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The effect of increased mission interaction on the life consumption for the RM12 engine using LTS

Master's thesis in Applied Mechanics

MARTIN CARLSON
NIKLAS GUSTAFSSON

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Division of Material and Computational Mechanics
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ISSN 1652-8557
Department of Applied Mechanics
Division of Material and Computational Mechanics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: +46 (0)31-772 1000

Chalmers Reproservice
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Abstract

GKN Aerospace have developed and implemented their own system to calculate the life consumption for the engine in JAS 39 Gripen, RM12. The system is called Life Tracking System (LTS) and it uses the actual flight loads, which are registered for each flight. It calculates the life until crack initiation.

The current system assumes that the engine always starts with a uniform temperature distribution corresponding to the nordic median. In addition, the system adds a fixed stress and temperature state after the engine has been shut off. This does not account for the variable state that the engine may be in when shut off. This does however, makes it possible to consider each flight separately in the life consumption calculations. There are often several flights during one day so the engine might not have cooled down to the ambient temperature before the next flight, which is assumed in the current system. By considering a variable starting state for the engine and simulating for the time between missions, the accuracy of the system will increase, allowing a lower safety factor and possible savings for spare parts.

This thesis work will study the effect of a variable metal start temperature and stress state in the engine for the life consumption calculations, based on previous FE-models. The study has been done by modifying the current system into also calculating the cooling process until the next flight. By doing so, the flights for each day can be assembled into one sequence since the flight now depends on the previous flight. The work has been performed on the high pressure turbine, since it is one of the parts with the highest temperatures and the largest effect is assumed to be found here.

From the analysis it was shown that including a variable start state in most cases decrease the life consumption due to changed strain levels. In the old method the fixed end state was considered conservative, but due to differences in strain behavior when calculating the time after the mission, this was not the case. When combining all missions during one day into one sequence, there was a small difference in life consumption, mainly due to a larger global cycle. It was also found that the effect from a changed ambient temperature was small.

Keywords: LTS, RM12, LCF, Thermomechanical Fatigue

Sammanfattning

GKN Aerospace har utvecklat och implementerat ett system för att beräkna livskonsumtionen för komponenterna i RM12:an som är motorn i det svenska stridsflygplanet JAS 39 Gripen. Systemet kallas *Life Tracking System* (LTS) och det använder data med laster från varje enskilt pass. Det beräknade livet är baserat på tiden till sprickinitiering.

Det nuvarande systemet antar att motorn alltid startar med en uniform temperatur som är satt till den nordiska mediantemperaturen. Systemet använder även en metod med ett fixerat sluttillstånd efter samtliga analyserad pass. Dessa förenklingar har medfört att uppdrag kan analyseras enskilt oberoende av övriga uppdrag under dagen. Eftersom planen ofta genomför flera flygningar per dag kan det vara så att motorn fortfarande är varm vid nästa start vilket skulle kunna påverka livsuppskattningen. Genom att ta hänsyn till en variable starttemperatur i motorn samt analysera tiden mellan uppdragen så kan noggrannheten i beräkningarna öka vilket kan tillåta en lägre säkerhetsfaktor.

Tesen kommer att studera effekten av en variabel starttemperatur samt startspänning och hur dessa implementeringar ändrar livsuppskattningen med den nuvarande FE-modellen. Genom modifikationer i det nuvarande systemet där avsvalningsförloppet till nästa uppdrag analyserats så har dessa tillstånd kunna hämtats vilket medfört att analysernas starttillstånd baserats på det föregående uppdraget. Tesen har undersökt effekten på Högtrycksturbinen då effekten av implementeringarna antas vara som störst här pågrund av de höga temperaturerna som förekommer.

Analyserna visade på att ett längre liv uppskattades med en högre starttemperatur i motorn till följd an förändrade töjningsnivåer. Genom att använda sig av ett konservativt antagande för de avslutande tillstånden hade längre liv förutspåtts men resultaten visar istället på förkortat liv för flertalet komponenter. Resultaten komer från skillnader i temperaturer och spänningar då motorn stängs av. När samtliga analyser för en hel dag sattes samman till en lång utmattningssekvens kunde små skillnader urskiljas, mestadels pågrund av en större global cykel. En förändrad omgivningstemperatur gav endast små skillnader vilket till stor del berodde på att tiden mellan flygpassen är relativt kort.

Preface

This project is the final part of the Master in Applied Mechanics, a part of the five year Mechanical Engineering program at Chalmers. It has been carried out at GKN Arospace in Trollhättan during January 2014 to June 2014. The study is about the effect of increased interaction between missions in their system that predicts the life consumption, LTS, for the RM12 engine.

Acknowledgements

Foremost we like to express our gratitude to our supervisors at GKN, Magnus Andersson and Henrik Eckervald, for all guides and advises during the thesis. We also want to thank the others at GKN that has help us during the thesis. We want to give our sincere thanks to Lennart Josefsson, Professor at Chalmers University for being our examiner and teacher. Last but not least, we like to thank our families and friends for all their support and always being there for us.

Martin and Niklas
Trollhättan, Sweden, 2014

Nomenclature

FC	Fan compressor
FCP	Forward cooling plate
GUI	Graphical user interface
HPC	High preassure compressor
HPT	High preassure turbine
LCF	Low Cycle Fatigue
LE	Life Engine
LPT	Low preassure turbine
LTS	Life Tracking System
NH	High pressure rotor speed
NL	Low pressure rotor speed
OPB	Outer Balance Piston
RFC	Rain-Flow counting
RM12	Engine in the Gripen fighter
SWT	Smith Watson Topper
TMF	Thermo-Mechanical Fatigue
UUID	Universally unique identifier

List of symbols

Symbol	Units	Description
E	MPa	Modulus of elasticity
ϵ	-	Strain
ϵ_a	-	Strain amplitude
ϵ_{pa}	-	Plastic strain amplitude
σ	MPa	Stress
σ_m	MPa	Mean stress
k_t	-	Notch concentration factor
k_σ	-	Stress concentration factor
k_ϵ	-	Strain concentration factor
N_f	-	Number of cycles to fatigue failure
e	-	Nominal strain
S	MPa	Nominal stress
σ'_f	MPa	Fatigue strength coefficient
ϵ'_f	-	Fatigue ductility coefficient
b	-	Fatigue strength exponent
c	-	Fatigue ductility exponent

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1 Introduction

This chapter describes the background to this thesis, the main objectives as well as the limitations. The thesis project was carried out at GKN Aerospace in Trollhättan.

1.1 Background

GKN Aerospace has developed and implemented a life prediction system to follow up the life-span of the RM12 engine which is the engine in the Swedish fighter aircraft JAS 39 Gripen. The system is called Life Tracking System (LTS) and uses registered loads from flown missions to predict the fatigue life consumption. During the development of the system, simplifications in the analyses where made, not fully corresponding to the actual case which creates uncertainties in the accuracy of the results.

The background of this project lies in the investigation of different types of improvements in the thermal and stress FE analyses and evaluate how these effect the life of different engine components in the high pressure turbine (HPT).

Increased accuracy in the analysis could beside change the life prediction also act as an incentive for a lower safety factor. This could in its turn lead to a lower cost for spare parts.

1.2 RM12 engine

The RM12 is based on the F404 engine from which it has been modified to work as a single engine. The RM12 contains 3 fan compressor (FC) stages. After the fan module the air is divided into two large air flows where one fourth is led to the afterburner and the rest is led into the compressor. The air is compressed via a 7 stage high pressure compressor (HPC) and after the fuel has been added and ignited, it expands through a single stage in both the HPT and low pressure turbine (LPT), see Figure 1.1. The HPT and LPT are also powering the FC and HPC. Directly after the HPT comes the afterburner where additional fuel can be added to get extra drag force. Since the JAS 39 Gripen only have one engine it sets extra demands on the reliability of the engine and so far more than 200.000 accumulated flight hours have been flown without a single engine related accident [1].

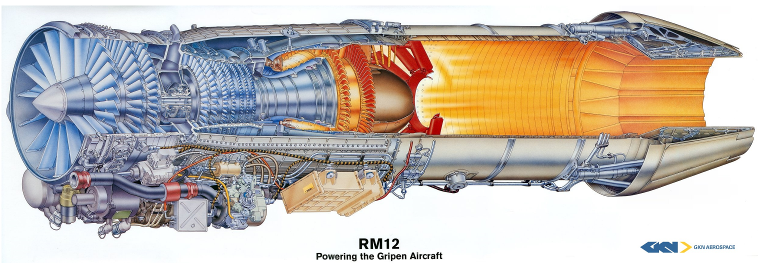


Figure 1.1: *The RM12 engine.*

1.3 Objective

The main objective is the implementation of new methods in the FE-analysis and investigate the effect on the predicted life. The implementations investigated are variable starting temperature, starting stress and ambient temperature as well as strain and temperature behavior between flights and the fatigue damage for several missions as one sequence. By analyzing mission data, an average user profile is determined which is used to weight the results.

1.4 Limitations

The investigation will only be performed on the HPT since it is one of the warmest areas in the engine.

The fatigue damage will only be evaluated for the possibly life limiting points defined by LTS.

There will be no experimental verification of the results.

Fatigue calculations are based on FE-results from an existing FE-model.

2 Theory

This chapter will cover the fatigue theories used by the fatigue model in LTS.

2.1 Fatigue

Fracture due to repeated loading is called fatigue and it is a common cause to failure in e.g. machines or components. Two usually considered fatigue situations are *high-cycle fatigue* (HCF) and *low-cycle fatigue* (LCF). HCF is associated by a relatively large number of cycles with primarily elastic deformations resulting in a long life and a large number of cycles to failure. The other, LCF, is associated with both elastic and plastic strain during a cycle. Therefore the life is relatively short and failure is caused by a relatively small number of cycles.[2]

Temperature changes due to repeated heating and cooling can also cause failure due to fatigue. This is because when the material experience a temperature change there will be thermal expansion or contraction. If there exist any constraints preventing the thermal expansion or contraction, thermal stresses are generated. The constraints can be both external and internal. External constraints could be some type of mounting and internal could be due to a temperature gradient.[3]

In low cycle fatigue, there are usually high loads that will cause some degree of plastic deformation. Particularly at location where stress concentrations exists. It is then more appropriate to consider a strain-based approach for the fatigue life calculations to more accurately capture the effects of the plastic deformation [4].

2.1.1 Strain based approach

For strain based approach a relation between the strain amplitude and the life can be given by.

$$\epsilon_a = \frac{\sigma'_f}{E}(2N_f)^b + \epsilon'_f(2N_f)^c \tag{2.1}$$

To solve life, $\mathrm{N_f}$, for a given strain amplitude you need to iterate using either graphical or numerical iterations [5]. The first part in equation 2.1 correspond to the elastic component of the strain and the second by the plastic component. For lower number of cycles/(LFC) the plastic part till be dominant while for higher numbers of cycles/(HCF) the elastic part will dominate. The relation between the elastic strain and the life is analogues to the Basquin equation suggested in 1910 [5] as.

$$\sigma_a = \sigma'_f(2N_f)^b \tag{2.2}$$

The relation between the plastic strain and the life was suggested as.

$$\epsilon_{pa} = \epsilon'_f(2N_f)^c \tag{2.3}$$

This relationship is known as the Coffin-Manson relation and was proposed in 1960 [5]. The constants σ'_f, b, ϵ'_f and c are material properties that is obtained from fitting test data into a log-log plot. The constant are usually obtained from test evaluated at $N = 0.5N_f$ and thus the use of $2N_f$ in the equations.[4]

2.1.2 Mean stress correction

In the fatigue calculations it is not sufficient to only consider the strain amplitude, the mean stress has to be taken into account. A tensile mean stress will give a higher fatigue damage while a compressive mean stress will give the opposite effect.

When plastic deformations are present, there is likely to be stress relaxation in the material that will reduce the mean stress. Sometimes there exist a stable nonzero mean stress. If that is the case or if the plastic deformation is not large, there will remain some mean stress that can affect the fatigue life.[4]

One approach for mean stress correction is the Smith Watson Topper (SWT) approach. This approach has been used in LTS for the analysis in this thesis project and it is described below.

Smith Watson Topper, SWT

In the SWT approach it is assumed that the life depend on the product of the strain amplitude and the maximum stress for any situation of mean stress.

$$\sigma_{max}\epsilon_a = h''(N_f) \tag{2.4}$$

Where $h''(N_f)$ specifies a function, depending on the number of cycles to fatigue, N_f. The maximum stress is by definition, $\sigma_{max} = \sigma_m + \sigma_a$. Thus the same life could be expected for completely reversed loading as for loading with a mean stress if the product of σ_{max} and ϵ_a has the same value. If multiplying equation 2.1 with $\sigma_{\max}$, where $\sigma_{\max}$ is based on the Basquin equation, Eq. 2.2, you obtain the following equation.[4]

$$\sigma_{max}\epsilon_a = \frac{\left(\sigma'_f\right)^2}{E}(2N_f)^{2b} + \sigma'_f\epsilon'_f(2N_f)^{b+c} \tag{2.5}$$

This can then be used to give a corrected hypothetical life for the mean stress by comparing the value to test results, at a different mean stress. The SWT approach gives reasonably accurate results for a wide range of materials.[4]

2.1.3 Palmgren-Miner Rule

A method to determine the damage when having a variable amplitude loading is the *Palmgren-Miner* rule of linear damage. It states that failure is expected when the sum of all damage fractions is 1. The damage fractions are the damage done by each cycle that is identified. The identification of the cycles could be done using for example *Rain flow counting*, see Chapter 2.1.4. The damage done during the cycle is the inverse hypothetical life that could be expected if only exposed repeatedly to this cycle. The total damage done by the sequence can be expressed as.

$$\sum_{j=1}^{k} \frac{1}{N_j} \tag{2.6}$$

here k is the number of cycles that was identified and N_j is the hypothetical life for respective cycle. The order in which the cycles are occurring is assumed not to affect the damage in the Palmgren-Miner rule.[4]

2.1.4 Rain-Flow counting

One method to identify cycles in an irregular sequence is called *Rain flow counting*. It uses the peaks and valleys in the irregular time history as direction of the loading change. The sequence is assumed to be repeatedly applied and for the counting it is suitable to rearrange the sequence so it starts and ends at the highest peak or the lowest valley. The sequence is then searched and a cycle is counted when the stress range of the consecutive peak and valley, $\Delta\sigma_{BC}$, is bigger or equal than the former stress range, $\Delta\sigma_{AB}$, see Figure 2.1. When a cycle is counted the stress range, $\Delta\sigma$, and mean stress, σ_m, is recorded. If temperature is of importance in the calculations, it could also be recorded. The former peak and valley is then assumed not to exist for further cycle counting and the search starts from the beginning. This procedure is repeated until the global cycle is recorded.[6]

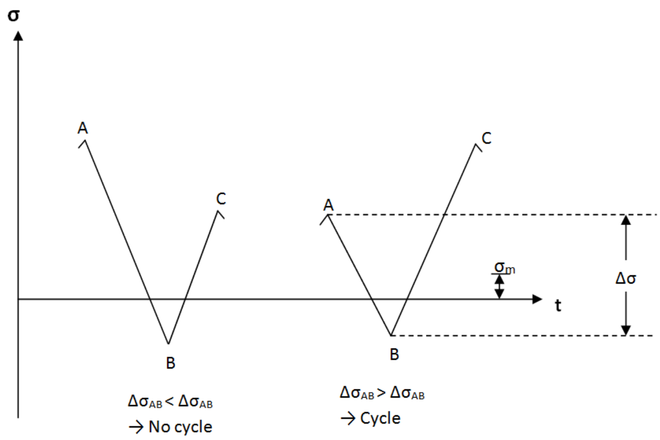


Figure 2.1: *Example of the condition for a cycle using Rain-Flow counting.*

2.1.5 Stress correction

Instead of performing elastic-plastic FE-analysis, correction can be done on the linear elastic results to estimate the notch stress and strain during the plastic deformation. One commonly used rule for correction of the plastic deformation is the *Neuber* rule. It is used together with a stress-strain curve of the material, to estimate the stress and strain at the notch. When there is a considerable amount of plastic deformation, it is still however, preferable to use elastic-plastic FE-analysis. This requires a more complicated elastic-plastic strain-stress relationship that is harder to implement and the analysis take more time compared to a linear-elastic analysis.

Neuber's rule

During elastic loading the ratio between the maximum stress and the nominal stress is equal to the ratio between the maximum strain and the nominal strain and they are both equal to the notch concentration factor, k_t. When plastic deformation begins at the notch, the ratio between the stress at the notch and the nominal stress become less than k_t. While the ratio between the maximum and nominal strain becomes larger than k_t. These ratios are called stress and strain concentration factors and they are defined as.

$$k_\sigma = \frac{\sigma}{S}, \quad k_\epsilon = \frac{\epsilon}{e} \tag{2.7}$$

where σ and ϵ are stress and strain and e is the nominal strain corresponding to the nominal stress S.[4] During plastic deformation Neuber's rule states that the geometric mean of the stress and strain concentrations factors remains equal to k_t.

$$\sqrt{k_\sigma k_\epsilon} = k_t \tag{2.8}$$

If you do not have fully plastic yielding the nominal strain can be expressed as $e = S/E$ [4] which gives.

$$\sigma\epsilon = \frac{(k_t S)^2}{E} = \text{constant} \tag{2.9}$$

The corrected stress and strain is obtained by taking the intersection of the stress-strain curve and the hyperbola created by the Neuber rule. Using the maximum nominal stress S_{max}, will result in the maximum stress, σ_{max}, and strain, ϵ_{max}, which correspond to point A in Figure 2.2. To get a correction of the minimum stress and strain, Neuber's rule can be applied to the range of the stress, strain and nominal stress, giving equation 2.10. It is used together with a stress-strain curve for the unloading.

$$\Delta\sigma\Delta\epsilon = \frac{(k_t \Delta S)^2}{E} = \text{constant} \tag{2.10}$$

The intersection of this hyperbola and the stress-strain curve for the unloading, see point B in Figure 2.2, gives the changes in stress and strain. Here point A is now taken as origin. The minimum can then be calculated, using the maximum value together with the stress and strain range.

$$\sigma_{\min} = \sigma_{\max} - \Delta\sigma, \quad \Delta\epsilon_{\min} = \epsilon_{\max} - \Delta\epsilon \tag{2.11}$$

Usually Neuber's rule tend to overestimate the strain, except for fully plastic yielding where the strain will be underestimated [4].

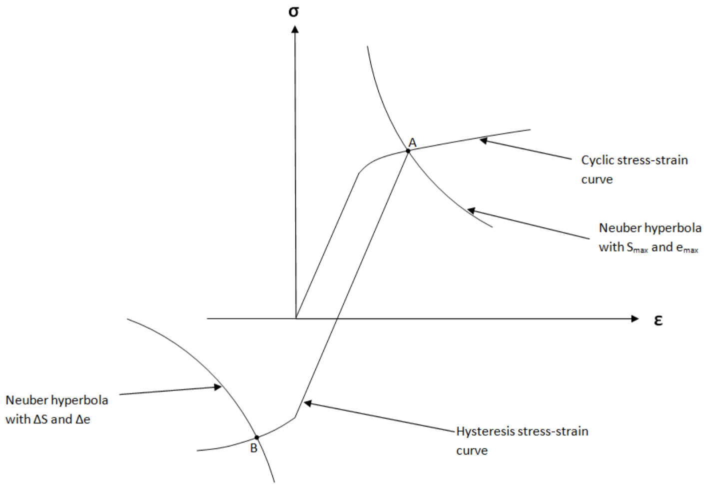


Figure 2.2: *Illustration of Neuber's rule.*

2.1.6 Fatigue measurement

Generally you obtain multi-axial results from the calculations while when performing material test the tests are often of uni-axial nature. It is therefore necessary to transform the multi-axial stresses/strains to something that is comparable to the uni-axial test data. The one that is used in LTS for this thesis is described below.

Maximum principal strain hypothesis

In the maximum principal strain hypothesis the principal strain that shows the largest strain range during a cycle is chosen as fatigue measure. That is to say that the most critical direction, during the cycle, is assumed to be the direction associated with largest principal strain range.

3 System description

This chapters cover some introduction to LTS and describe the system structure to give a better knowledge before the method chapter.

3.1 Life tracking system for the RM12

To perform the life simulations on the RM12, LTS was used. LTS uses registered data from flown missions and evaluates the life consumption of each component by calculating for a number of critical locations. The registered data, called mission data, contains the most important engine parameters as well as load data from the flown mission. One advantage of this compared to before when the consumption was only dependent upon the High Pressure rotor speed and a predefined usage profile is that LTS predict the life consumption independent of the mission profile. LTS consists of three subsystems, Pre-LTS, LTS-System and Life Engine (LE), see Figure 3.1. In addition there is also Life Management which is the project where valid life analysis models are developed.[7]

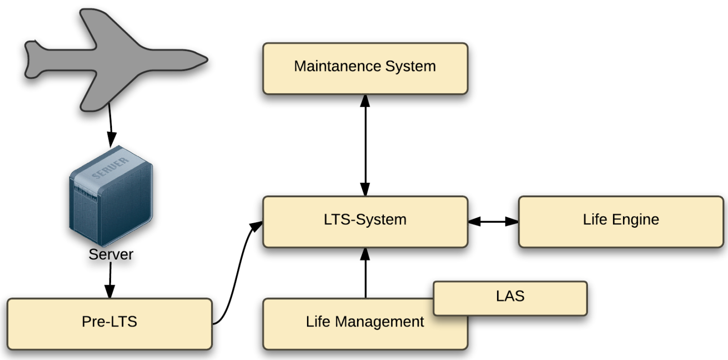


Figure 3.1: *Overview of LTS.*

Pre-LTS

The non-filtered load data from the aircraft is first sent to Pre-LTS. Here it is checked for errors and filtered so that all classified data is removed. When the information is filtered the mission load data files are complemented with information from the Steady State data creator (SSDC). The SSDC have calculated all the unmeasured steady state conditions in the engine based on a possible flight mixture of the RM12.

LTS-System

In the LTS-System, each part mounted in the specific engine are matched with the stored mission data. The LTS then initiates a task to LE, which calculates the life consumption of the engine parts. The life consumption data are then periodically sent to the Maintenance system which keep track of the life consumption of all components.

Life Engine

LE is a fully automatic life analysis flow. It enables the possibility to predict the life consumption for all the life limiting parts of the RM12 engine. Currently the only implemented failure mode in LE is the Low Cycle Fatigue Crack Initiation. To calculate this, LE uses the in-house software CUMFAT to predict the life consumption for each mission based on the stress and temperature time histories. To calculate the damage, CUMFAT uses the Palmgren Miner rule and Coffin-Manson and add all mission contribution together.

The stress and temperature histories are calculated in different ways depending on whether the thermal stresses can be neglected or not. Since the focus for this thesis have been the HPT, the thermal stresses have to be taken into account. To do this the software ANSYS is used, and the loads are implemented using the in-house software FE-loads. The version of FE-loads used in this project is 3.12.

Life Analysis System

Life Analysis System (LAS) is a GUI to LE and can be seen as a supportive program that connects the underlying programs in the analysis. In LAS it is possible to construct each part of the analysis path for a desired analysis model, identify the life limiting location and calculate the predicted life for to a specific mission.

3.2 The FE model used by LTS

The analysis was performed using FE-model 1.2.14 and LTS configuration 4.10.122, which was the latest released versions when the thesis project started. How the LTS-configuration interact with LE is seen in Figure 3.2.

3.2.1 LTS Inputfiles

The input data used are divided into synthetic mix data and mission data. The raw mission data that comes from the plane are constructed in a similar way as the synthetic data, which is that the time steps decrease in length when the gradients of the ingoing data are large. In this thesis project, the wc20ts3 format is used where the raw data has been filtered into one time step every three seconds, see example in table 3.1. This filtering is used to shorten the analysis time when the dense data is not essential and is performed by using interpolation of the closest data points.

The mission data files are divided into two types, real missions or synthetic created ones. In the report they will be denoted missions or synthetic missions depending on what type it is referred to. The missions are then divided into two types, flight and ground missions. The ground missions are usually short and could for example consist of idle running on the platform.

Table 3.1: Data filtering from raw to wc20ts3 format.

Raw format [s]		wc20ts3 format [s]
180.0000	$\longrightarrow$	180.0000
180.2670		183.0000
180.9330		186.0000
181.2000		
182.5330		
183.7330		
185.4670		
187.0670		

When the loads are recorded during a mission, each time point is given a case number that represent the state that the engine had. These case numbers are then used by FE-loads to construct a ANSYS load data file.

3.2.2 LTS-configuration

The LTS configuration is read when starting LAS and it control how the analysis should be performed. It consists of several files where the ones below are the files and parameters that have relevance for this thesis.

area.xml:

In the area.xml file the critical areas are assigned with a universally unique identifier (UUID). To each area information used in the fatigue analysis are defined. This could be the selected critical node for the area, how to handle the material model, mean stress correction and what fatigue criterion used. Here you also define if ANSYS should be used or if you can do mechanical scaling of the stresses.

If analyzing a mission you can control whether a rollout point should be added after the last calculated time step. Since the recordings stops when the engine is shut off, you could add this point to capture the behavior afterwards. Stress and temperature values for these points comes from the synthetic missions where the worst case for each area have been extracted.

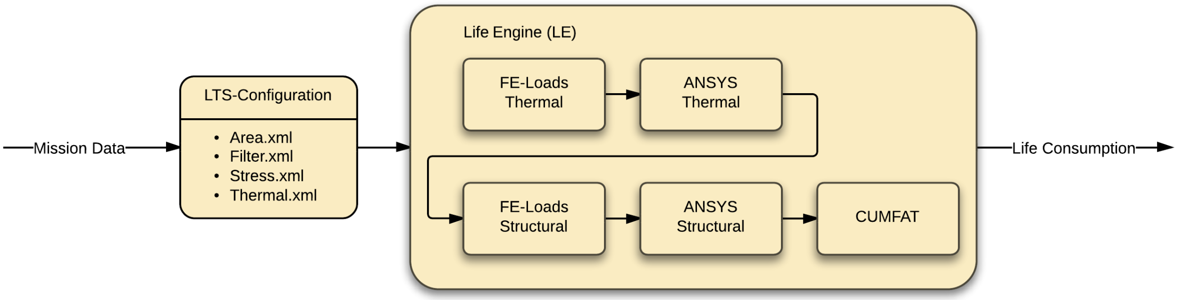


Figure 3.2: *The interaction between the LTS-configuration and LE.*

filter.xml:

The filter.xml file are only used for the synthetic missions and it identifies the type of synthetic data. Types can be raw, synthetic or synthetic finestart. For the synthetic missions, instead of a single rollout point you instead define a rollout time. A script then creates additional load steps after the mission corresponding to this time. The added load steps are dense in the beginning of the rollout and become sparser over time since the gradients stagnate over time.

stress.xml and thermal.xml:

The thermal.xml and stress.xml files controls what version of the FE-model that is used for the analysis.

3.2.3 FE-model

The model used for the analysis is a combined 2D/3D hybrid model, see Figure 3.3 where most is constructed as 2D axisymmetric with relatively coarse mesh. Based on the 3D part of the hybrid model there also is a submodel with a finer mesh. For the most critical areas of this submodel there are additional submodels. However the time to analyze these submodels with ANSYS are very long and instead scaling factors are used between the coarser mesh and the finer mesh. The scale factors projects the stress state from the coarser mesh onto the finer mesh. Loads applied can be divided into two parts, thermal and mechanical loads. When performing the thermal analysis it is possible to use a coarser mesh without loosing accuracy in the results.

This is not possible for the stress analysis where a much finer mesh is needed. To be able to apply the thermal loads from the thermal analysis, these are interpolated in both time and space.

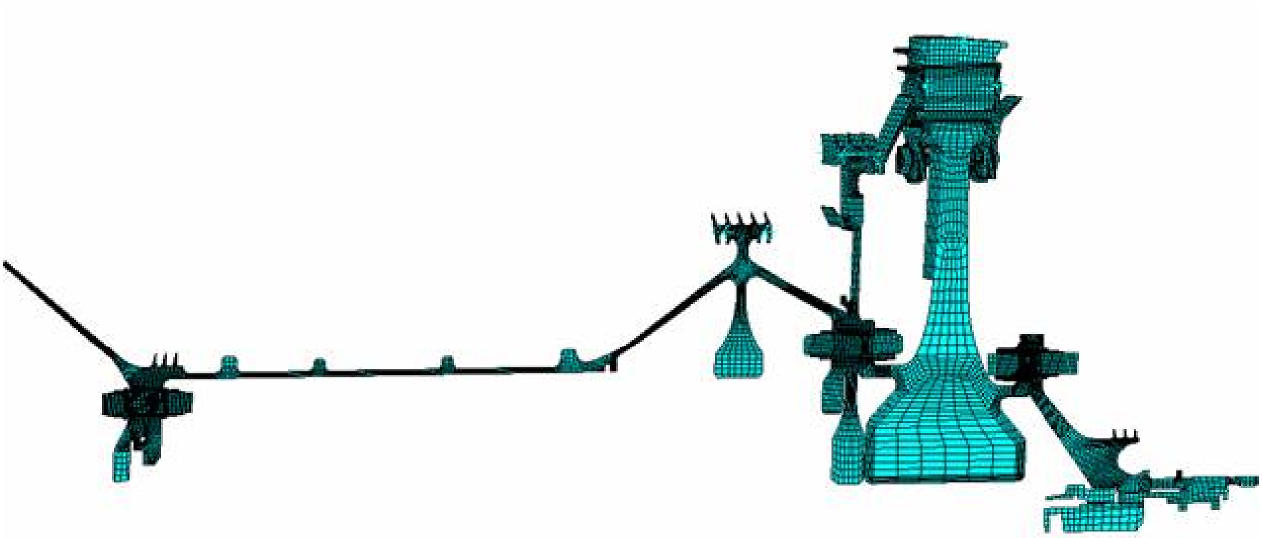


Figure 3.3: *The 2D/3D hybrid model of the HPT.*

This model contains 21380 nodes and 16690 elements where some of the nodes have a coupled dependence. A coupled dependence means that a node acts as a slave node and get it properties from another node, could be if they have almost coinciding coordinates

Before the thermal analysis starts the loads are created by the use of the in-house software FE-loads. FE-loads create the loads based on the mission file and these are then implemented in ANSYS. The ANSYS analysis is controlled by .ans files, one for the thermal- and one for the stress analysis, both named start.ans, see Figure 3.6.

3.2.4 Points that are investigated

The points that are investigated are determined in advance in the Life Management program. Six components in the HPT are investigated, shown in Figure 3.4. Each component are evaluated at one or more critical locations that could be limiting for the fatigue life, referred to as areas. A total of 16 areas will be evaluated and these can be seen in Table 5.2.

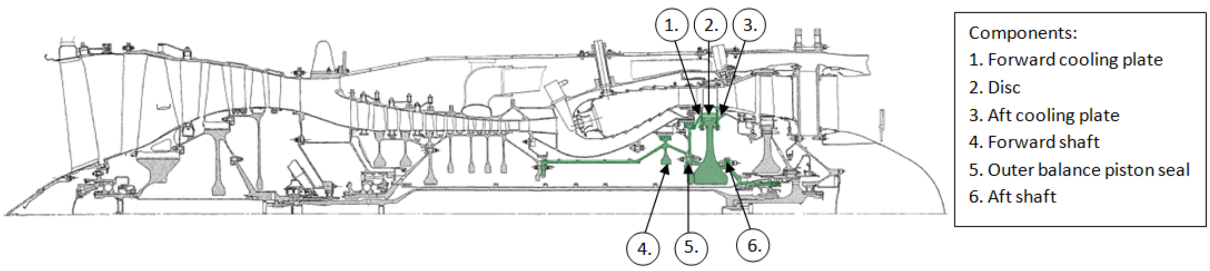


Figure 3.4: *Evaluated components in the HPT.*

3.2.5 Material data

The material data used is classified and can not be presented in detail. Still, it can be seen that the correlation between what life is achieved for a specific temperature and strain level is not always consistent, shown in Figure 3.5. The material properties change for different strain levels and temperatures. Up to a certain point the life improves for an increased temperature but at a certain level it decreases and instead give a shorter life. This type of behavior also varies for different strain levels which makes it hard to predict when analysing missions.

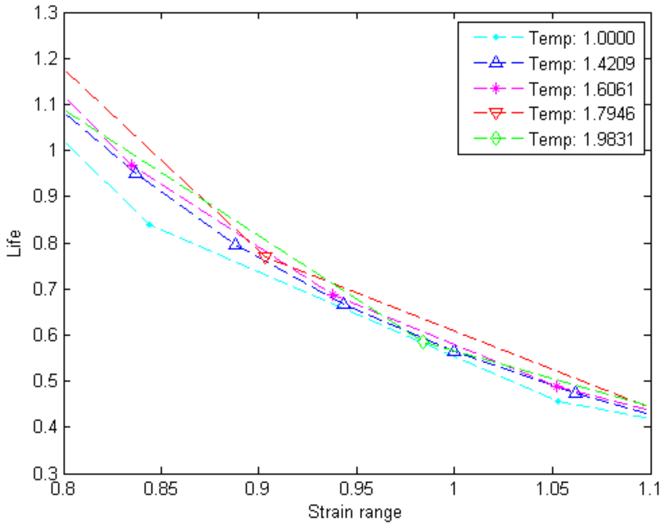


Figure 3.5: *Material properties change depending on the temperature and strain range. The values has been normalized.*

3.2.6 CUMFAT

CUMFAT is the in-house program used to calculate the fatigue damage based on the thermal and stress histories, see Figure 3.6. The figure shows the different steps in the fatigue calculations.

From the FE-analysis you obtain a multi-axial stress field. Since most of the test data for the material is uni-axial, the multi-axial stress field must be converted to be comparable with the test data. CUMFAT has four different options for handling the multi-axial stress field. In this thesis project, linear-elastic analysis with plastic correction and as fatigue measurement method, maximum principal strain, see Chapter 2.1.6, is used. In CUMFAT it is assumed that the largest absolute value of the principal strain is the most dangerous when considering fatigue. The direction corresponding to that principal strain is the critical direction. This direction is then used for the whole loading history, and the principal strains for each cycle is projected onto this direction.

The principal strains have the same direction as the principal stresses in the linear elastic case. The strain range can then be calculated by dividing the difference between the maximum and minimum stress with the elastic modulus. Mean stress is calculated by dividing the maximum plus the minimum stress by two.

To identify the cycles the Rain-Flow counting method is used, see Chapter 2.1.4 together with the stress or strain results. Before the cycle counting, the data is searched for consecutive data points that do not create a *peak* or a *valley*, which are then removed. Data points that are exactly the same as the previous data point is also removed. Now the sequence only consist of points that causes turning points in the load history. When finding a cycle CUMFAT records the mean stress, the stress range as well as the temperatures at the peak and

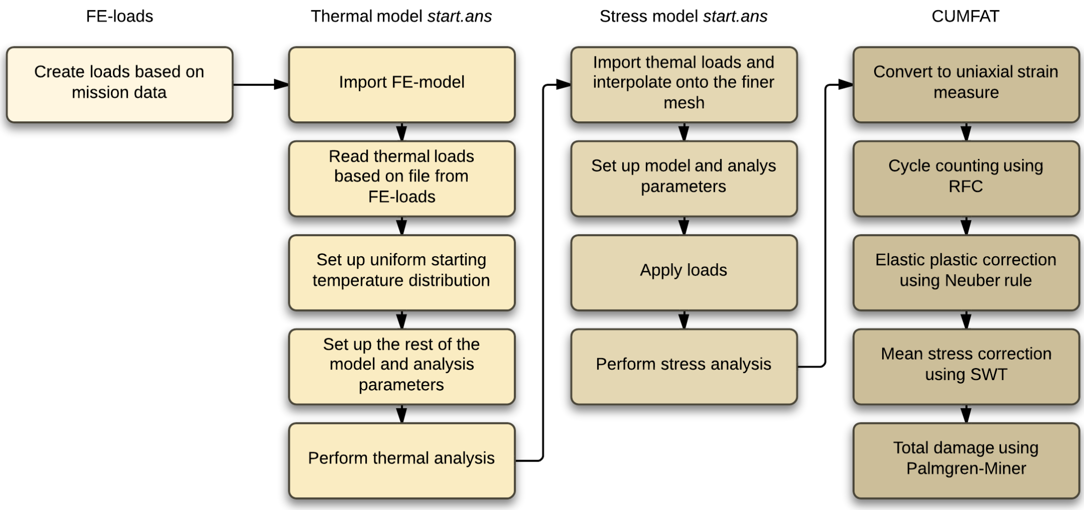


Figure 3.6: *Solution procedure when using ANSYS in LTS.*

valley.

CUMFAT can use FE-results from both linear elastic and elastic plastic analyses. When working with linear elastic results in CUMFAT, an elastic plastic correction is done, in this thesis by using the Neuber rule, Eq. 2.9. The highest temperature during the cycle is used with the material data when performing the correction of the stress and strain. Though when working with considerable plastic deformation it is preferable to use elastic-plastic FE-analysis.

To capture the effects of mean stress three hypotheses are available and the one used for the calculations is the SWT-approach, see Chapter 2.1.2. From the SWT-approach you obtain a value that could be used with adjusted test data to get the hypothetical life. The value is compared with test data at the maximum, minimum and mean temperature for the cycle. From this, three hypothetical life until crack initiation is obtained in number of cycles. The worst case of these is taken as the hypothetical life for the cycle. If test data do not exist for the exact temperatures, interpolation is done to get more relevant fatigue data.

The fatigue damage is estimated by the Palmgren-Miner rule, 2.6 using the cycles identified by the Rain-Flow counting and after all corrections has been done.

For a for more detailed description on how CUMFAT performs the different stages in the fatigue calculation see the internal CUMFAT manual [8].

4 Method

To evaluate the effect on the predicted life of the different implementations, a number of missions were analysed. After a suitable set of missions had been chosen, the method changes were implemented and evaluated one by one to get the individual effect of each change. In this section implementation, as well as the mission selection is covered.

4.1 Analysing mission data and choosing missions

Since the analyses were lengthy in time, each implementation could only be evaluated for a limited number of missions. The missions where chosen to capture different types of usage regarding the aspects time between flights, ground mission interaction and mission length.

To be able to draw conclusions about the overall life change based on the analysed missions, usage profiles for different engines, used under different circumstances where assembled. By looking at the flight missions regarding flights per day and time between missions an average profile could be determined. Data regarding number and length of ground missions were taken from an already performed internal compilation. To this, additional statistics about how many days that start with ground missions, or have one between two flights, was compiled.

Data for different engines were taken randomly except for one engine that is known to be a pre-fleet engine. This is done to see if the pre-fleet engine has a different usage profile. Pre-fleet engines were taken into use before the great majority of engines and they are taken back regularly for careful investigation to be able to detect errors and defects early.

4.2 Implementations in LTS

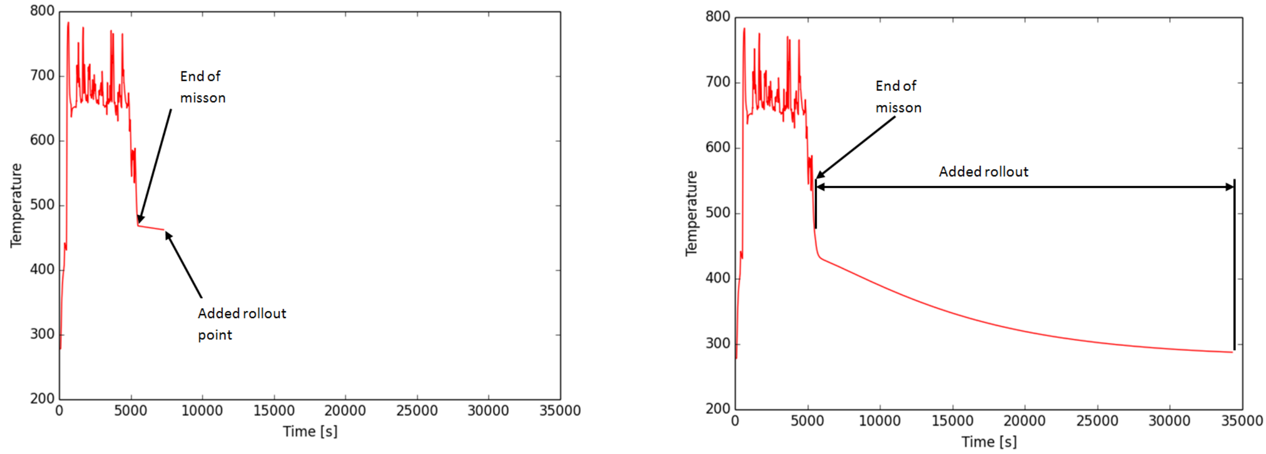
The existing FE-models were executed using ANSYS 14.0 APDL scripting. The new methods were implemented by modifying and adding parts to the existing method covered in Chapter 3.2 together with some created supporting scripts.

4.2.1 Rollout effect

In LTS there is a significant difference how the the program handles the time after the last registered load step for synthetic- and missions. For a synthetic mission, a number of load steps with case 0 are added after the engine is shut off. How long time that is added is controlled via the *filter.xml* file. For the missions however, instead of using case 0 one extra load step is added after the mission has ended. The values for these points are based on the analysis of synthetic missions and is fixed for each different area regardless of the last calculated time point, see Figure 4.1(a).

Verification of the rollout function compared to experimental data can be seen in the internal report [9].

To implement a rollout effect on the missions, first an analysis of the synthetic m69 mission with a 8 hour long rollout was done. Data files from this analysis was then used when analysing the missions. The implementation in LTS was done by manually changing the thermal and stress model *start.ans* files. After all the mission load steps had been solved, the variables was cleared and the *rollout.dat* data file from the synthetic m69 mission was read. This file contains the loads and boundary conditions. By continue solving from the time step in the synthetic mission where the rollout started, the rollout effect were added to the mission, see Figure 4.1(b). The



(a) Fixed rollout point. (b) Calculated rollout.

Figure 4.1: *Difference between the fixed point and the calculated rollout for one of the critical areas.*

last point that was added in the old method was now excluded by changing the settings for each area in the *area.xml* file.

The length of the rollout after the mission were controlled via how many extra load steps that were added, see table 4.1.

The chosen maximum rollout time was set to 8 hours because the temperature have more or less returned to the original state and the stress state for any area are barely effected by a longer rollout. The small changes that might occur after this time were assumed negligible.

4.2.2 Variable starting temperature

To implement a variable engine starting temperature in the model, the thermal *start.ans* file was modified so that the temperature was based on an input file, rather that just an uniform temperature distribution. This input file was created by an *output* command after the thermal analysis was solved, combined with the *prns* command that writes the nodal temperature solutions. To exclude all header information for the *prns*, a command that removed all headers was implemented. With the constructed python script (1), see Appendix A, an input file was created, the coupled slave nodes were deleted and each node value were combined with a D-command. The D-command in ANSYS APDL will constraint the temperatures to the nodes when reading the input file.

Table 4.1: Example of how different number of time points give different rollout time.

Added time points	Added rollout time [min]
33	15
36	24
39	37
40	42
43	58
63	165
70	240
81	360
93	480

Rollout and variable starting temperature in LTS-system

In addition to the manual way in LAS, where each simulation, for a specific day, had to be manually started after the previous a more automated method was created for the LTS-system. The flowchart for the script can be seen in Figure 4.2. By adding all mission data files for the day that should be analysed to the mission folder and then run a python script (2), see Appendix A, all necessary files and folders are created together with a batch *.sh* file. When run, this file creates the needed temperature and rollout files for the missions and start each subsequent simulation when the previous is finished. It also set the logger path to a chosen destination defined in the python script. By running this file, the LTS-system will analyse the missions in sequence without any further manual interaction needed. The downside with this was that the cluster could not be used together with this script so it had to be run locally on a computer which limited the number of simultaneous analyses.

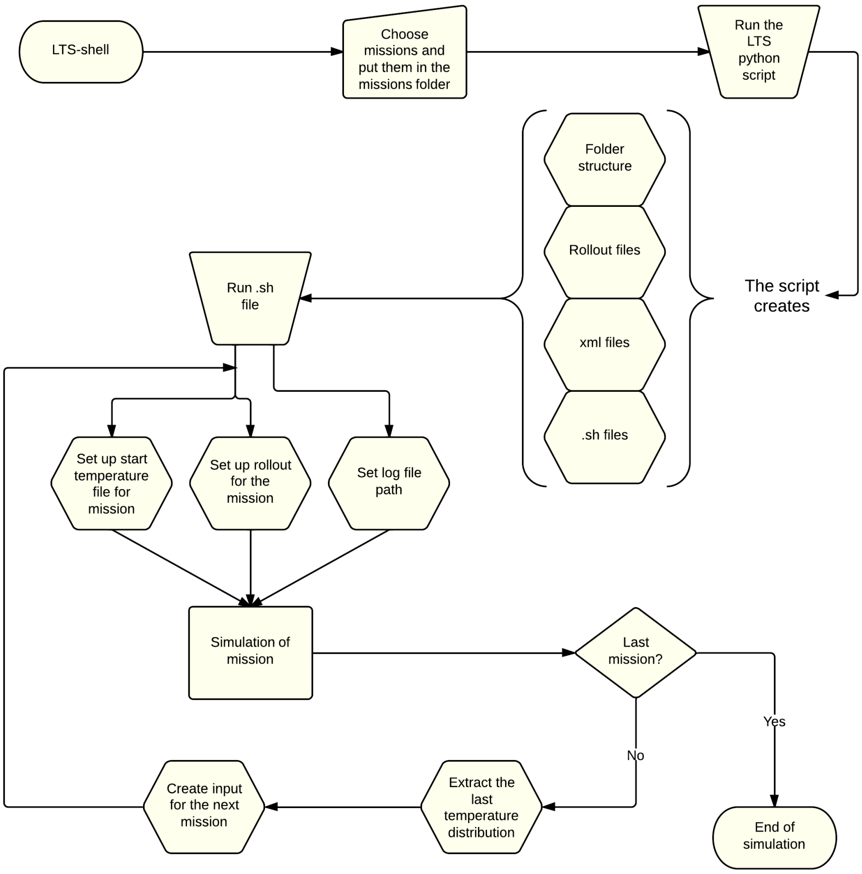


Figure 4.2: *Flowchart of how the analysis is done, using the script with LTS-system.*

4.2.3 Changing ambient temperature

The main goal of this method change was to see how a variable ambient temperature during the time between flights could affect the life of the components. Since the Jas 39 Gripen are used globally, planes could have various life consumption based on the ambient temperature where they are used. The evaluation of the ambient temperature effect was performed for 253K and 303K, compared to the Nordic median of 278K that has been used for all analyses. The chosen upper temperature was based on the fact that the plane operates in warmer climates e.g. Thailand, where the average temperature is around 303K. Based on this value, 253K was chosen as the lower limit since equal temperature differences give more perspicuous results.

The implementation was performed by using the *m69.tbl* file from the previous analysis with 8 hours rollout. FE-loads uses this file when creating the *ansys_data.dat* file, containing the boundary conditions for the analysis.

In the *m69.tbl* file the temperature for all case 0 during the rollout was changed from 278K to first 253K and then 303K. FE-loads was manually run with the changed *.tbl* files to generate the new *ansys_data.dat* files. To perform the synthetic m69 analysis with different ambient temperature, the thermal model *start.ans* was altered to call for the new files instead of the one that FE-loads create during the analysis. The Figure 4.3 show how the temperature during the rollout differs between the different ambient temperatures

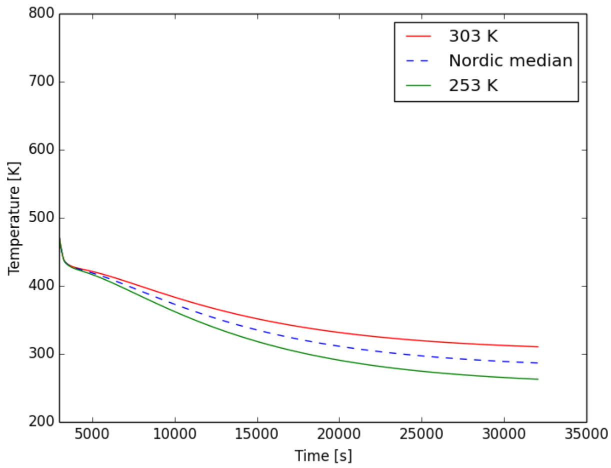


Figure 4.3: *The rollout for different ambient temperatures in the changed synthetic mission m69.*

The implementation for missions was done in the same way as in Chapter 4.2.1, with the only change that the *ansys_data.dat* for the rollout was changed. When analysing missions, consideration was not taken to the actual ambient temperature for the missions. This was because analysing the same missions, with different rollout temperatures, gave a good evaluation of the effect.

4.2.4 A whole day as one fatigue sequence

When calculating the fatigue for each mission separately instead of performing a rain flow count for the whole day you risk missing a larger stress cycle. This could happen if you have the lowest stress measure during one mission and the highest during another, see Figure 4.4. To see if this was the case and if it was worth taking into account the stress histories in the *ansysjob.cns* for all missions during one day where combined into one file. This was accomplished with a python script, see script (3) in Appendix A. The merged file was then analysed with CUMFAT through LAS to get the damage contributions. To exclude the ANSYS analysis in LAS and only perform the fatigue analysis in CUMFAT the setting stress method was changed for each HPT area in *area.xml* from ansys to import. The merged cns file could then be loaded and analysed from the mission folder.

4.2.5 Variable starting stress

When analysing the results from the variable starting temperature, it was seen that due to nonlinear behavior due to friction, there occurred residual stresses in some of the contact points. Because of this, the stress state didn't return to the state it started from. The variable starting temperature implementation transfer the thermal loads but not the residual stresses so there became a gap in the stress between two different missions, see Figure 4.5. By using this method, each new analysis uses the start state of a new engine which has been found very conservative for some of the areas.

To eliminate the gap in the stress state between missions during one day, the method in ANSYS, restarting from a previous analysis was used. This is often used if a simulation crashes and one don't want to restart the simulation from the beginning but rather start from the place where it crashed. For this specific case the aim

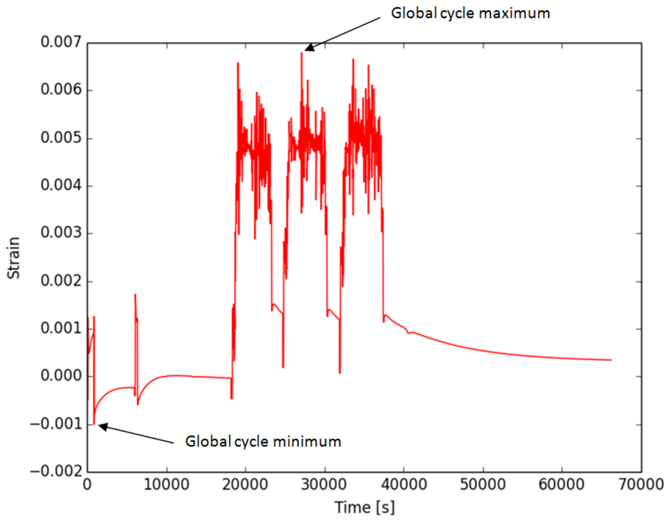


Figure 4.4: *Merging the missions for one day into one sequence creates a larger global cycle.*

was instead to restart from the last load step in the previous analysis and then continue with the load steps from the consecutive mission. By starting the next mission based on the ending stresses and strains of the previous, continuity was created, resulting in a smaller strain range for some of the large fatigue cycles. The

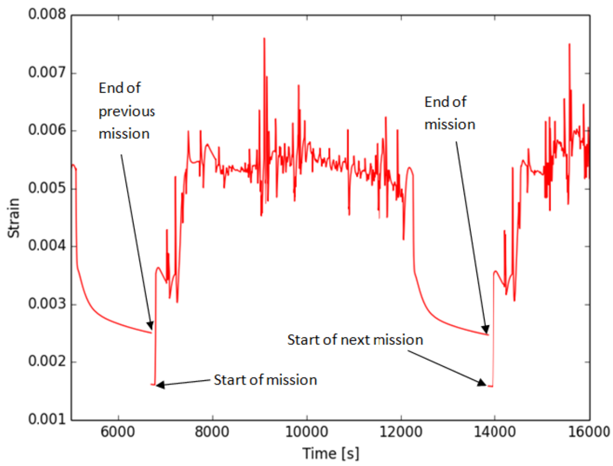


Figure 4.5: *The gap between missions due to residual stresses.*

implementation was done through modifications of the *start.ans* file for the stress model. First the program checks if it is the first mission of the day. If so, run the program as normal with only exception that the command *RESCONTROL* is implemented. This command activates the saving of the *ansysjob.rdb*, *ansysjob.ldhi* and *ansysjob.Rnnn* files that are needed to perform a restart. If it is a consecutive mission the program instead perform a restart using the command *ANSTYPE,,rest*. When calling this command ANSYS will perform the following actions:

- Resume using the database *ansysjob.rdb*.
- Rebuild the loading and boundary conditions from the *ansysjob.ldhi* file.
- Rebuild the ANSYS solution commands and status from the *ansysjob.Rnnn* file.

For the restart, the files *ansysjob.cns*, *ansysjob.db* and ansysjob.rst from the previous analysis was also needed. The *ansysjob.cns* file allowed to keep the previous results and continuously add load steps to the result file. This gives a total result file for all missions analysed in sequence. After the restart is performed the program clear all scalar variables except the ones that is user defined and reload the *ansys_data.dat* file containing the loads and boundary conditions for the current mission that should be analysed. The analysis is then performed as before but with the difference that the start state is based on the last state of the previous analysis. To match the start time with the previous missions end time, a new time shift variable was introduced that contains the last time step of the previous mission. This variable is read from a input file and after each analysis the updated time shift is written to the file.

Stress restart in LTS-shell

The implementation of the stress restart method in the LTS-script was performed by adding some new commands into the LTS-shell .sh control file, see Figure 4.6.

- Copy input file containing variable that are controlling the restart to analysis directory.
- Copy file containing the time shift variable with the time for the last time step for the previous mission.
- Move all restart files necessary from the previous analysis to the current analysis directory.

This way automatically implement the method described in Chapter 4.2.4. Since each mission was added after the previous, the results from the last mission contained the total fatigue damage for the hole day seen as one sequence.

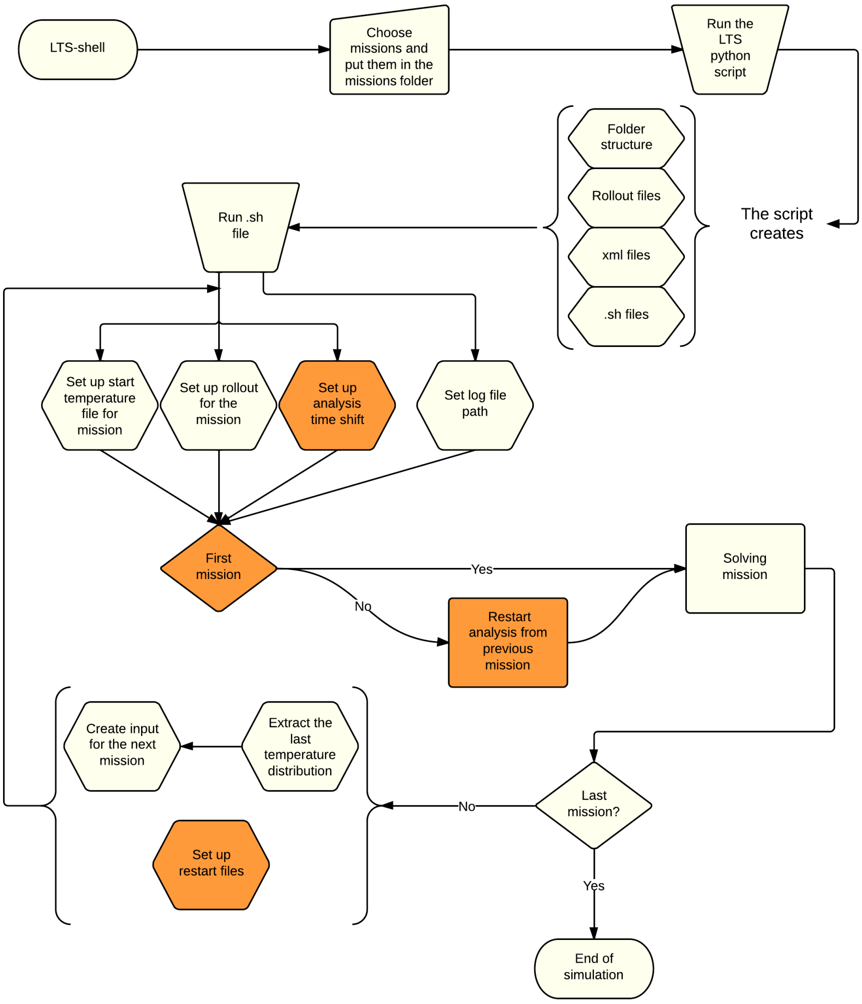


Figure 4.6: *Flowchart of how to do the stress-restart analysis using the script and LTS-system. New boxes are marked in orange.*

5 Results and discussions

The results are organized in the same way as in the method chapter. Implementations are presented and analysed one by one and finally, the total difference in life are compared to the old method. Results will often be divided into limiting and non limiting areas, since the life of the component depends on its limiting area. This limiting area for a component can change between missions but was in this thesis always constant for the average results of all the implementations.

5.1 Mission data

The total average number of missions per day for the investigated engines are 2.25 missions/day. Regarding the time between missions, more than one flight per day will in average be flown, within a time frame where significant interaction regarding temperatures and stresses occur.

In addition to the overall profile, data for two individuals was compiled. One of the engines, noted as E101, is a pre-fleet engine and has a higher average number of flights per day than the others. With an average of 2.65/day and a higher percentage flown within one hour, this results in a higher influence from mission interaction effects. This was suspected since the injunction is that a pre-fleet engine should be used more than the regular engines. In comparison to the pre-fleet engine there is also engines with less usage. The engine that was found to have the lowest usage, noted as E102, has an average of 1.74 flights per day and less percentage flown within one hour. The differences between flight profiles are important since the engines will get different results from some of the implementations based on its profile.

To be able to properly weight the results, regarding the effect of ground missions, two complementing summaries to the the internal material was done. This material covered the number and length of the ground missions but did not take into account when they occurred. For example, if a ground mission is before a flight mission, it could heat the engine, depending on how close to the flight that it occurs. If it is between missions, it could possibly either cool or heat depending on the circumstances. To cover this, two compilations were done. Regarding how many days that started with a ground mission it was found that this occurred for 16% of the analysed data. It was also found that almost twice the days had one or several of occurrences where a ground mission was between two flight missions.

The missions that were analysed are from the E101 database and can be seen in Table 5.1. They are mainly chosen to cover different circumstances rather than to represent the average profile. This could be the duration, time between missions and different set-up between flight and ground missions. Achieved results from these missions can be weighted versus the average profile to get the estimated overall change in life. To only use missions from the E101 database was because only this data was accessible in the beginning of the project. How the results would change if a mix of mission from different engines would have been used is not evaluated in the thesis.

5.2 Fatigue analysis

The results for the implementations will be presented as an average of the analysed missions. In addition to the average results the deviations will be presented by the maximum and minimum values. Finally the achieved results are weighted versus the overall usage profile to get an estimate of the actual change.

The average results are achieved from the percentage life change of the concerned missions. Another way is to take the average of the damage. This would lead to that missions with a higher life consumption will have a higher effect on the average results. Since the thesis do not cover any conclusions that link changed life to the amount of damage on a specific area, this was not considered suitable. Compared to using the average of the

Table 5.1: Chosen missions to analyse.

Mission number	Date and start time [YYYYMMDD hhmmss]	Type	Length [min]	Time to previous flight mission [h]
1	19970109 091948	flight	54,7	8+
2	19970109 105056	ground	5,8	
3	19970109 110947	flight	56,2	<1
4	20080915 064823	flight	68,4	8+
5	20080915 120935	flight	73,2	4<5
6	20090224 172151	flight	72,8	8+
7	20090224 193016	ground	5,5	
8	20090224 204827	flight	72	2<3
9	20101124 114446	ground	12,4	
10	20101124 131753	ground	4,4	
11	20101124 163338	flight	82,3	8+
12	20101124 182335	flight	91,0	<1
13	20101124 202657	flight	89,9	<1
14	20130311 105138	ground	13,4	
15	20130311 111656	flight	173,5	8+
16	20130311 174527	flight	106,3	3<4
17	20130506 082226	flight	84,1	8+
18	20130506 102210	flight	71,4	<1
19	20130506 120536	flight	74,1	<1

damage was however found to give maximum a couple percent in difference, but is still believed to give a better result when only a few missions are analysed.

From the fatigue data, it was noted that for most cases, the damage is mainly driven by the global cycle. This is because the uni-axial strain characteristics for most areas is that it starts and ends at low value. During the missions the mean strain increases but the amplitude for each cycle is relatively small compared to the global, leading to a small damage contribution.

Besides change of the global cycle, some changes in life was found to be related to the material properties at different temperatures. In Chapter 3.2.6, it is stated that CUMFAT use the worst case temperature for the cycle. It was found that both longer and shorter life could be achieved for an increased temperature. Because the material data are not consistent, see Chapter 3.2.5, it is hard to predict and draw good conclusions for life changes related to this.

In some cases the results showed slightly unpredictable and non realistic behavior, mainly during the rollout. The effect is noted as a non realistic temporary change in the strain levels, often for a single time step. This could occur due to the convergence criteria is in some cases not set strict enough so that several solutions could be found in the FE-analysis. Knowledge about this was achieved from an internal investigation. The effect was rather small and is not believed to have any significant effect on the results.

The results are assumed to be reasonable since they are based on the existing calibrated model. Results will be presented for each area via an individual number, see table 5.2 where the location of the components can be found in Figure 3.4. The individual results for the missions are listed in Appendix B, together with summarizing results for each implementation.

5.2.1 Rollout effect

When the stress state was calculated instead of using a fixed point, it is seen that it for most areas had an impact on the fatigue life. The points added in the old method where based on the worst case found for

Table 5.2: The area numbering.

Number	Area
1	Aft CP - 1
2	FCP - 1
3	FCP - 2
4	FCP - 3
5	Disc - 1
6	Disc - 2
7	Disc - 3
8	Disc - 4
9	Disc - 5
10	Disc - 6
11	Aft Shaft - 1
12	Forward shaft - 1
13	Forward shaft - 2
14	OPB seal - 1
15	OPB seal - 2
16	OPB seal - 3

each area, when analysing the synthetic missions. By using the worst case the method has been considered conservative but in Figure 5.1, the results show that many of the areas will get a shorter life than before.

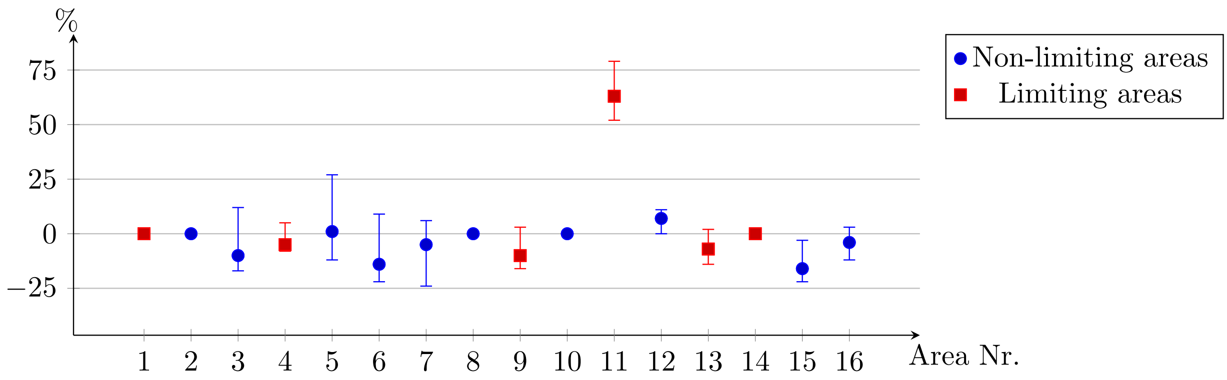


Figure 5.1: *Change in life for the critical areas when rollout is implemented compared to the old method.*

The negative results are mainly caused by a lower strain value during the calculated rollout than the fixed end state, resulting in a larger global cycle, see Figure 5.2(b). On the other hand, a higher minimum strain , see Figure 5.2(a), results in a smaller global cycle giving a positive effect on the life. In addition to the effect from a changed strain range in the global cycle, a changed temperature for the minimum value could affect the life by changing the material properties.

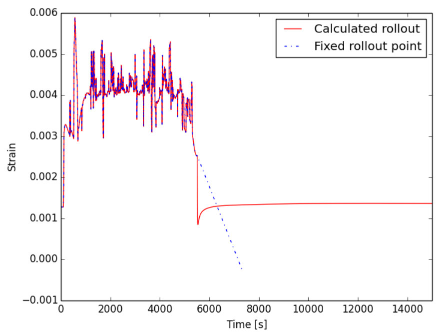
One area highly effected by the decreased strain range for the global cycle is 11, with an average increase in life of 63%. The results separates from the rest both in magnitude and the fact that it is improving the life. Because of this strange result, the fixed end states was verified by analysing the synthetic missions where the values was taken from. When comparing the fixed and the calculated values some differences was found, especially for area 11. This indicates that the model has been changed in some way since the value was extracted. For the other areas, the values corresponded well with a few exceptions but none differed as much as area 11 and no relation to change in life because of this was found.

A positive change in life related to changed material properties was found for area 12. In Figure 5.3(a) and 5.3(b) the strain measure and temperature is seen for mission 15. For the calculated rollout, a new minimum point and a larger strain range for the global cycle is achieved. Based only on this, the result should be negative, but the temperature at the calculated point during the rollout is higher than in the old method where the start state is the minimum. Because of this, the material parameters improves and the area gets a longer life.

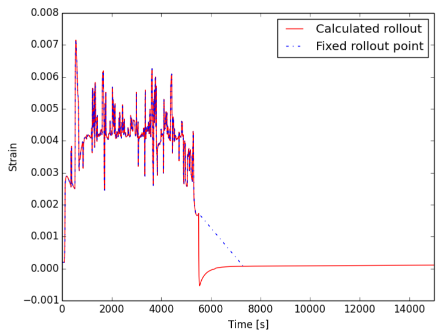
Some of the areas achieves the same effects as mentioned above but with no effect on the life. Example of this is seen in Figure 5.2(c). In the figure the fixed end state do not fully correspond to the calculated rollout but since the strain at the start of the mission is still the minimum, there is no effect on the global cycle. For areas 1, 2, 8, 10 and 14 this is the case and that is why the added rollut give no change in life. However if the starting strain would change so that it exceeds the calculated minimum value during the rollout, these areas would also be affected.

The lower dip when the engine is shut off is believed to have a correlation to the idle running time and the mission profile. The average idle running time for the analysed missions are 259 seconds and for the synthetic missions the idle running is set to 660 seconds. The shorter idle running time will result in a higher temperature when the engine is shut off and possibly a changed stress state. To find out how the idle running time effects, the average results from the missions with the shortest and longest idle running were compared, see Table 5.3. The areas included in the average results are the ones that had a negative total change in life due to the added rollout. The method to take the results from the mission shortest and longest idle running for each day was used since the mission flown during one day tend to have a similar profile.

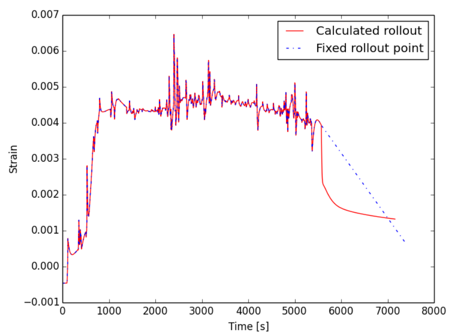
These results indicate a correlation between the idle running time and the negative change in life. It is further strengthen by the results achieved from mission 17 which had a 648 seconds long idle running. This was the only mission which had an idle running time close to the one used in the synthetic mission and the average result became an increase in life by 2% for the same areas combared in Table 5.3. However it is found that the change in life is not only based on the idle running time but also has a close correlation to the mission itself. This was not investigated further in the thesis.



(a) Positive impact on the life due to a higher minimum.

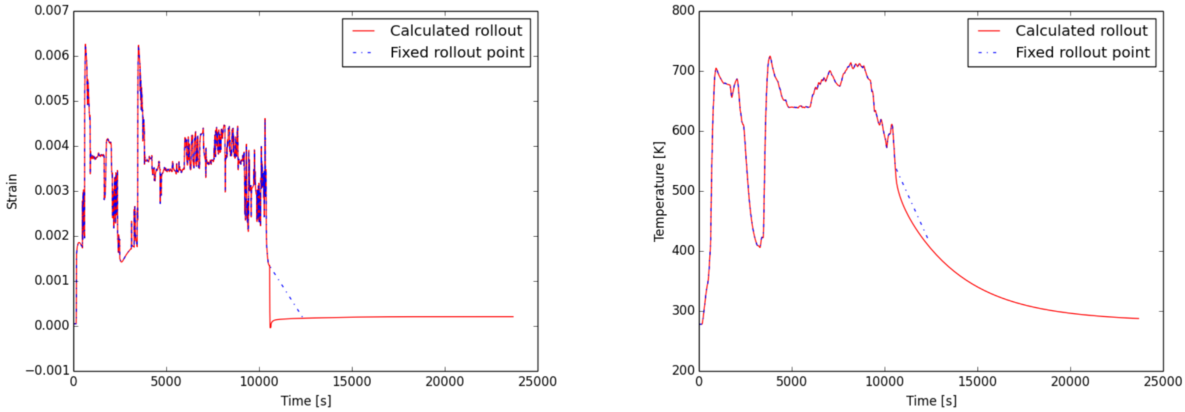


(b) Negative impact on the life due to a lower minimum.



(c) No impact on the life.

Figure 5.2: *The effects of the calculated rollout compared to the fixed point for arbitrary critical areas.*



(a) Strain measure. (b) Temperature.

Figure 5.3: *A representative area that is affected by a changed material behavior.*

Table 5.3: Change in life for areas that had a negative effect from added rollout, results are from the missions with the shortest and longest idle running for each analysed day.

Average idle running time	Change in life
191	-9.6%
345	-7.8%

The average change in life for the implemented rollout effect is close to zero, but if area 11 is excluded the average become -4,8%. Excluding area 11 from the average results probably gives a more representative value, since this change is based rather on a non correct fixed state than an effect from the added rollout. When comparing the calculated results, see Appendix B, to the overall profile no relation is found between the rollout effect and the number of missions per day or the time between them.

5.2.2 Variable starting temperature

In the total results regarding a variable starting temperature, Figure 5.4, it is seen that for almost all areas, a longer or unchanged life is achieved. The positive changes are mainly due to two different aspects, a changed starting strain, see Figure 5.5(a) or a changed early maximum or minimum point, see Figure 5.5(b). These will result in a smaller global cycle which will have a large impact on the estimated life. The negative change for a couple of the areas are mainly driven by another phenomena than the global cycle, which is changed material properties due to a changed temperature.

These three aspects are the most important when considering a variable starting temperature and they will be presented further in separate sections.

Effect of changed starting strain

A changed starting strain especially have an impact for areas where the starting strain are the minimum value of the global cycle, see Figure 5.5(a). Areas highly affected by a changed starting strain are number 1, 2, 8 and 10. When analysing the uni-axial strain measures, these areas have one thing in common, the strain values are not returning to the starting value after the mission, see Figure 5.5(a). As long as the new starting value is still the minimum, the global cycle will decrease with the same amount as the strain has changed.

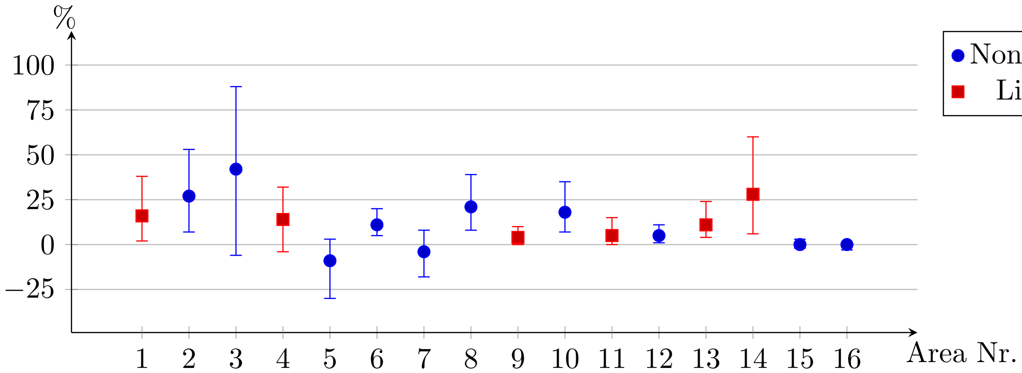
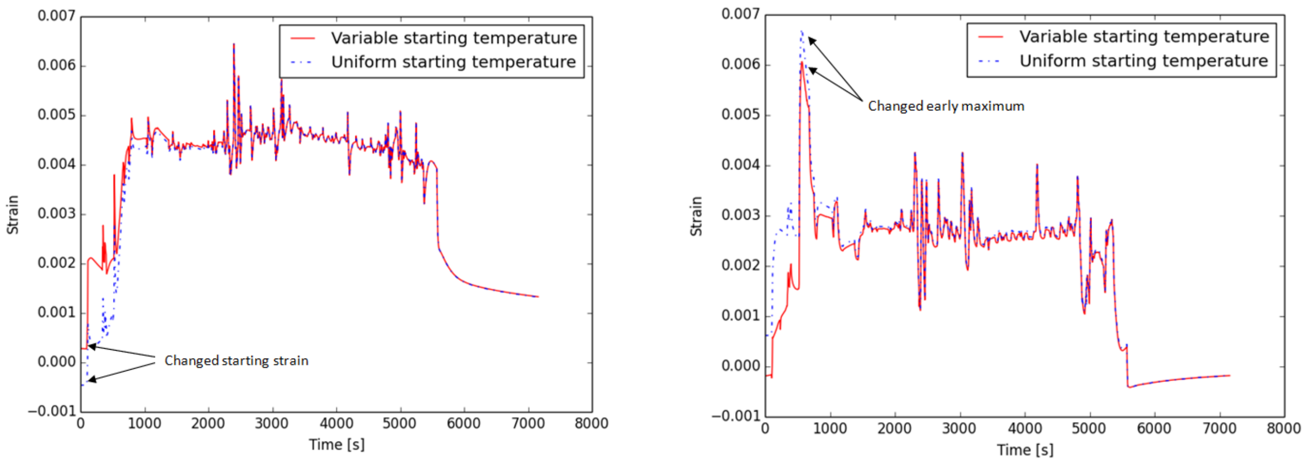


Figure 5.4: *Change in life for the critical areas when implementing a variable start temperature and excluding the first flight mission each day, compared to the results from added rollout.*

Effect of changed maximum or minimum

This positive effect also come from a change of the global cycle. The difference is that for several of the areas the starting strain does not act as neither a maximum nor a minimum strain. Instead areas like 3, 10 and 14 gets their change in life, mainly due to a changed minimum or maximum value that occur early in the mission. These areas still get a changed starting strain which effect the early maximum or minimum, but since it is not a part of the global cycle it won't effect the life significantly. Instead area number 3 get a lower starting strain for mission 12, resulting in a lower maximum, see Figure 5.5(b). Since only the maximum and not the starting strain is a part of the global cycle, the life increases.



(a) Changed starting strain give a smaller global cycle. (b) Changed early minimum strain give a smaller global cycle.

Figure 5.5: *Two of the behaviors that give a changed global cycle.*

Effect of changed material data

The effect of changed material data due to a higher temperature is found, particularly for area number 5. This is one of the areas that cools slowly because of its solid geometry. From the resulting list of fatigue cycles for the missions where the life got reduced, it can be seen that the strain range is close to unchanged and the only parameter that is changed is the temperature. At first, the results was believed to be closely linked to the time between missions but when comparing the subsequent missions 12 and 13 with 18 and 19 the differences are striking. While the missions 12 and 13 have an average of 28.0% loss in life 18 and 19 have a very small but still positive change in life of average 1.5%. In the fatigue data it is found that mission 19 is unaffected by the variable starting temperature because the peak for the global cycle occurs later in the mission where the temperature difference has vanished. For mission 18, the temperature for the global cycle is increased but this time the life increases. Other areas might also get an effect of a changed temperature but it is for this area that it is most noticeable.

The effect of ground missions was analysed for two cases, before the first flight and between two flights. When considering ground missions before the first flight, this occurred for two of the analysed days. Mission 14 was 13 minutes long which is far more than the average length of a ground mission which is 4.6 minutes. Relative to this, mission 10 is more representative with a length of 4.4 minutes. Besides the duration, the time between the ground mission and flight mission is also important for the temperature. For the two occurrences mentioned, the time is 192 and 13 minutes respectively and the average result can be seen in Table 10.1. It show an improvement in the life for most of the areas and with behaviors similar to the ones observed in Figure 5.4. In the statistics regarding the time between the first flights each day and their preceding ground missions, it is seen that the majority are occurring close to the flight mission. Of these, 58% is within one hour which indicates that the results achieved should tend towards the expected overall results.

Table 5.4: Results from the ground mission interaction.

Area	Before first flight	Between flights
1	-2%	-1%
2	6%	0%
3	12%	3%
4	1%	-1%
5	0%	0%
6	7%	2%
7	-1%	-3%
8	0%	-1%
9	5%	-1%
10	0%	-2%
11	2%	1%
12	2%	4%
13	4%	1%
14	9%	3%
15	1%	0%
16	0%	0%

Considering ground missions between flights, this also occurred for two of the analysed days, 1997-01-09 and 2009-02-24. Both of the ground missions are between five and six minutes which can be considered representative for the average and the time between the flight missions is approximately one and two hours respectively. To see what effect the ground missions had on the predicted life, the analysis for the affected days was performed without the ground missions. Results in Table, 10.1 are based on the flight missions that are subsequent to ground missions. It indicates that the ground missions between the flight missions change the life slightly. Changes may seem almost negligible but in Appendix B it is seen that the variations are relatively high between the two analysed missions. Example can be seen for area 3 where the average change is 3% but the deviation between the results are 22%. This indicates that the interaction can not be seen as negligible after all but more analysis is needed to draw any conclusions.

The variable that was found to give the most impact on the life was the time between the flight missions. When excluding the first flight mission each day, the average total change in life was calculated to 11.8%. In Figure 5.4 it is seen that the deviations for several of the areas are large, mainly originating from the varying time since its preceding mission. If only taking into account the analysed missions with approximate 30 minutes since its preceding mission, the results shows a much higher average increase in life and with smaller deviations, see Figure 5.6. The affected missions are 12, 13, 18 and 19 and when only considering these, the average increase in life was 18.9%. Since 36% of the missions are flown within one hour of the previous, a large amount of the missions can be considered to have this larger increase in life.

Results weighted against the overall profile could be a better benchmark to the change in life for the average engine. The weighting is done by dividing the results from the analysed missions into parts depending on the time since its previous mission, see Appendix C. This data is used together with the data from the overall user profile and the results is listed in Table 5.5. It is seen that the calculated results corresponds relatively well to the overall profile. In addition to this a comparison was done between E101 and E102 to see how the results could vary between engines with different usage profiles. The results between the engines is found to be highly individual and dependent on its profile. For example, area 14 which is a limiting area get 7.7% difference in the results between the engines.

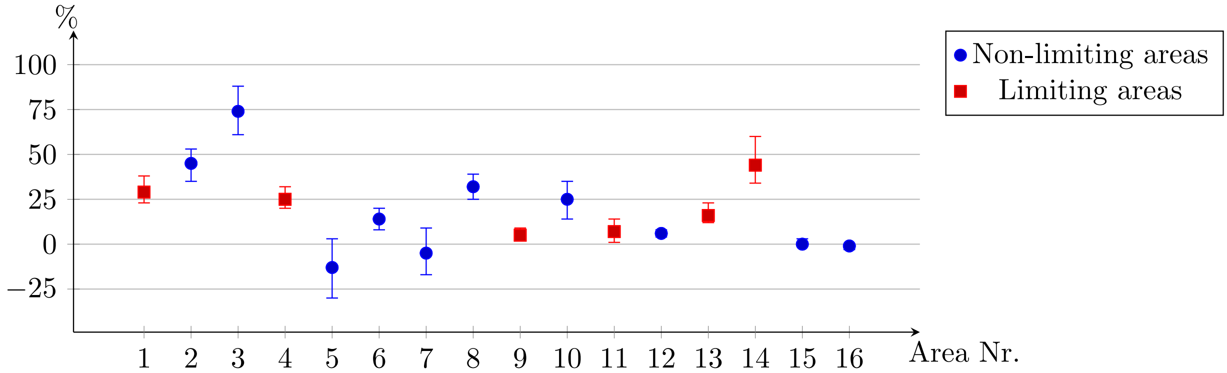


Figure 5.6: *Change in life for the critical areas when only considering subsequent flight missions approximately 30 minutes apart, compared to the results from added rollout.*

Overall, the results give a fairly good estimation how a variable starting temperature affect the life, however, with only one analysed mission between one and three hours, and two between three and five hours since the previous flight uncertainties in the results exists. To improve the results, more analyses within these time frames since its preceding mission should be performed, also including missions between five and eight hours since the previous flight.

Table 5.5: Change in life for variable starting temperature.

Area	Calculated	Overall profile	Difference Overall vs Calculated	E101	E102	Difference E101 vs E102
1	9.5%	8.8%	0.7%	10.7%	5.6%	5.1%
2	15.6%	16.3%	-0.7%	17.5%	9.6%	8.0%
3	26.9%	25.6%	1.3%	30.4%	17.2%	13.2%
4	9.2%	8.2%	1.0%	10.4%	5.9%	4.5%
5	-6.2%	-4.9%	1.3%	-7.0%	-4.7%	-2.3%
6	6.4%	7.0%	-0.6%	7.1%	4.7%	2.4%
7	-3.2%	-2.4%	0.8%	-3.7%	-2.6%	-1.1%
8	12.4%	12.0%	0.4%	14.0%	8.3%	5.7%
9	1.8%	2.8%	-1.0%	1.9%	1.1%	0.8%
10	10.6%	10.3%	0.3%	11.8%	6.8%	5.0%
11	3.0%	3.1%	-0.1%	3.4%	2.2%	1.2%
12	2.9%	2.9%	0.0%	3.2%	1.8%	1.4%
13	6.0%	6.5%	-0.5%	6.7%	4.0%	2.7%
14	16.6%	17.1%	-0.5%	18.6%	10.9%	7.7%
15	0.2%	0.2%	0.0%	0.2%	0.2%	0%
16	0%	-0.2%	0.2%	0%	0%	0%
Avg.	7.0%	7.1%	0.2%	11.5%	4.4%	3.4%

5.2.3 Changed ambient temperature

When alternating the ambient temperature, change in life mainly occur due to a changed starting temperature. This effect also applies on the first mission each day since the uniform starting temperature for these missions is changed. The reason why the ambient temperature does not affect the minimum strain value during the rollout is because it happens close to when the engine has been shut off. The difference in engine temperatures are at this time almost negligible. Ambient temperature should based on this, give results similar to the ones from the variable starting temperature with effects from changed starting strain, maximum or minimum strain and material properties. The average results in Figure 5.7 agrees well with this except for one area that sets apart. This area is number 1 and for a higher ambient temperature it gets a shorter life and vice versa.

Besides the unexpected life change, area 1 also have large deviations in the results regarding the higher ambient temperature. Despite no average change in life it deviates with plus 7% and minus 5% between different missions. Both results are due to a changed starting strain, effecting the global cycle. Why the difference in starting temperature in one case gave higher starting strain and in the other a lower, could based on these two occurrences not be explained. When the ambient temperature is 253K, the area gets a longer life and it is with very low deviations in the results. Neither this behavior corresponds to what is expected for this particular area based on previous results when implementing a variable starting temperature. A higher starting temperature is expected to result in a higher strain value and vise versa and no reasonable explanation is found why this area behaves differently for this implementation.

The results for area 9 differed from the rest by the magnitude of the increased life. For the variable starting temperature it was one of the areas with the lowest change in life but for this implementation it is one of the areas that gets the highest.

Overall the results point towards a slight change in life if the ambient temperature is considered. The average result in Figure 5.7 shows a 1.25% respectively -0.75% change in life. With only one area exceeding an average change greater than 3% compared to using the Nordic median temperature, the effect compared to the other implementations seem to be of less importance. Still, considering usage in Thailand where the engine is know to be used and where the average temperature is around 303K, the temperature difference will give a slightly higher life for most of the areas.

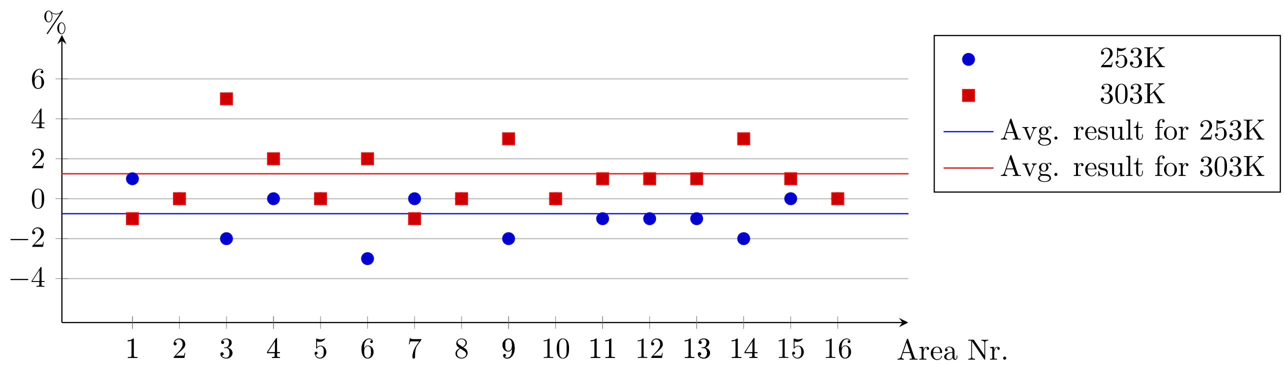


Figure 5.7: *Comparison between the average results for the critical areas when the ambient temperature is 253K and 303K.*

5.2.4 A whole day as one fatigue sequence

When calculating the fatigue damage for one whole day instead of for each mission separately and then adding the fatigue damage contributions, RFC might find different fatigue cycles.

Analysing the average results from all six days, see Figure 5.8, it is seen that a small negative effect is found for two areas, number 1 and 10. It occurs when the first flight mission is preceded by one or several ground missions. The areas experience the lowest strain value during the one of the ground missions and the maximum during one of the flight missions. Of the analysed days, there are two occurrences where the first flight mission is preceded by one or several ground missions. For these, area 1 and 10 will have an approximate 10% decrease in life and since 16% of the days with flight missions have one or several ground missions before the first flight. Based on this overall average decrease in life will be approximate -1.5% for these areas. Area 5 and 7 get a positive positive change in life that is seen in Figure 5.8. It is mainly due to that RFC record other temperatures for some of the larger cycles which change the material properties. The effect is rather small and uncertain since it is not occurring for all days.

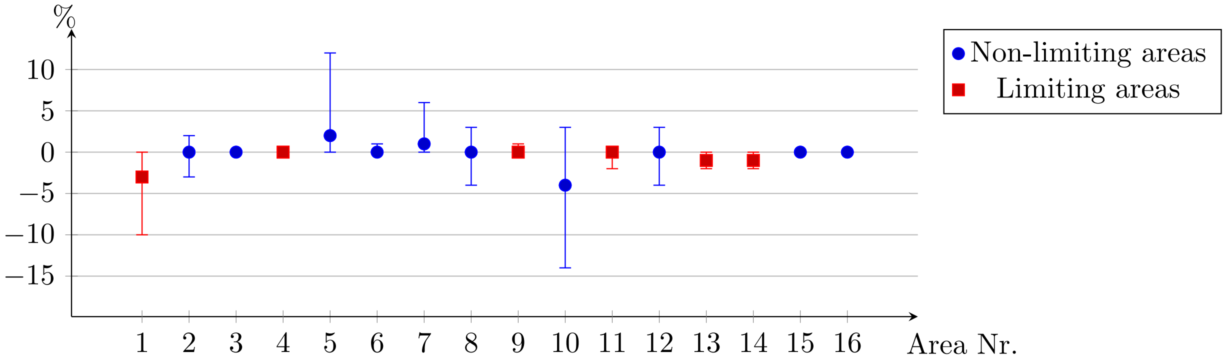


Figure 5.8: *Change in life for the critical areas when consider all mission during each day as one fatigue sequence, compared to the sum of each missions separate contribution.*

In this thesis each day has been evaluated as one sequence, but to go further, all missions for the whole life could instead be seen as one long sequence. Based on the results, extending to all missions as one long sequence are not believed to give any significant effect. However, since the effects that are achieved are negative for all areas except 5 and 7, this indicates that seeing all missions as one sequence would result in a slight further reduced life for most of the areas.

5.2.5 Variable starting stress

When implementing the variable starting stress, areas 1, 2, 8 and 10 achieved a large increase in life, see Figure 5.9. This is because they have the largest strain gap between missions when a variable starting stress is not taken into account. When analysing with a variable starting stress, all missions during the day is analysed in

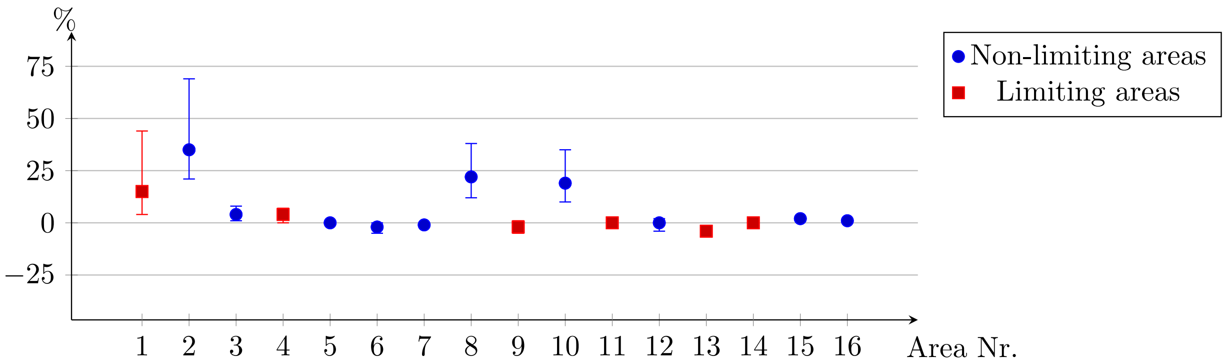


Figure 5.9: *Change in life for the critical areas when implementing variable stress state compared to the results from whole day as a fatigue sequence .*

one sequence. The first mission each day is still using the start state of a new engine which will give conservative results. However it is believed, based on the strain plots with eight hours of rollout, that a new less conservative starting state could be found. This is since the strain value for each area tend to stabilize. By changing the start state for the first mission each day, the predicted life could further increase. However in this thesis, no new start state will be proposed since it is believed that further analyses are needed.

Since the results from the variable stress state are calculated for each day it is difficult to weight the results towards the overall profile but since the results from the average starting temperature corresponded well, these results will be considered representative.

5.2.6 Total change in life

Comparing the average results from the variable starting stress to the result when using the old method is presented in Figure 5.10. It is seen that 4 out of 6 limiting areas will get an improved life with an average of 22%. The results from the variable starting stress includes all implementations that has been presented except the changed ambient temperature. The low variations in the results for the areas with a negative change in life are because they mostly depend on the added rollout. Areas with high deviations are instead depending more on a variable starting state i.e. the implementations depend more on the mission set-up then the effect from the added rollout.

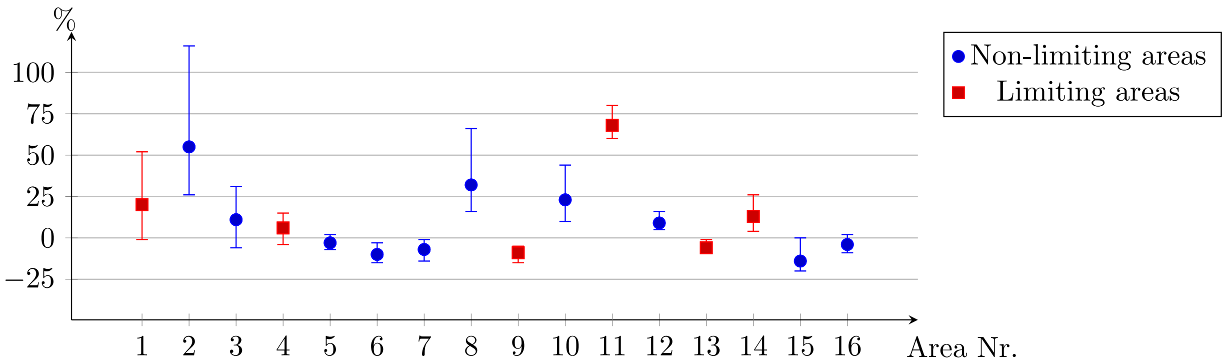


Figure 5.10: *Change in life for the critical areas when implementing variable stress state compared to the old method.*

Because the results from the variable starting temperature corresponded relatively well to the overall profile and since the added rollout is not depending on the preceding mission, the total changes is seen as representative for the overall profile. However to better ensure what the overall change in the predicted life will be, the influence of the ground missions and idle running has to be further investigated.

6 Conclusions

When the results from all implementations are compared to the old method, the predicted lives are increased for four out of six components based on their limiting areas. The average increase in life for these four areas is 26.8% and the average decrease of the remaining two is 8%. The changed life is found to have a close correlation to changes of the global cycle. Because of this, mission length and fatigue damage has no close correlation. The decision to base the average results on the percentage change rather then the damage for each mission only gave slight differences, but is considered to give better results for the limited number of analyses in this theses.

When implementing the rollout effect, it disproved the assumption that the method used is conservative. The changes are in most cases due to a changed minimum in the global cycle but also depends on the material properties. When the fixed points are compared to analyses of the synthetic missions from which they was extracted, variations are found for some of the areas, see Appendix B. This indicates that the used model have been changed since the values where extracted. It is believed that the positive change in life for area 11 are mainly due to this fact. When analysing the data with respect to the changed minimum strains, some correlation between the idle running time and the decreased lives is found. This conclusion is further strengthened by the fact that the worst case values are extracted from synthetic missions with much longer idle running then the average that are for the missions. To fully conclude on this relation, more analyses has to be performed with longer idle running.

When implementing a variable starting temperature for the missions, a close correlation between a changed life and time since the previous mission is found. The life changes are mainly due to a decreased global cycle but also because of changed material parameters. For most areas the effect is positive and a decreased damage contribution is achieved. The interaction of ground missions before the first flight and between missions are found non-negligible but considering the statistics regarding their occurrence the overall effect is relatively small. Regarding ground missions between two missions, no certain trend could be found regarding how they affect the life, and more analyses needs to be preformed for any conclusions about the overall effect to be made.

Changing the ambient temperature gave an indication that the results will be similar to the ones from a variable starting temperature but less distinct. Areas which got an increased life from a variable starting temperature also got it from an increased ambient temperature. The effect is small, but shows that engines used in warmer climates get a slightly increased life.

Considering all missions during each day as one fatigue sequences gave for most areas a reduced life. The largest negative effect that was found, and could be drawn any conclusions from, was when the first flight mission is preceded by a ground mission. This results in a larger global cycle and shorter life for the two affected areas. Overall the results have a tendency to give shorter life, which indicates that if all mission during the entire component life would be seen as one sequence, the life would rather decrease then increase. Compared to previous implementations the effects are small, but since it is nonconservative it can still be of importance to take into consideration.

The areas with contact elements and non linear behavior, achieved a much longer life when implementing the variable starting stress. This could possibly be further increased by also changing the starting state for the first mission each day.

If the idle running can be concluded to be the reason for much of the extended damage from the implemented rollout, it needs to be investigated how a changed idle running will effect the life from the variable starting state implementations. A longer idle running could possibly decrease the life gained from these implementations due to, for example a lower temperature.

7 Future work

This chapter will present ways to continue the work with the implementations that has been investigated.

Since the results from the added rollout are relatively constant it might be possible to adjust to a new fixed states and achieve a conservative result. However it is recommended to first run more analyses to fully conclude how the results change under different circumstances, for example changed idle running time. If the results show that a fixed state no longer seem suitable, it is proposed to add load steps to the mission load data file with case 0 corresponding to the rollout that is desired. If the temperature is to be extracted and used for the next subsequent mission, time steps for the whole time between the missions should be added. Variables like rotor speed and temperatures could be added to the time steps via decreasing functions that has to be constructed. If continuing to use a fixed last point, the recommendation is to continuously verify the values when larger changes in the used models are implemented.

If the method above is implemented where the rollout is analyzed, it should be possible to extract the temperature state from the last time step like it is done in this thesis. This is proved to work but it is also recommended to consider alternative ways of implementation.

The ground mission interaction considering a variable temperature from a ground mission preceding the first mission might be easy to implement depending on what model is chosen to use for the rollout and variable starting temperature. If the variable starting temperature is to be extracted from the preceding mission this could also be done for the ground missions. Since it is not fully concluded how a ground mission between two flight missions will affect the life, the only recommendation is to perform more analyses to find this.

The implementation of a variable ambient temperature is not suggested to be implemented, since the effect was relatively small, however, if it is wanted, the ambient temperature has to be measured as an input. These have to be verified towards experiments and as a final conclusion it is recommended to save this implementation to last, since it requires a lot of work for a small change in life.

When analysing the missions for one day as a sequence, a small negative effect was found for area 1 and 10 when a ground mission was preceding the first flight flight mission. This could possibly be implemented via a correction factor based on how many occurrences that are noted. Besides this, the changes in life for the other areas was so small and with no deviations that they could possibly also be corrected via a small correction factor for the whole life.

The non-linear effect in some of the areas with contact elements is suggested to be further investigated and verified. If everything seem in order it is recommended in the short term to search for a new starting state for the effected areas. This would give a significant increase in life without much effort. In the long term a more advanced model that base the start state on the previous mission could further increase the life for missions that occur closely after another. This is however not recommended in the nearest future since the changes to the current system is predicted to have to be very large.

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8 Appendix A - Python scripts

Further documentation about the scripts can be found in each induvidual readme.txt file

1 - create_lasttemp.py

Create an temperature input file for the subsequent mission. One program to be used with LAS and one with LTS.

Located on an internal drive:
/project/las4/InReview/VOLS_10196261-000-01/PythonScripts/Create_lasttemp

2 - LTS-shell

Located on an internal drive:
/project/las4/InReview/VOLS_10196261-000-01/PythonScripts/LTS-shell

LTS_variable_temp.py

Create the necessary folders when using LTS and create the *xml* files and *.sh* file with a variable starting temperature implemented.

LTS_variable_stress.py

Create the necessary folders when using LTS and create the *xml* files and *.sh* file with a variable starting temperature and stress implemented.

3 - cns_add.py

Add the cns files for all missions during a day into one cns file so you can use it in CUMFAT to calculate as a whole sequence.

Located on an internal drive:
/project/las4/InReview/VOLS_10196261-000-01/PythonScripts/Add_CNSfiles

9 Appendix B - Results for the implementations

In this appendix the results in percentage is presented for the different section. First a table of the average results for the implementations is presented.

Table 9.1: The average results in percentage for the different implementations.

Area	Added rollout	Variable starting temperature	Changed ambient temperature (253K)	Changed ambient temperature (303K)	A whole day as one sequence	Variable starting stress	All implementations
1	0 %	16 %	1 %	-1 %	-3 %	15 %	20 %
2	0 %	27 %	0 %	0 %	0 %	35 %	55 %
3	-10 %	42 %	-2 %	5 %	0 %	4 %	11 %
4	-5 %	14 %	0 %	2 %	0 %	4 %	6 %
5	1 %	-9 %	0 %	0 %	2 %	0 %	-3 %
6	-14 %	11 %	-3 %	2 %	0 %	-2 %	-10 %
7	-5 %	-4 %	0 %	-1 %	1 %	-1 %	-7 %
8	0 %	21 %	0 %	0 %	0 %	22 %	32 %
9	-10 %	4 %	-2 %	3 %	0 %	-2 %	-9 %
10	0 %	18 %	0 %	0 %	-4 %	19 %	23 %
11	63 %	5 %	-1 %	1 %	0 %	0 %	68 %
12	7 %	5 %	-1 %	1 %	0 %	0 %	9 %
13	-7 %	13 %	- 1%	1 %	-1 %	-4 %	-6 %
14	0 %	28 %	-2 %	3 %	-1 %	0 %	13 %
15	-16 %	0 %	0 %	1 %	0 %	2 %	-14 %
16	-4 %	0 %	0 %	0 %	0 %	1 %	-4 %

Added rollout

Table 9.2: Results in percentage for calculated rollout compared to the old method.

Date [YYYYMMDD hhmmss]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109 091948	0 %	0 %	-17 %	-7 %	-4 %	-21 %	-3%	0 %
19970109 105056	-48 %	14 %	11 %	44 %	-52 %	37 %	21%	-98 %
19970109 110947	0 %	0 %	-7 %	-5 %	-2 %	-7 %	1%	0 %
20101124 114446	-20 %	-29 %	39 %	83 %	180 %	47 %	-6%	-16 %
20101124 131753	-52 %	-17 %	27 %	80 %	171 %	60 %	24%	-99 %
20101124 163338	0 %	0 %	-15 %	-6 %	12 %	-16 %	-12 %	0 %
20101124 182335	0 %	0 %	-13 %	-6 %	23 %	-18 %	-6 %	0 %
20101124 202657	0 %	0 %	-9 %	-5 %	27 %	-13 %	6 %	0 %
20090224 172151	0 %	0 %	-15 %	-7 %	-5 %	-21 %	-10 %	0 %
20090224 193016	-2 %	-5 %	29 %	88 %	171 %	18 %	12 %	-97 %
20090224 204827	0 %	0 %	-10 %	-6 %	0 %	-14 %	3 %	0 %
20130311 105138	-48 %	-10 %	145 %	161 %	-29 %	18 %	13%	-8 %
20130311 111656	0 %	0 %	-13 %	-5 %	-4 %	-16 %	-24 %	0 %
20130311 174527	0 %	0 %	12 %	5 %	1 %	9 %	1 %	0 %
20080915 064823	0 %	0 %	-4 %	0 %	-4 %	-11 %	-1 %	0 %
20080915 120935	0 %	0 %	-3 %	0 %	-5 %	-12 %	-3 %	0 %
20130506 082226	0 %	0 %	-15 %	-5 %	-12 %	-17 %	-9 %	0 %
20130506 102210	0 %	0 %	-17 %	-7 %	-13 %	-25 %	-17 %	0 %
20130506 120536	0 %	0 %	-15 %	-8 %	-3 %	-18 %	-4 %	0 %

Date [YYYYMMDD hhmmss]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
19970109 091948	-14 %	0 %	63 %	8 %	-7 %	0 %	-22 %	-12 %
19970109 105056	-27 %	-79 %	491 %	0 %	0 %	-98 %	-4%	-100 %
19970109 110947	-4 %	0 %	71 %	0 %	-2 %	0 %	-14 %	-10 %
20101124 114446	-20%	-75 %	358 %	-33 %	-48 %	-90 %	-29 %	85 %
20101124 131753	-19 %	-78 %	578 %	0 %	-26 %	-100 %	0 %	-100 %
20101124 163338	-11 %	0 %	54 %	8 %	-9 %	0 %	-19 %	2 %
20101124 182335	-12 %	0 %	61 %	8 %	-11 %	0 %	-21 %	3 %
20101124 202657	-8 %	0 %	70 %	10 %	-7 %	0 %	-17 %	3 %
20090224 172151	-13 %	0 %	59 %	9 %	-9 %	0 %	-21 %	-8 %
20090224 193016	-9 %	-78 %	423 %	0 %	-29 %	-100 %	-4 %	42 %
20090224 204827	-8 %	0 %	58 %	11 %	-7 %	0 %	-15 %	-2 %
20130311 105138	-25 %	-75 %	381 %	-20 %	-44 %	-55 %	-24 %	-100 %
20130311 111656	-10 %	0 %	47 %	5 %	-9 %	0 %	-16 %	-2 %
20130311 174527	3 %	0 %	74 %	0 %	-5 %	0 %	-10 %	-2 %
20080915 064823	-14 %	0 %	60 %	0 %	2 %	0 %	-2 %	-4 %
20080915 120935	-15 %	0 %	57 %	7 %	0 %	0 %	-3 %	-9 %
20130506 082226	-10 %	0 %	69 %	8 %	-8 %	0 %	-22 %	-5 %
20130506 102210	-16 %	0 %	69 %	8 %	-14 %	0 %	-22 %	-3 %
20130506 120536	-11 %	0 %	66 %	11 %	-8 %	0 %	-22 %	-8 %

Variable starting temperature

Table 9.3: Results in percentage for variable starting temperature compared to calculated rollout.

Date [YYYYMMDD hhmmss]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109 091948	0 %	0 %	0 %	0 %	0 %	0 %	0%	0 %
19970109 105056	31817 %	2588 %	19074 %	1956 %	48 %	2586 %	165%	-86 %
19970109 110947	3 %	11 %	13 %	2 %	-2 %	4 %	-2%	8 %
20101124 114446	0 %	0 %	0 %	0 %	0 %	0 %	0%	0 %
20101124 131753	129 %	117 %	566 %	194 %	158 %	560 %	40%	-99 %
20101124 163338	2 %	4 %	3 %	-2 %	0 %	4 %	-1 %	2 %
20101124 182335	25 %	47 %	68 %	23 %	-26 %	11 %	-7 %	39 %
20101124 202657	23 %	45 %	61 %	20 %	-30 %	8 %	-18 %	32 %
20090224 172151	0 %	0 %	-2 %	0 %	0 %	0 %	0 %	0 %
20090224 193016	- %	- %	9199 %	1329 %	-54 %	1892 %	65%	-75 %
20090224 204827	5 %	10 %	28 %	10 %	-16 %	11 %	-9 %	15 %
20130311 105138	3 %	0 %	2 %	-3 %	0 %	1 %	0%	-1 %
20130311 111656	-6 %	7 %	18 %	3 %	0 %	9 %	-1 %	-1 %
20130311 174527	3 %	7 %	9 %	-4 %	1 %	5 %	1 %	8 %
20080915 064823	-1 %	-2 %	-1 %	0 %	0 %	0 %	0 %	0 %
20080915 120935	2 %	10 %	-6 %	4 %	0 %	10 %	0 %	9 %
20130506 082226	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
20130506 102210	29 %	53 %	88 %	24 %	3 %	19 %	-5 %	32 %
20130506 120536	38 %	34 %	-79 %	32 %	0 %	16 %	8 %	24 %

Date [YYYYMMDD hhmmss]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
19970109 091948	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
19970109 105056	1726 %	-51 %	289 %	-33 %	510 %	-100 %	-1670 %	76 %
19970109 110947	0 %	17 %	0 %	11 %	4 %	10 %	0 %	0 %
20101124 114446	0 %	0 %	0 %	0 %	0 %	0 %	0%	0 %
20101124 131753	284 %	-53 %	107 %	0 %	145 %	-100 %	186 %	19 %
20101124 163338	2 %	2 %	1 %	0 %	2 %	5 %	0 %	0 %
20101124 182335	4 %	34 %	5 %	7 %	14 %	35 %	-1 %	-3 %
20101124 202657	5 %	18 %	2 %	4 %	12 %	34 %	-1 %	0 %
20090224 172151	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
20090224 193016	873 %	-63 %	345 %	- %	480 %	-100 %	880 %	-19 %
20090224 204827	1 %	10 %	5 %	2 %	7 %	18 %	1 %	0 %
20130311 105138	-2 %	0 %	0 %	- %	0 %	0 %	0 %	0 %
20130311 111656	8 %	-2 %	3 %	2 %	5 %	11 %	1 %	0 %
20130311 174527	0 %	7 %	-1 %	0 %	4 %	6 %	0 %	0 %
20080915 064823	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
20080915 120935	9 %	8 %	5 %	1 %	7 %	14 %	1 %	0 %
20130506 082226	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
20130506 102210	10 %	35 %	15 %	8 %	23 %	60 %	3 %	0 %
20130506 120536	3 %	14 %	8 %	4 %	14 %	46 %	-1 %	0 %

Ground mission preceding the first flight mission

Table 9.4: Results in percentage for the missions with a preceding ground mission.

Date [YYYYMMDD]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
20101124 163338	2%	4%	3%	-2%	0%	4%	-1%	2%
20130311 111656	-6%	7%	18%	3%	0%	9%	-1%	-1%
Date [YYYYMMDD]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
20101124 163338	2%	2%	1%	0%	2%	5%	0%	0%
20130311 111656	8%	-2%	3%	2%	5%	11%	1%	0%

Ground mission occurring between two fights flight mission

Table 9.5: Results in percentage for the mission where a ground mission was occurring between two fights.

Date [YYYYMMDD]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109 110947	-3%	-4%	-5%	-6%	0%	2%	0%	-6%
20090224 204827	2%	5%	12%	5%	1%	3%	-6%	3%
Date [YYYYMMDD]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
20101124 163338	1%	-8%	1%	8%	0%	1%	0%	0%
20130311 111656	-4%	3%	2%	1%	2%	5%	1%	0%

Changed ambient temperature

Table 9.6: Results in percentage for changed ambient temperature to 253K compared to Nordic median.

Date [YYYYMMDD]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109 091948	1%	0%	-6%	-2%	-1%	-3%	0%	0%
19970109 105056	-46%	-11%	4%	1%	-1%	-20%	-6%	3%
19970109 110947	1%	1%	-1%	-2%	0%	-1%	0%	1%
20101124 114446	-2%	-31%	-45%	-33%	14%	-36%	-9%	86%
20101124 131753	-29%	-32%	-34%	-22%	-1%	-37%	-4%	1630%
20101124 163338	1%	1%	0%	2%	0%	-3%	0%	2%
20101124 182335	0%	1%	0%	0%	0%	-1%	0%	1%
20101124 202657	3%	2%	0%	1%	0%	-1%	0%	-8%
20090224 172151	0%	0%	0%	4%	1%	-3%	-4%	0%
20090224 193016	-100%	-100%	-25%	-13%	-1%	-20%	-3%	-1%
20090224 204827	1%	1%	-2%	1%	0%	-3%	3%	2%
20080915 064823	3%	1%	-1%	0%	0%	-3%	0%	0%
20080915 120935	2%	-2%	-4%	-1%	0%	-5%	0%	-2%
Date [YYYYMMDD]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
19970109 091948	-2%	0%	-1%	-1%	-2%	-3%	-1%	0%
19970109 105056	-30%	-29%	4%	0%	-2%	1%	-6%	-5%
19970109 110947	-1%	2%	0%	-1%	0%	0%	0%	0%
20101124 114446	-30%	17%	-18%	-25%	-29%	-42%	-28%	-6%
20101124 131753	-28%	-16%	-6%	0%	-9%	96%	-9%	-2%
20101124 163338	0%	2%	0%	-1%	0%	0%	-1%	0%
20101124 182335	-2%	1%	0%	-1%	-1%	-1%	0%	0%
20101124 202657	-1%	0%	0%	0%	-1%	-1%	0%	0%
20090224 172151	-1%	-1%	0%	-1%	-1%	-3%	0%	0%
20090224 193016	-15%	-17%	4%	-100%	-2%	13%	0%	-2%
20090224 204827	-3%	2%	0%	-1%	-1%	-2%	-1%	0%
20080915 064823	-4%	0%	-2%	-1%	-2%	-4%	-1%	0%
20080915 120935	-4%	-2%	-3%	-2%	-3%	-5%	-1%	0%

Table 9.7: Results in percentage for changed ambient temperature to 303K compared to Nordic median.

Date [YYYYMMDD]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109 091948	-3%	0%	10%	1%	1%	8%	0%	0%
19970109 105056	193%	25%	-28%	-25%	9%	55%	6%	-10%
19970109 110947	6%	-1%	1%	0%	0%	3%	0%	-2%
20101124 114446	-13%	128%	256%	156%	-27%	222%	17%	-65%
20101124 131753	126%	161%	121%	79%	-17%	153%	11%	78%
20101124 163338	0%	9%	10%	3%	-4%	6%	-1%	1%
20101124 182335	-4%	-4%	-3%	-2%	1%	3%	0%	-3%
20101124 202657	-7%	-4%	0%	-1%	-1%	3%	0%	6%
20090224 172151	-2%	1%	11%	0%	0%	5%	4%	1%
20090224 193016	283%	10%	48%	19%	3%	84%	7%	-9%
20090224 204827	-3%	-3%	9%	3%	1%	4%	-7%	-4%
20080915 064823	-5%	1%	10%	5%	1%	7%	-1%	1%
20080915 120935	-2%	1%	8%	2%	0%	9%	1%	4%
Date [YYYYMMDD]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
19970109 091948	6%	1%	2%	2%	4%	7%	1%	1%
19970109 105056	55%	88%	-7%	0%	4%	-3%	12%	12%
19970109 110947	4%	-3%	0%	1%	0%	0%	1%	1%
20101124 114446	175%	-20%	51%	0%	93%	-23%	111%	14%
20101124 131753	147%	43%	17%	0%	27%	-83%	27%	7%
20101124 163338	4%	1%	2%	3%	2%	6%	1%	0%
20101124 182335	3%	-3%	0%	1%	1%	1%	1%	1%
20101124 202657	2%	2%	0%	1%	1%	1%	1%	1%
20090224 172151	6%	1%	1%	2%	3%	5%	0%	1%
20090224 193016	37%	62%	-8%	0%	4%	-23%	4%	4%
20090224 204827	7%	-4%	1%	2%	2%	3%	1%	1%
20080915 064823	6%	0%	3%	3%	5%	9%	1%	1%
20080915 120935	8%	3%	4%	5%	6%	10%	2%	1%

Whole day as a sequence

Table 9.8: Results in percentage for whole day as a sequence compared to the sum of each missions separate contribution.

Date [YYYYMMDD]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
20101124	-9 %	-2 %	0 %	0 %	0 %	0 %	6 %	0 %
20090224	0 %	0 %	0 %	0 %	12 %	0 %	4 %	0 %
20130311	-10 %	-3 %	0 %	0 %	0 %	1 %	0 %	-4 %
20080915	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
20130506	0 %	2 %	0 %	0 %	1 %	0 %	0 %	3 %
Date [YYYYMMDD]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
19970109	0 %	-2 %	0 %	-4 %	-1 %	-1 %	0 %	0 %
20101124	0 %	-8 %	0 %	0 %	-1 %	-2 %	0 %	0 %
20090224	0 %	-2 %	0 %	0 %	-1 %	0 %	0 %	0 %
20130311	1 %	-14 %	-2 %	3 %	-2 %	0 %	0 %	0 %
20080915	0 %	-2 %	0 %	0 %	0 %	0 %	0 %	0 %
20130506	0 %	3 %	0 %	0 %	0 %	-1 %	0 %	0 %

Variable starting stress

Table 9.9: Results in percentage for variable starting stress compared to a whole day as a sequence.

Date [YYYYMMDD]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109	12 %	29 %	1 %	0 %	0 %	0 %	-1 %	22 %
20101124	44 %	69 %	8 %	4 %	0 %	1 %	-2 %	37 %
20090224	3 %	21 %	2 %	3 %	0 %	-3 %	-1 %	11 %
20130311	10 %	53 %	1 %	4 %	0 %	-3 %	-2 %	27 %
20080915	13 %	22 %	5 %	7 %	0 %	-5 %	-2 %	16 %
20130506	17 %	38 %	7 %	6 %	0 %	0 %	-2 %	20 %
Date [YYYYMMDD]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
19970109	-1 %	17 %	0 %	1 %	-3 %	1 %	2 %	2 %
20101124	-2 %	35 %	0 %	0 %	-4 %	0 %	2 %	1 %
20090224	0 %	9 %	0 %	-4 %	-2 %	0 %	2 %	1 %
20130311	-4 %	27 %	1 %	1 %	-2 %	-1 %	2 %	1 %
20080915	-5 %	20 %	-1 %	1 %	-5 %	0 %	2 %	1 %
20130506	1 %	10 %	0 %	2 %	-6 %	0 %	2 %	1 %

All implementations

Table 9.10: Results in percentage for all implementations (variable starting stress) compared to the old method.

Date [YYYYMMDD]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
19970109	14%	36%	-7%	-5%	-4%	-11%	-1%	27%
20101124	52%	116%	31%	11%	-3%	-8%	-8%	67%
20090224	6%	26%	0%	1%	2%	-15%	-4%	17%
20130311	-1%	58%	11%	3%	-1%	-3%	-14%	26%
20080915	13%	26%	-2%	9%	-5%	-11%	-4%	21%
20130506	37%	69%	30%	14%	-7%	-12%	-9%	41%
Date [YYYYMMDD]	Area 9	Area 10	Area 11	Area 12	Area 13	Area 14	Area 15	Area 16
19970109	-9%	22%	68%	6%	-7%	4%	-16%	-9%
20101124	-9%	44%	70%	13%	-6%	23%	-18%	3%
20090224	-9%	10%	66%	6%	-7%	7%	-16%	-4%
20130311	-5%	12%	60%	9%	-8%	8%	-12%	-1%
20080915	-15%	22%	61%	5%	-1%	8%	0%	-5%
20130506	-8%	25%	80%	16%	-6%	26%	-20%	-5%

10 Appendix C - Results from variable starting temperature based on time since previous mission

Table 10.1: Results based on time since previous mission.

	Time since previous mission [h]			
Number	<1	1<3	3<5	5<8
1	24%	5%	2%	-%
2	38%	10%	9%	-%
3	62%	28%	2%	-%
4	21%	10%	0%	-%
5	-11%	-14%	0%	-%
6	12%	11%	8%	-%
7	-5%	-9%	0%	-%
8	27%	15%	8%	-%
9	4%	1%	4%	-%
10	24%	10%	8%	-%
11	6%	5%	2%	-%
12	7%	2%	1%	-%
13	13%	7%	5%	-%
14	37%	18%	10%	-%
15	0%	1%	1%	-%
16	0%	0%	0%	-%