to use for each specific component. The main goal for this research challenge will however be to present a framework for the choice of classification model. This means that according to taxonomy, a set of classification principles needs to be developed that then will set rules for how the OC-parts should be grouped into different domains based on the estimated remaining life.

5. HOW THE CHALLENGES WILL BE ATTACKED

Four research challenges have been identified and presented in this paper. These challenges will be approached individually starting with research challenge 1 “OC-part selection” where all existing parts in RM12 will be evaluated and analyzed with purpose to come up with definitions of factors that determines what OC-parts that needs to be incorporated in the developed framework, see Fig. 2.

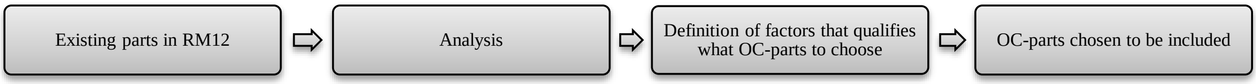

Fig. 2. Illustration of process to address research challenge 1.

Next research challenge, “classification resolution” that is illustrated in Fig. 3, will begin with the results from research challenge 1, which is the identified parts that need to be incorporated in the framework. For these components, an analysis of current taxonomy and remaining life approaches that are used to estimate remaining life will be carried through. From this information, estimates of how many groups of classes that are needed will be made and taxonomy of OC-parts based on different estimates of fault modes using existing information and knowledge can then be developed. These results will be used as a dataset to estimate the sensitivity of the taxonomy and the optimization model. This will result in an evaluation of how robust the optimization model is regarding the size of remaining life estimation errors.

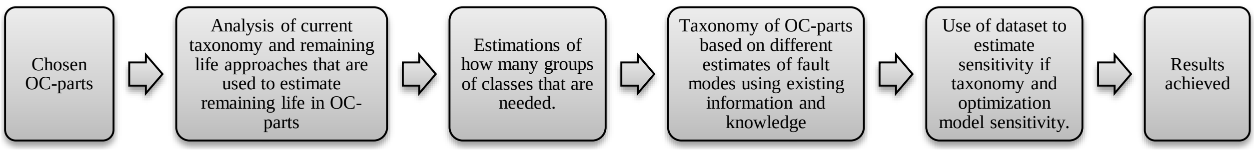

Fig. 3. Illustration of process to address research challenge 2.

Third research challenge illustrate in Fig. 4, “How to perform classification”, will begin with identification of existing classification models like the IOQA scores, see (Orcesi and Cremona 2011), that are used to describe the overall condition for a component. Another aspect to study is how estimation of remaining life can be done by combining expert judgments with operating feedback, see (Procaccia, Cordier et al. 1995), or multivariate statistics as in (Braglia, Gionata et al. 2012). Here will also the aspect of studying aircraft engine health monitoring systems, as described in (Tumer and Bajwa 1999), be addressed. All identified existing classification methods need then to be analyzed and evaluated to see what information and knowledge can be used in this specific case. Having access to past data and the classification made using these, each subsequent analysis must be able to relate the analysis result to past data. Interesting questions would be to see if the present condition is something completely new or if it can relate to what already has happened. This would then give information on how present data can be used for future status prediction of the OC-parts and result in an answer whether it is possible to predict status of an OC-part based on previous classification and knowledge.

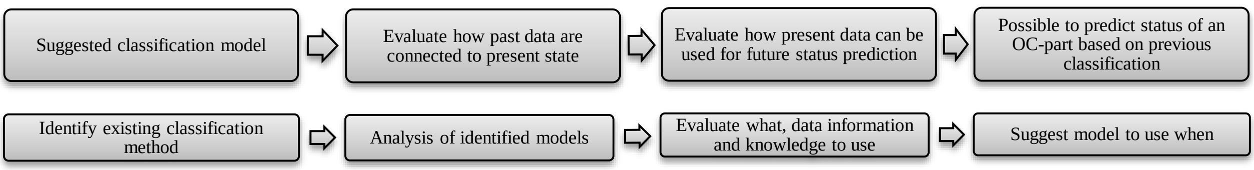

Fig. 4. Illustration of process to address research challenge 3.

The last challenge, “Framework and method for classification of OC-parts”, is the one focusing on development of the framework for classifying the OC-parts. Here will the outcome from “How to perform classification” be used as input and next step will be to identify how each fault mode in the classification is connected to remaining life and perform an analysis of how combined fault modes is affecting remaining life. From this it should be possible to perform overall remaining life estimations and to define a method and framework for how to estimate the remaining life in OC-parts. This process is illustrated in Fig. 5.

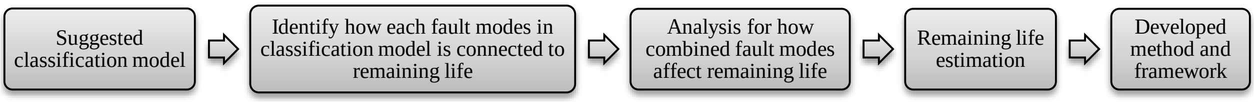

Fig. 5. Illustration of process to address research challenge 4.

6. EXPECTED RESULTS

A company related problem, and the required research to solve it, has been identified and presented in previous sections of this paper. Related to this are there also expected outcomes to the project and expectations on how the hypothetical solutions are supposed to influence the organization.

a. Research challenge 1: OC-part selection

This research challenge aims to define which components that must be incorporated in the optimization model. The basis for that decision is all component that drive or pursue maintenance and/or influence the extent of the maintenance.

b. Research challenge 2: Classification resolution

The expected results from the second research challenge is primarily a review over a suitable balance between the derived estimates of remaining life for OC-parts and what is required to get reliable plans from the optimizations model. This will be done by presenting following things:

- How good estimations that can be achieved due to inherent conditions.
- What the reasonable effort is to classify OC-parts and their remaining life.
- An analysis over robustness for the mathematical replacement model, i.e., how sensitive is it to "errors" in the estimates of remaining lives

c. Research challenge 3: How to perform classification

The third part of the work will present results consisting of a review over available classifications methods and a description over how these can be applied from an aircraft engine perspective.
This part will further also present a review over what classifications can be based on, and an evaluation of whether it is possible to predict the status of an OC-part based on the previous classification that was made at a previous maintenance occasion.

d. Research challenge 4: Framework and method for classification of OC-parts

The main goal with the fourth research challenge, and with the complete project too, is to define a framework to classify the OC-parts with regard to their remaining life estimates.

A potential solution on how to gain better life length estimates is to define a framework to classify the components based on, for example, their consumed flight time and identified fault modes. Several possible fault modes will need to be considered for each component and then be compiled, in an orderly manner, to classify and estimate the remaining life of each component. A framework used in practice will probably have to consider many more aspects as, for example, existing cracks and their potential to grow.

7. IMPROVEMENTS OF AIRCRAFT ENGINE MAINTENANCE THROUGH RESEARCH

By performing this research project, and address the research challenges that have been presented in previous chapters, the results will lead to changes and improvements in different aspects that both affects GKN perspective but also the academic and theoretical perspective. Those perspectives are presented in below.

a. Changes in work process in workshop

A short introduction to present maintenance process and how a maintenance occasion is planned was presented in chapter 1. All maintenance activities in the maintenance process are however not directly affected of the framework that this research project intends to develop. The processes that will be affected are those for receiving inspection, disassembling the engine, cleaning of engine components and the process of non destructive testing, see 6.

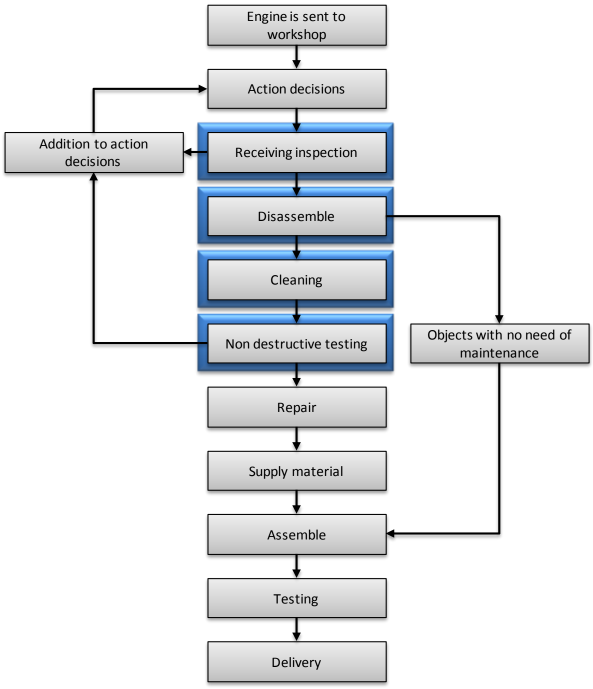

Fig. 6. Maintenance activities that are directly influenced by this research project.

The main difference in the work procedure for the GKNs workshop will, by the new developed framework, be that a component not only will be approved, or not, for continued operation. The components total status will be evaluated by considering all detected fault modes. By combining this information with information regarding how much flight time the component already has consumed, the remaining life the OC-part will be estimated. The framework that this research project aims to develop will therefore give a more comprehensive understanding of how much remaining life there is in each OC-part.

b. More reliable optimization results

Better estimations of remaining life for OC-parts that also affect and pursue maintenance through the developed framework will make it possible to get better estimates for the improve the mathematical optimization, i.e. to calculate what components that is optimal to exchange at each maintenance occasion given cost, consumed life in components and available parts in stock. The better the estimates are, the better and more reliable will the optimization results be. More reliable optimization results will also lead to better maintenance plans and thereby hopefully lower the Life Cycle Cost for the complete engine fleet.

c. Theoretical contributions

Since this project is a research project there is also an intention to present theoretical improvement for aircraft engine maintenance. This will in first hand be done by contributing with increased knowledge for how knowledge, data and information about remaining life of components can be handled and estimated. This knowledge will also contribute to better methods of how to classify, and group, components to ease and improve the planning of each maintenance occasion

8. CONCLUSIONS

A potential to improve aircraft engine maintenance and maintenance optimization results by developing a classification framework for OC-parts based on estimations of their remaining life has been identified and presented in this paper. The development of a the framework will lead to a more standardized way of working with life estimations since GKN today only evaluates the components against allowed boundaries for faults and approval for continued operation or not. The present maintenance method has no support for how much longer an OC-part will be able to be kept in operation but this will be added by this research project. To end up in a developed framework the work has been divided into four separate research challenges that needs to be addressed and a plan on how to attack these challenges has also been presented. The expected results from these challenges consist, in a first step, of defined rules for which components that should be incorporated in the replacement model. Second, an expected outcome is a review over a suitable balance between the derived estimates of remaining life for OC-parts. A third challenge of the project will be a review over available classification methods and descriptions for how these can be applied from an aircraft engine perspective. The fourth challenge is to define a framework to classify the OC-parts based on, for example their consumed life time and identified fault modes. This research project originates from a development work at GKN and will therefore lead to improvements and changes at the company. As a research project is there also a goal to come up with theoretical improvements for aircraft engine maintenance. Theoretical improvements will for example be fulfilled by contributing with increased knowledge for how data, information and knowledge about remaining life of components can be handled and estimated. From a company perspective the main difference will be that the developed framework will lead to changes in the work procedures at the maintenance workshop. Better estimations of remaining life for OC-parts from the developed framework will also make it possible to better represent the incorporated the OC-parts in the mathematical optimization model to calculate what components that is optimal to exchange at a specific maintenance occasion given costs, consumed life in components and available parts in stock. The better estimates of remaining life, the more reliable will the maintenance plans become. More reliable optimization results would lead to better maintenance plans and thereby hopefully lower the LCC-cost for the complete engine fleet.

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